Network Science

Final Project: Network scientific analysis about the vulnerability of the Swiss Railway network

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ABSTRACT

Railway networks are of great importance for every economy (Pagani et al. 2019) Thus, it is all the more important to understand the reasons why and how they can fail. Yet, due to the size and complexity, their susceptibility to failures is not completely understood (Pagani et al. 2019) This research project investigates the vulnerability of the Swiss railway network using network scientific models.

1 INTRODUCTION

Railway systems need to perform well even under suboptimal circumstances (Pagani et al. 2019) Cascade delays and cancellations are daily challenges for both passengers and railway companies (Pagani et al. 2019) Existing research showed that the network topology has an effect on the performance of a railway system (Lin and Ban 2013) More recently, Pagani et al. (2019) analyzed the resilience and robustness of a UK railway network. They showed that poor performance correlates more with cascade effects that failures (Pagani et al. 2019)

Needless to say, the are many reasons why railway systems can fail. For this reason, the focus of this study is the Swiss railway system for which only few studies exist. In 2008, the authors Erath, Löchl, et al. (2009) published a graph-theoretical analysis of the Swiss railway network over time. They've used measures such as degree/betweenness centrality to characterise the growth of the Railway network (Erath, Löchl, et al. 2009) However, they've suggested further research to explain the robustness of the network. In 2009, the authors Erath, Birdsall, et al. (2009) proposed a generalized linear model (GLM) to assess the vulnerability of the Swiss road network. The downside of their approach is that they assumed the failures to be mutually exclusive (Erath, Birdsall, et al. 2009)

This research projects extends the work of Erath, Löchl, et al. (2009) and Erath, Birdsall, et al. (2009) using network scientific models. The primary focus is to analyze the Swiss railway network regarding graph characteristics and vulnerabilities.

1.1 Transport Networks

Transport networks are essential for people and economy (Erath, Löchl, et al. 2009) . Early research on transport networks focused on geometric and topological properties (Erath, Löchl, et al. 2009) . Later, with the availability of computational power, the research shifted towards network structures (Erath, Löchl, et al. 2009) Recently, papers such as Pagani et al. (2019) and Monechi et al. (2018) used graph properties to model robustness and delay dynamics.

There are several differences to other networks such as social networks (Erath, Löchl, et al. 2009) Transport networks represent real objects such as lines and railway stations (Erath, Löchl, et al. 2009) These physical objects have constraints themselves which influences the degree distribution (Erath, Löchl, et al. 2009) Additionally, monetary constraints apply as well, thus restrict the ability for them to be scale-free (Erath, Löchl, et al. 2009)

1.2 The Swiss Railway Network

According to the "European Railway Performance Index", Switzerland has one of the best performing railways (*The 2017 European Railway Performance Index* 2017) Yet, the increased load over the past years is a constant challenge. Every delay or cancellation might result in cascade failures.

Every railway network is slightly different. This is due to their history and how they grew over the years (Erath, Löchl, et al. 2009) The Swiss railway network is special because its early growth was purely driven by economic values (Erath, Löchl, et al. 2009) This means that cities were prioritized and urban areas were not considered in the planning process (Erath, Löchl, et al. 2009) Moreover, due to competition of private companies, the networks grew more or less independent of each other (Erath, Löchl, et al. 2009) Today, most railways belong to the Swiss Federal Railways (SBB).

2 MEASURES

This section described the basic measures used in this research project.

2.1 Degree Centrality

The degree centrality is a fundamental measure based on the degree of the node (Lin and Ban 2013) The degree represents the number of connections a node has (Lin and Ban 2013) Hence, the degree centrality assumes that nodes with a large number of connections are more important (Lin and Ban 2013) It was first introduced by Freeman (1977) and Freeman (1979)

$$C_i^D = \frac{k_i}{N-1} \tag{1}$$

where

$$k_i = \sum_{j \in N} a_{ij} \tag{2}$$

In railway networks, the degree centrality is constrained by spacial and economic limits (Erath, Löchl, et al. 2009)

2.2 Betweenness Centrality

The betweenness centrality is the number of shortest paths passing through the node (Lin and Ban 2013) It was introduced by Freeman (1977) and Freeman (1979) as well:

$$C_i^B = \sum_{j \neq k} \frac{n_{jk}(i)}{n_{jk}} \tag{3}$$

where, for the nodes j and k, the shortest path is defined by $n_{jk}(i)$. In transportation networks, the betweenness centrality can be used to measure the impact of a node. (Lin and Ban 2013)

2.3 Closeness Centrality

The closeness centrality measures how close the node is to all other nodes (Lin and Ban 2013) It is therefore the inverse of the mean shortest path to all other nodes and defined as: (Lin and Ban 2013)

$$C_i^C = \frac{1}{\sum_{j \neq i} d_{ij}} \tag{4}$$

The closeness centrality depends on the geographic position of the nodes as well as the size of the network (Erath, Löchl, et al. 2009) This restricts the comparability of different sized networks (Erath, Löchl, et al. 2009).

2.4 Clustering Coefficient

The clustering coefficient measures the probability of two neighbours being connected (Lin and Ban 2013) It can therefore be defined as:

$$C_i = \frac{2m_i}{k_i(k_i - 1)} \tag{5}$$

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The 2017 European Railway Performance Index (Apr. 2017)