ENCORE Feasibility Study Call 2
Final Report

Title: **Nature Inspired Routing for Resilient Networked Systems**
Thematic Areas: *Resilience in Network and Process Dynamics, Leveraging Natural World Examples of Complex Systems*

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Abstract: Human built systems are increasingly under the strain of both natural and man-made stressors. Many of the critical infrastructure systems have network dimensions. Despite their national importance, the complexity of interdependent and multi-scale networks means we do not fully understand how to invest and adapt them to different risks and uncertainties. The study analysed the rail transport infrastructure in the Greater London area at the morning commute time, multiplexing different services that spanned local and regional travel patterns. The analysis focused on both the network's resilience to cascade delays and robustness to station closures. It was found through hierarchical trophic coherence analysis that the network was **not at all resilience to delay cascades** due to its highly incoherent nature, but **extremely robust against station closures** due to its relatively large interconnected core.

Introduction

Problem Statement: Critical infrastructures (CI) have network topologies that are multi-modal, multi-scale, and interdependent. These multiplexed complex networks often suffer from a variety of man-made and natural perturbations. These cause elements of the network to cease functioning, leading to ***failure cascades*** and the creation of ***new hidden topological vulnerabilities***. Traditional data-driven agent-based-models (ABMs) have been used to inform planning and management (i.e., driver route selection behaviour for ITS [1]). Iterative scenario testing coupled with historical data allows network planners and operators to understand most problems and causal mechanisms. Yet, extreme circumstances that result from a unique combination of coinciding events and decisions can cause difficult to predict and catastrophic outcomes.

Aim and Scientific Novelty: This project will conduct a feasibility study in order to identify where the greatest opportunities and challenges are in bio-inspired resilience, so that a proposal can be written using evidence from this study. The study will leverage on a recent key scientific advance: ***"ecosystems under stress adapt its energy exchange network (predation habits) in accordance to global resilience and not selfish behaviour"*** [2]. The natural food webs rewire their networks to minimize cascade failures and co-evolve with both natural stressors and predation habits. In ecosystems, the distributed intelligence in adapting under future uncertainty may help us develop connected thinking and build dynamic approaches to resilience. In order to map CI networks to food webs, the feasibility study will focus on better understanding **three challenges**: **(1)** energy transfer hierarchies in CI networks, **(2)** degrees of freedom in CI networks, **(3)** complexities of multiplexed CI networks with different spatial dependencies [4] and recovery time effect on failure cascades [3-5].

Methods

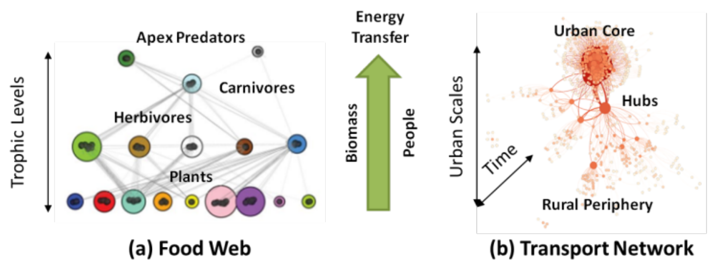

Figure 1: Analogy between Ecology Food Web and Transport Network Energy Transfer Expressed as a Hierarchical Graph with Trophic Levels.

WP-1 (Network Construction and Resilience): Using topological data (OpenStreetMap) and flow data (TransportAPI), we construct transport network maps and identify coherent trophic levels of hierarchical energy transfer, which allows networks to grow in both size and complexity whilst retaining resilience [6]. Trophic coherence is a property of directed graphs that defines how much a graph is hierarchically structured. Johnson et al. [6] proved that "a maximally coherent network with constant interaction strengths will always be linearly stable" and that it is a better statistical predictor of linear stability than size or complexity. We measured the coherence of the network through the in-coherence parameter, a measure of how much the trophic distance of the nodes is concentrated around its mean value.

WP-2 (Rewiring - Nature Inspired Traffic Rerouting): To study of the robustness of the network we firstly evaluated the structure of the network, analyzing its core and periphery nodes. Finally, we attacked the network, removing some of the nodes and studying the connectivity of the resulting network. The nodes to be removed are chosen randomly and following some classification metrics. The objective of node removal is two-fold. Firstly, we study which nodes are more central in the network or more crucial for its well-functioning, focusing on detecting hubs (higher in or out degree/strength), major intermediaries (higher betweenness) or top nodes in the trophic hierarchy (high trophic level). With such measures we can rank nodes by their importance, and then proceed to attack the network by sequentially removing the top nodes of such rank. To assess the effect of this attacks on the network, and thus the criticality of each node, we study both the connectivity (e.g., size of the largest strongly connected component) and the increase of mean path length (which can be related to travel time). An additional quantity to be considered is the change in mean edge/node betweenness after removal of nodes, as a measure of overload due to rerouting of flows.

Through this process, we aim to uncover the relationship between hidden mesoscopic structures (e.g. core-periphery ratio) and failure cascades with recovery times [2, 3]. This will lead to the development of nature inspired rewiring mechanisms that maximize network resilience against cascade failures by preserving hidden structures. The results will allow us to co-explore with stakeholders on how the steps can transform network rewiring methods into data-driven algorithmic approaches to inform real-time traffic rerouting, with sensitivity analysis on degrees of freedom and cost trade-off.

Results

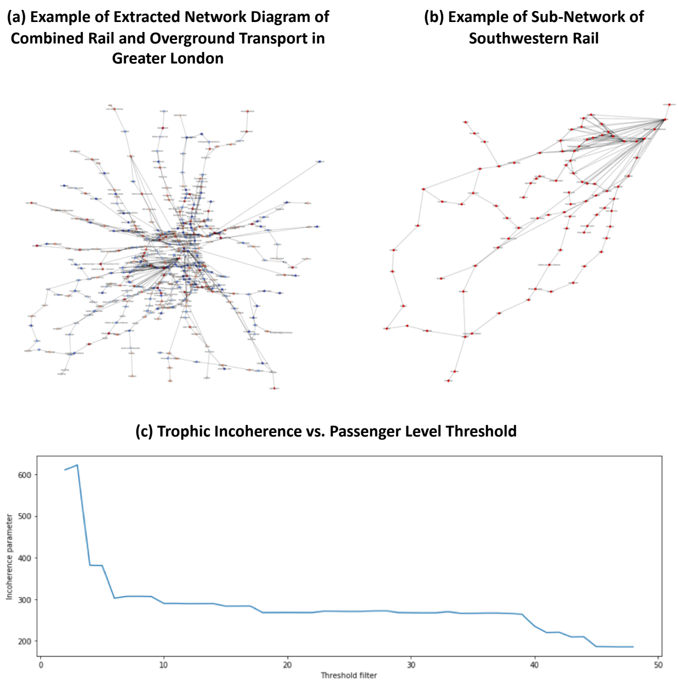

Figure 2: Transport Network and Trophic Incoherence.

WP-1 (Network Construction and Resilience): We first construct a directed and weighted (passenger volume) graph. This is shown in Figure 2a for the Greater London example. It can also be partitioned into operator based sub-graphs, such as Southwestern Rail in Figure 2b.

We define trophic level as an increasing order of stations that have more passengers coming in than going out (energy transfer). Trophic level 1 is defined as We consider trophic coherence (or incoherence) in the morning commute time, when passenger volumes are mostly going from suburban to urban areas. Nonetheless, there are always non-zero passenger flow from urban back to suburban areas, and as such the trophic levels are not well defined. To overcome this, we set a threshold filter, whereby passenger volumes below a value is considered as not important to congestion effects. Figure 2d shows that as we increase the threshold number past 10, we reach a plateau between 10 and 40, whereby the incoherence level stabilizes. That is to say, beyond a small number of 10, the network incoherence is approximately 280, which is still extremely high. This indicates that the rail transport network is extremely vulnerable to cascade delays, even during the morning commute hours.

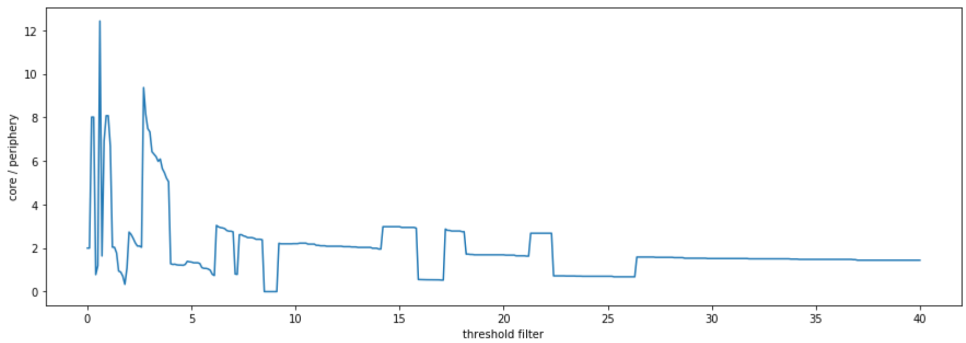

Figure 3: Core-Periphery Size

WP-2 (Rewiring - Nature Inspired Traffic Rerouting): To analyze the robustness of the morning peak-hours network (around 500 station/nodes) we evaluated the ratio between the core of the network and its periphery: when the trophic level of the nodes is computed using the basal nodes enforcement technique the resulting ratio (see Figure 3) fluctuates between 1 and 12, depending on the number of enforced basal nodes. The fluctuations are higher when the number of enforced basal nodes is low, the core-periphery ratio then stabilizes around 6 when the enforced basal nodes are between 30 and 40 and it decreases to around 2 when there are more than 40 basal nodes. Regardless some oscillations in the core periphery-ratio, both the approaches shown a big core in the structure of the network meaning that the rail transport net- work during morning peak-hours is robust to disruptions in single stations.

Conclusions

The study analysed the resilience to cascade delays and robustness to station closures of the rail transport in the Greater London area during the morning commute hours, when most of the passengers will travel from suburban to urban areas. It was found through hierarchical trophic coherence analysis that the network was not at all resilience to delay cascades due to its highly incoherent nature, but extremely robust against station closures due to its relatively large interconnected core.

Next Steps

Dissemination: Complete write up into a journal paper to be submitted to a complexity or a multi-disciplinary journal. This has been completed for the work outlined in this report, but we are enhancing it to include national scale data and/or correlate with real delay statistics from national office for transport.

Engagement: This is now being done via joint ENCORE and Turing (Lloyds Register Foundation's Data-Centric-Engineering Program) workshop on 23rd May. We will use the evidence from the feasibility study to contribute to developing a pathway to engage with industry for InnovateUK and future EPSRC proposals.

References (Participants/Collaborators in Bold)

[1] "An agent-based approach to modelling driver route choice behaviour under the influence of real-time information," H. Dia et al., Transportation Research C, vol. 10, 2002

[2] "Drought rewires the cores of food webs," **X. Lu** et al., Nature Climate Change, 2016

[3] "Core Identification and Attack Strategies against Regenerative Complex Networks," **W. Guo**, **X. Lu**, IET Electronics Letters, 2016

[4] "Community structure in time-dependent, multiscale and multiplex networks," P. Mucha et al., Science, 2010

[5] "Optimal weighting scheme for suppressing cascades and traffic congestion in complex networks," R. Yang et al., Physics Review E, 2009

[6] "Trophic coherence determines food-web stability," **S. Johnson** et al., Proc. of Nat. Academy of Sciences, 2014

Breakdown of Financial Expenditure

Resources Requested: The project asks for £9.6k (12k at 100% FEC). The table below outlines the expenditure summary at University of Warwick (UoW). Detailed line item reports will be submitted by UoW finance team.

Type	Spent	Comments
Directly Incurred Travel 1 (DI Travel 1)	3944	UK Travel for Investigators and Researchers.
Directly Incurred Travel 2 (DI Travel 2)	1820	Warwick and Cranfield Joint Study Week where 7 members (4 Warwick and 3 Cranfield) took part.
Directly Incurred Travel 3 (DI Travel 3)	220	International Invited Talk at Chinese Universities (Tsinghua, BUPT, and BJT) and explore future UK-China collaboration (leveraged on another mol.com workshop to get collaborations)
Directly Incurred Equipment (EQA)	4393	1 Self-Assembled High-Performance Computer and 2x Laptop for Graph Analysis
Total	**£10377**	**from 12000 (100% FEC)**