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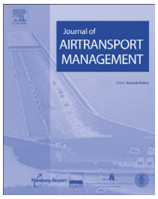

Measuring the cost of resilience

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ABSTRACT

Air traffic management research lacks a framework for modelling the cost of resilience during disturbance. There is no universally accepted metric for cost resilience. The design of such a framework is presented and the modelling to date is reported. The framework allows performance assessment as a function of differential stakeholder uptake of strategic mechanisms designed to mitigate disturbance. Advanced metrics, cost- and non-cost-based, disaggregated by stakeholder sub-types, are described. A new cost resilience metric is proposed and exemplified with early test data.

1. Introduction

The primary objective of the ‘ComplexityCosts’ project is to better understand European air traffic management (ATM) network performance trade-offs for different stakeholder ‘investment’ mechanisms. We define such mechanisms as those designed to afford resilience for one or more stakeholders during disturbance, and to which we may assign a monetary cost. Hence they may be considered as ‘investments’, and quantified as such – since we are also able to monetise their impact. As a simple example, an airline may strategically add buffer to a schedule in order to mitigate tactical delay costs. We include both advanced and basic mechanism types, in order to compare the relative efficacy of simpler (often cheaper) solutions with those afforded through the implementation of advanced technologies. The types of mechanism are further differentiated as shown in Table 1.

To better reflect operational realities, for each investment mechanism ultimately adopted in the model the rate of adoption will be differentially assessed within the stakeholder groups, for example as a function of the airline business model. Although high-level roadmaps have been developed within the European ATM Master Plan (SESAR, 2012) and associated contexts (such as the Pilot Common Project (European Commission, 2013a; SESAR, 2013)), the ComplexityCosts model will further refine the relationship between selected mechanisms and stakeholder uptake.

Whilst some components of the model are already implemented, our focus is very much on reporting the design thereof, its wider methodological framework, and the context of resilience in complex networks. Having cause to frequently refer to disturbance, we define this at the outset as an event, either internal or external to a system, capable of causing the system to change its specified (stable or unstable) state, as determined by one or more metrics. This will be expanded upon further both in the discussion on defining resilience (Section 2) and on the early modelling itself (Section 3). Each model scenario comprises a given set of starting (input) conditions, not only defining the disturbance, but also including the input traffic, assumed capacities, and mechanisms applied. In this paper, we describe both the model design and the mechanism selection process, with a focus on the supporting metrics.

2. Defining and measuring resilience

The objective of Section 2 is to consolidate some of the key literature on complex networks, especially where these have addressed the issue of defining and measuring resilience. Complex systems are those that display collective behaviour, which cannot be predicted through analyses or modelling of the individual

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Table 1
Mechanism classifications.

Mechanism		Summary description	Example
Type	Advanced	SESAR Essential Operational Changes[a] and sub-components thereof (or equivalent advanced or supporting technologies/tools).	Airport collaborative decision making (A-CDM).
	Basic	Non-advanced, does not centrally involve implementing new technologies/tools.	Airline adding buffer to its schedule.
Disturbance focus	Mitigation[b]	Primarily aimed at mitigating the impacts of disturbance; may be more loosely considered as targeting unexpected demand patterns.	Spare aircraft crews with dynamic rostering.
	Nominal[b]	Primarily aimed at improving the nominal (according to plan) functioning of the system (e.g. by increasing capacity); may be more loosely considered as targeting expected demand patterns.	Additional runway capacity.

[a] See Section 3.3.
[b] Non-mutually exclusive.

components, but which emerges instead from the interactions between them. All complex systems have interconnected components, such that complex networks play a central role in complexity science (Newman, 2003; Boccaletti et al., 2006). Many of the roots of complexity science can be traced back to statistical physics, nonlinear dynamics and information theory (Anderson, 1972). We will conclude the section by examining the particular challenges associated with the design of corresponding metrics in ATM, and newly formulate such a metric.

2.1. Wider perspectives

Table 2 synthesises a literature review exploring the commonalities of complex networks: the energy that drives them and the disruptive actions and frictions which impede their flows – across the domains of biology (Barthélemy, 2011; Heaton et al., 2012), ecology (Holling, 1973; Zetterberg et al., 2010), utilities (Piratla and Ariaratnam, 2013; Prasad and Park, 2004; Saldarriaga and Serna, 2007; Todini, 2000; Trifunovic et al., 2012), transportation (Blom and Bouarfa, 2016; Cook et al., 2013; Omer et al., 2013; Zanin and Lillo, 2013) and telecommunications (Babarczi et al., 2013; Bhatia et al., 2006; Scheffel, 2005). Commonalities may be observed even across these diverse domains. Nodes represent collections of assets (as a generic term for the mobile entities in the network – all with intrinsic value to the system) that need to be transported along edges and through various media. Such flows are all driven by some form of energy. This is typically counted in monetary terms within the transportation sectors, although it could be expressed as a fuel burn energy, *inter alia*. These flows may be disrupted by breakage or loss of capacity, and work against metaphorical and literal forms of friction.

Real-world networks are often co-dependent, such as laying water pipelines under roads, water distribution networks being powered by electrical pumps and inter-modal transport exchanges. More rarely, a vital edge in one network (such as a main road) could be the disruption event for an edge in another network (e.g. prohibiting safe species dispersal). Unlike other (biological) transport networks, the network formed by fungi is not part of the organism – rather, it *is* the organism.

A number of these networks also share common functional themes. Capacity is expressed through various metrics, such as pipe diameters, cable bandwidths, (aircraft) seating configurations or vehicle (aircraft) movements. Telecommunications terminologies for hub-and-spoke networks such as (packet) scheduling, service denials, backbones, routing protocols (with distance restrictions), traffic delivery rates, traffic forecasts, and (node) diversions have obvious analogues with air transport. We often talk of 'downstream' propagation effects were the terminology is literal in the context of water distribution and metaphorical in others.

There is an implicit trade-off that pervades transport systems, which is particularly closely echoed in telecommunications: hub-and-spoke networks are especially efficient from an economic and design perspective *but* they are also particularly susceptible to system failure or targeted attack. (There is a wealth of literature on this that we do not have space to review here.) Rerouting during disruption is a common theme across many types of network. Sometimes this is (practically) instantaneous, for example in the water distribution and telecommunications contexts. In the latter, data are insensitive to the routing (unlike passengers), as long as they are distributed within corresponding time constraints. Whilst changes of route are possible in air transport, changing mode or destination is much less common. System responsiveness during disruption is often described as

Table 2
Network properties across multiple domains.

Network	Node	Edge	Flow	Disruption (example)	Flow cost
Generic	collection	transport	asset	loss of capacity	E
Transportation					
Air – flight-centric	airport	flight	aircraft	mechanical failure	€
Air – pax-centric	airport	flight(s)	passengers	missed connection	€
Urban (road)	junction	road segment	vehicles	bridge collapse	€
Rail	station	track segment	trains	signal failure	€
Goods	warehouse	road segment	goods	traffic congestion	€
Services/utilities					
Water	plant, reservoir	pipe	water	pipe breakage	E
Electricity	(sub) station	cables	electrons	cable breakage	E
Telecoms	hub, router	wire/fibre	data packets: electrons/photons	cable breakage	E
Biology/ecology					
Mammalian brain	distinct grey-matter regions	white-matter fibre bundles	electrical impulses; neurotransmitters	breakage (e.g. disease)	E
Fungal ecology	branch point, fusion, tip	cord (e.g. packed with hyphae)	aqueous nutrients	breakage (e.g. grazing)	E
Animal ecology	habitat patch	landscape segment	species dispersal	road segment	E

Key. E = energy; € = monetary.
Source: Cook and Zanin (2016). (Used with permission from Ashgate Publishing.)

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