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Increasing the resilience of air traffic networks using a network graph theory approach

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ABSTRACT

Air traffic networks are essential to today's global society. They are the fastest means of transporting physical goods and people and are a major contributor to the globalisation of the world's economy. This increasing reliance requires these networks to have high resilience; however, previous events show that they can be susceptible to natural hazards. We assess two strategies to improve the resilience of air traffic networks and show an adaptive reconfiguration strategy is superior to a permanent re-routing solution. We find that, if traffic networks have fixed air routes, the geographical location of airports leaves them vulnerable to spatial hazard.

1. Introduction

Air travel is critical to the functioning of countries and the world economy as a whole. In 2012 approximately 2.9 billion people used air transport to meet their business and tourism needs, with over 115 million passengers travelling using UK air carriers and over 736 million using US air carriers (International Civil Aviation Organization, 2012; The World Bank, 2013). It has also been estimated that approximately 51 million tonnes of freight was carried by air transport in 2012 (International Civil Aviation Organization, 2012). These figures have been steadily increasing year-on-year, with a 5.5% increase in air passenger numbers from 2011 to 2012 (International Civil Aviation Organization, 2012), showing a growing demand and reliance on air transport, both for passengers (tourism and business) and freight.

The resilience of air traffic networks is therefore of great importance, and it is critical that the system is designed to minimise the impact to passengers and economic losses to businesses due to disruptive events, such as extreme weather events, strike action or terrorist threats, for example. However, many recent events have shown that air transport networks are particularly susceptible to disruption. To give an example, in February 2010 snowstorms along the Eastern coast of the US caused the cancellation of more than 20,000 flights (4.2% of all flights) scheduled during the month. On the peak day of disruption (10 February) 23% of scheduled flights were cancelled. This large number was mainly due to the near or complete closure of on a few Northeastern hub airports, including Washington Regan, John F. Kennedy, Baltimore Washington and Newark Liberty. The total cost of these cancellations is unknown due to the difficulties in quantifying the exact cost to each carrier (as this depends upon the carriers ability to rebook passengers); however, across all carriers it has been estimated that cancellations from snowstorms over the whole month cost between $80–100 million (Credeur and Schlangenstein, 2010). Within the US the greatest proportion of weather-related events, on average, occurs during the winter months

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(December–February) when snowstorms can reduce the ability of an airport to function normally. In these months weather-related cancellations account for approximately half of all cancellations and the five worst months on record for weather-related cancellations have all occurred within the last 7 years (Bureau of Transportation Statistics, 2010). The US is not the only country to experience air traffic disruption due to snowstorms; in December 2010 Heathrow airport was closed for arrivals and departures on 18 December, with only a limited number of flights operating the next day, due to 70 mm of snow falling in one hour. This event caused the cancellation of over 4000 flights, disrupting the travel plans of many passengers during what was predicted to be Heathrow's busiest weekend of the year (Heathrow Winter Resilience Enquiry, 2011). One further notable example of air traffic disruption in recent years affected European airspace and was caused by the ash cloud from the erupting Eyjafjallajökull volcano (Iceland) in early 2010. This event caused parts of European airspace to become restricted and no fly zones to come into operation from the 14 April (Brooker, 2010). The resulting airport closures and flight cancellations caused more than 10 million passengers to be delayed and the event was estimated to have cost $1.7 billion (in terms of revenue lost for air carriers between 15–21 April) (Mazzocchi et al., 2010). It is also worth noting that the majority of these disruptive events can be distributed over wide geographic areas and have the potential to affect multiple airports simultaneously.

In the UK, Heathrow airport has already taken steps to minimise disruption caused by extreme weather events, particularly snow/ice hazard, by reducing the capacity of scheduled flights per day in the winter season to 1279, in comparison to 1341 flights in the summer season (Transport Committee, 2013a). However, this is only a slight reduction and they *'do not believe that there is further scope to reduce the winter schedule without damaging the range of flights and destinations available to passengers*' (Heathrow, 2013). Therefore additional strategies to increase the resilience of air traffic networks are needed.

There are a number of academic studies that have assessed the impact of extreme weather events on transportation networks, including those by Koetse and Rietveld (2009), Suarez et al. (2005) and Chang et al. (2010). In one study Stamos et al. (2015) developed a framework that could be used by policy makers or planning authorities for assessing the resilience of passenger transportation networks (including air traffic networks). They expressed this impact in terms of passenger differentiated flows for several extreme weather events, including: wind gusts, snowfall, heavy precipitation and adverse temperatures to transportation infrastructure, and the impacts that this may have to consumers. However, there are far fewer studies which consider strategies aimed at adapting transportation infrastructure to cope with these extreme weather events. Those that do exist tend to focus on long-term strategies to overcome the potential impacts of climate change (Arkell and Darch, 2006; Schwartz, 2010; Rattanachot et al., 2015). There are a handful of previous studies that have considered increasing the resilience of air traffic networks to hazard, but these studies have tended to focus on the operations of individual air carriers, rather than the functioning of the air traffic network as a whole (Wuellner et al., 2010). The majority of studies regarding air traffic networks focus on using network graph theory to classify the topology of the network (Li et al., 2006; Bagler, 2008; Han et al., 2008) and have found that many air traffic networks including the European, US and China air traffic networks show the same topological characteristics (Dunn, 2014). Whilst, other network theory studies use measures to consider the importance of individual airports (Guimera et al., 2005) or focus on the optimisation and efficiency of the network (Li et al., 2010; Silva et al., 2014; Gillen et al., 2015).

In this paper we develop two strategies to increase the resilience of air traffic networks when subjected to a 'growing' spatial hazard. One resilience strategy 'adaptively' modifies the topology of the network as airports become closed by the hazard (crisis management) and the other 'permanently' modifies the topology (hazard mitigation). We apply these resilience strategies to the European air traffic network (EATN) as a case study example, as its hazard tolerance and evolution has previously been studied in detail by Wilkinson et al. (2012). We initially quantify the ability of these two strategies to increase the resilience of the EATN by plotting the proportion of cancelled air routes against the proportion of closed airports and closed area (defined as the area covered by the spatial hazard). We then assess the change in connectivity and performance of the network by applying two network graph theory metrics, maximum cluster size (MCS) and shortest average path length (APL).

2. Network model and identification of network resilience

We have chosen to use a network graph analysis of the air traffic networks in this paper, for several reasons. Firstly, air traffic networks are dynamic, with new routes continually opening and old routes expiring. Therefore, using modelling techniques that are applicable to specific networks are only valid at one point in time, whereas this approach is capable of capturing the generic properties of many real world networks. This has previously been shown by Albert et al. (1999), who argue that many real world systems actually share very similar patterns of connectivity and that generic networks with similar properties can be generated using simple rules (i.e. network generation algorithms). Secondly, network graph theory is most applicable for modelling the topological characteristics and connectivity of generic networks and also the impact that the resilience strategies has to this. And finally, network theory includes several measures that can be applied to assess the ease of navigation, or movement, around a network that can be used to compared networks of different types.

To develop a network model of the EATN we use the data of Openflights (2010), which contains 525 airports and 3886 air routes (Fig. 1(a)). Following network graph theory we use nodes to represent the individual airports and links to represent the air route connections between them (for a detailed discussion of using network theory to represent real world infrastructure networks the reader is directed to Dunn et al. (2013)). It is worth noting that in a similar manner to Wilkinson et al.

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