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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, non-linear 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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resilience. However, we need to formulate a more precise definition of this within our modelling framework.

2.2. What is resilience?

Regarding an agreed definition of resilience, it has been pointed out in a recent review (Henry and Ramirez-Marquez, 2012) that too many different definitions, concepts and approaches are being used, such that: " […] some definitions of resilience overlap significantly with a number of already existing concepts like robustness, fault-tolerance, flexibility, survivability and agility." An overview of the evolution of the term in various fields of research is presented in Gluchshenko and Förster (2013). For a thorough review with numerous ATM examples, see Blom and Bouarfa (2016). The first two milestones (see Table 3) in the development of the term were its initial introduction in material testing (Hoffman, 1948) and the later adoption in ecology (Holling, 1973). The latter led to widespread use of the term in the scientific literature.

A third important milestone with relevance to air transport was the 'resilience engineering' paradigm introduced in 2006 (Hollnagel et al., 2006), which led to (broader) qualitative modelling of resilience in ATM, from 2009 (EUROCONTROL, 2009).

The earlier 'engineering resilience' assumes one stable state only, with resilience being the ability to return to this original state, after disturbance. Ecological resilience, in contrast, refers to absorbing disturbance and access to multiple (stable or equivalent) states. An air transport system may also operate in (essentially) equivalent states of safety or cost. A recent systematic review (Francis and Bekara, 2013) across numerous domains, categorised three capacities of resilience, *viz.*: absorptive, adaptive, and restorative. These are summarised in Table 4.

The key feature (second column) is taken from Turnquist and Vugrin (2013), to which we have appended some key associations and main ATM phases with which the capacity may be typically associated – although these are not hard and fast. From a performance-focused perspective, reliability may be considered as the presence of all three capacities; vulnerability may be considered as the absence of any one of them. For clarity of reference and to accommodate a definition of robustness within our framework, we align robustness with the *inherent* strength or resistance to withstand stresses beyond normal limits, i.e. the absorptive capacity of resilience.

In Section 2.1 we referred to (practically) instantaneous recovery. An example is whereby surplus energy or resources are strategically made available to the system in order to deal with a tactical failure. In the water distribution context, this has been referred to as 'buffer energy' by Piratla and Ariaratnam (2013), and Trifunovic et al. (2012) similarly refer to buffer associated with increased investment costs and higher maintenance costs. Here, the analogy with air transport schedule buffers is clear. In general, however, the investment mechanisms in scope in ComplexityCosts may confer one or more of the three resilience capacities.

2.3. Resilience metrics

We are now equipped with sufficient resilience definitions to explore the corresponding metrics. Most of the investment mechanism costs are expected to be paid strategically (i.e. as sunk costs) – see later comments. However, we must also take account of any *tactical* costs associated with the investment mechanism, such as runway operation, or variable fuel burn during aircraft delay recovery, etc.

Fig. 1 shows that initially a system exists in some stable reference state, S_0. A disturbance (disruptive event) triggers system disruption (due to internal or external factors) and the system enters a disrupted state, S_d. In response, resilience action is taken, which triggers system recovery, enabling the system to revert to a recovered state, S_f (which, we note, could be the same as, or different from, S_0). In the simplifying case $t_d \cong t_s$, there is (practically) no steady disrupted state, S_d. (Returning to the absorptive resilience capacity, we observe that where $t_e \cong t_f$, (perfect) robustness is indicated, and the resilience action may be implicit – such as the consumption of schedule buffer.) With reference to Fig. 1, developing a metric for resilience Henry and Ramirez-Marquez (2012) commence with the formulation (1), where $\mathcal{A}(t)$ is the resilience of a system at time t. This thus describes the ratio of recovery at time t to loss suffered by the system due to a disruption event from t_e to t_d. If the recovery is equal to the loss, the system is fully resilient; if there is no recovery, no resilience is exhibited. (Omer et al. (2013) use similar ratios in the urban context: a relatively rare example of work using real estimated costs.)

$$\mathcal{A}(\mathrm{t}) = \frac{Recovery(t)}{Loss\ (t_d)} \tag{1}$$

The authors (Henry and Ramirez-Marquez, 2012) go on to define a quantitative 'figure-of-merit' function, $F(\bullet)$, which specifies a system-level delivery metric. It is time-dependent and changes as the system state changes. Multiple metrics could be included and combined with appropriate weights. Such inclusion is often a model requirement, as in ComplexityCosts for all output costs. However, since all of these components are cost functions, weights are not required in our model. Equation (1) is expanded (*ibid.*) to embrace a conditional figure-of-merit under a given disruptive event, and then further conceptually extended to include the time and costs required to restore the disrupted components.

Such situations are discussed with specific regard to investment mechanisms in Turnquist and Vugrin (2013), where the systemic impact (SI) on a network resulting from disturbance is illustrated. This event reduces a system performance metric, which returns to some nominal (target) level after a period of time, through recovery effort applied.

SI is the area of the degraded performance. The total recovery effort (cost) represents the cumulative resources used in a given recovery. Varying strategies for recovery may affect the SI and require different levels of recovery effort. Investment mechanisms implemented strategically would hopefully result in a reduction of the tactical magnitude of the disruption from a given disturbance, in addition to speeding up the system recovery. These expenditures are defined (*ibid.*) as "resilience-enhancing investments".

As is pointed out, when designing for resilience, it is important to consider all three elements: (i) systemic impact (SI); (ii) total recovery effort, and; (iii) resilience-enhancing investments. These will vary across the (disruption) scenarios modelled. The sum of the

Table 3
Three major definitions of resilience.

Terminology	Introduction	Field	State(s)	Key feature
Engineering resilience	Hoffman (1948)	material testing	one stable state	inherent ability of the system to return to its original state
Ecological resilience	Holling (1973)	ecology	multiple states	ability of the system to absorb disturbance
Resilience engineering	Hollnagel et al. (2006)	air transport	multiple states	safety-based design of socio-technical systems

Table 4
Three capacities of resilience.

Capacity	Key feature	Key association(s)	ATM focus
Absorptive	network can withstand disruption	robustness; little or no change may be apparent	strategic
Adaptive	flows through the network can be reaccommodated	change is apparent; often incorporates learning	strategic and/or tactical
Restorative	recovery enabled within time and cost constraints	may focus on dynamics/targets; amenable to analytical treatment	tactical

first two elements ((i) and (ii)) represents the total cost impact, and needs to include any *tactical* costs of the investment mechanism itself, as mentioned earlier. The SI measurement must include all the relevant performance metrics.

Complementing such discrete (*sic.*) treatments (*ibid.*) of performance curves, an extensive paper (Bocchini and Frangopol, 2012) reporting on an optimisation procedure for the restoration activities associated with the bridges of an urban network severely damaged by an earthquake, cites (2) as a “broadly accepted” formulation of resilience.

$$R = \frac{\int_{t_0}^{t_0+t_h} Q(t)dt}{t_h} \tag{2}$$

Here, the resilience index, R, is defined as the normalised integral over time of the network functionality, $Q(t)$. R is dimensionless and takes values in the range [0%, 100%]. In this formulation, t_0 is the time at which the disrupting event occurs and t_h is the investigated time horizon. In the specific case of the urban road network in the context of bridge damage, $Q(t)$ is a percentage based on traffic flows normalised with respect to all bridges open and all bridges closed.

For wider reviews of resilience metrics, see Blom and Bouarfa (2016) and Francis and Bekara (2013). In the ATM context, a resilience metric is defined in Jung et al. (2015) based on schedule non-conformance over elapsed time under different types of perturbation of performance-based navigation arrival operations. Perturbation and recovery are defined with respect to sustained, set thresholds of the metric. A review of air transport papers making extensive use of the theory of complex networks is presented in Zanin and Lillo (2013), focusing on network topologies and dynamics, considering the resilience properties of such networks to extreme events. We develop these ideas further in the next section, where we formulate a new cost resilience metric.

2.4. A new cost resilience metric for ATM

In all domains, ATM being no exception, metrics are needed that are intelligible (preferably to the point of being simple), pertinent (in that they accurately reflect the aspect of performance being

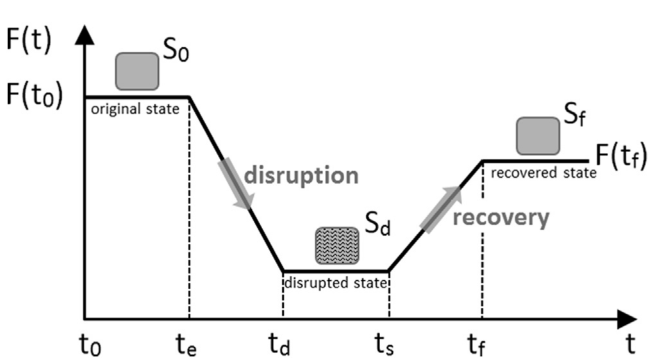

Fig. 1. State diagram. Source: adapted from Henry and Ramirez-Marquez (2012).

measured) and stable (we cannot refine them from one period to another without losing comparability). Let us consider resilience and connecting flights in an air transport network. Firstly, the time over which a recovery occurs is difficult to assign. For a three hour flight, departing ten minutes late but arriving on time, how much time should be assigned to the recovery? It could be effected during part of the en-route phase by increased speed, or realised on arrival due to schedule buffer. In either case, the recovery did not take three hours to achieve and the real impact is only on arrival. It is here, at the destination airport, measuring the actual arrival time relative to the schedule, that any delay impacts on other rotations, crew changes and passenger connections. It is here also that delay propagation effects come into focus (although normally only triggered by delays somewhat greater than ten minutes). Indeed, these propagation effects persist over many causally linked rotations during the rest of the operational day – as quantified in Cook et al. (2013), for example. We thus propose to use one operational day in European airspace as the boundary conditions for our analyses. Defining the scope of the resilience, we propose causal summations with specific regard to the mechanism and disturbance applied, with Σ_m denoting summation over events causally affected by the mechanism, and Σ^d for the disturbance. This will allow specific assessment of the mechanism, *relative* to the effect of the disturbance, and leads to a fundamentally system-based view of resilience.

Secondly, we are perhaps in a better situation than some other disciplines, whereby mixed-metrics are necessary and full costings are not available. Costs very often have to be hypothecated, for example by the length of an edge in data transmission (Babarczi et al., 2013) or a pipe diameter in water distribution (Saldarriaga and Serna, 2007). By design, our cost resilience metric (R_C) will fully comprise *cost-based* components, as a result of the selection only of mechanisms that can be monetised (see Section 3.3) and the cost of delay modelling described in Section 3.5.

Thirdly, whilst simple ratios satisfy the criterion for metrics to be straightforward, they may also be misleading. Take example A: a €50 recovery of a €100 disruption. This would yield the same simple resilience ratio as example B: a €50k recovery of a €100k disruption. Both would give $\mathcal{R} = 0.5$, according to (1), although we would deem the latter to be a better return on a €10k investment mechanism. Resilience metrics thus need to be understood in the context of these absolute values.[1] Resilience ratios are still attractive in their interpretability, however. To mitigate misleading reporting, we propose that the number of assessment units (u, such as flights or passengers) also be cited in their reporting, as with p values in statistical significance testing. The simple discipline of reporting “$R_C = 0.5$ (n = 1)” (example A) c.f. “$R_C = 0.5$ (n = 1000)” (example B) ($n = \Sigma\, u$) at least gives immediate insight that B had the wider reach. The cost associated with a disrupted flight or passenger at time t in the absence of a mechanism is denoted $C_u(t)$, and in the presence of a mechanism as. $C_u^m(t)$.

[1] In addition, a full trade-off analysis needs to be performed with regard to the *strategic* costs of the investment mechanisms – i.e. their cost of implementation. We plan to report on such trade-offs in a subsequent paper; a large part of ComplexityCosts is dedicated to these more traditional cost-benefit analyses.

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Fourthly, we take account of any tactical costs associated with each investment mechanism, $C_m(t)$. We earlier gave examples relating to runway operation costs, or variable fuel burn during aircraft delay recovery. The final formulation is presented as (3).

$$R_C = \frac{\sum_u^d C_u(t) \; - \; \sum_u^d \sum_m C_u^m(t) \; - \; \sum_m C_m(t)}{\sum_u^d C_u(t)} \tag{3}$$

where:

$$\sum_u^d C_u(t) > 0; \;\; \sum_u^d \sum_m C_u^m(t), \;\; \sum_m C_m(t) \geq 0 \tag{4}$$

Such that:

$$R_C \leq 1 \tag{5}$$

This expression for cost resilience (3) thus measures the effect of the investment mechanism with respect to the cost of the disturbance without the mechanism. Perfect resilience (complete cost recovery) gives $R_C = 1$, and no recovery gives $R_C = 0$. If the mechanism were to induce greater costs than the disturbance alone, $R_C < 0$ obtains. (The first term in (4), i.e. the total cost of the disturbance, could in theory be zero. An example would be a relatively small disturbance fully absorbed by schedule buffer, due to robustness. However, only disturbances with some positive tactical cost will be modelled, such that we exclude zero values.) All the models presented in the literature review were deterministic, whereas the ComplexityCosts model will include uncertainty. As we explain in Section 3.6 (where the model's (complementary) impact metrics are presented), statistical testing will thus be applied to the metrics, and will also be used to identify non-significant R_C ratios, for example.

3. The modelling framework

3.1. Overview of the model

The ComplexityCosts model is a stochastic, layered network model, including interacting elements and feedback loops. The multi-layer approach consists of a series of (*a priori*, independent) graphs, across which nodes are identified. Using the nodes' identification, the graphs can be projected to a single graph. Importantly, some metrics of the projected graph can be easily derived from metrics of the layer graphs. Stochastic elements will include systemic disturbance (usually relatively minor disruptions, such as *ad hoc* flight delays), which are not part of the over-arching modelled disturbance scenarios discussed later.

A busy September 2014 traffic day will form the baseline. Actual traffic data is preferred over forecast values, although either could be used, as long as each model run is based on the same traffic-passenger baseline day, thus rendering comparative analyses under various disturbance-mechanism scenarios valid. The selected baseline must be free of exceptional delays, strikes or adverse weather. The planned airport coverage is 200 in the European Civil Aviation Conference (ECAC) and 50 beyond this region, to map major extra-European flows. EUROCONTROL's DDR2 service[2] will be used for flight, capacity and airspace data. The allocation of passengers to these flights, with connecting itineraries and fares, is an important part of the model both with regard to the metrics and those mechanisms particularly associated with passenger service delivery. The passenger allocation algorithms will be based in part on previous passenger mapping from International Air Transport Association (IATA) PaxIS data (Cook et al., 2013). Supplementary data requirements (e.g. airport passenger flows) have been identified as part of this allocation process, primarily aimed at high-level model calibration.

3.2. Types of disturbance

The specific types of (non-systemic) disturbance included in the model scenarios may be broadly defined by their:

- type;
- frequency of occurrence;
- scope – spatial (localisation) and temporal (duration); and,
- intensity.

In terms of selection for the modelling, a cross-section of types is desirable (for comparison of impacts) and it is important to select disturbance types that have a significant impact on the system. Furthermore, the types of disturbance and mechanisms need to be co-selected such that each mechanism is aligned with at least one form of disturbance to be modelled, i.e. the mechanism must be expected to contribute in some way to system resilience under such disturbance. In this respect, accidents were excluded from the disturbance scope as we did not set out to investigate safety-improvement mechanisms.

As a further, significant constraint, it is important that data of sufficient quality are available in order to model the disturbance accurately, and that the fidelity of the model is sufficient to capture the corresponding impacts (e.g. if applied at an airport or ATC sector level).

A range of disturbances was initially considered, including: weather; ash plumes; air traffic flow management capacity restrictions (non-weather); strike actions; technical failures; passenger disruptions; and, military exercises. After consideration of the above selection criteria, the following three disturbance types were finally selected:

- meteorological events with localised effects at airports;
- ATC strike actions;
- ATC capacity constraints (excluding weather and strike actions).

Supporting data on the disturbance types, enabling the building of frequency, scope and intensity models, are sourced from EUROCONTROL (Central Office for Delay Analysis; Network Operations Portals (EUROCONTROL, 2014); DDR2 service, analysing reporting regulations) and METAR (METeorological Aerodrome Report) data.

Substantial instances of each disturbance type, previously occurring in Europe, will be modelled. Probability distributions will be fitted to historical data in order to define realistic implementations of each type. Each disturbance will be modelled through its observed impact on capacity and delay generation, which presents different challenges in each case due to the resolution and reporting of the data (on which we plan to report in a subsequent paper).

The specific impacts of the disturbances will be primarily quantified through complementary airline delay metrics, including associated costs, and through a set of passenger-centric metrics, as presented in Section 3.6. Further considerations regarding the modelling of the disturbances will be discussed in the next section, where we will consider joint effects with the mechanisms to be modelled, after having first outlined the mechanism selection process.

[2] Demand Data Repository (second phase).

3.3. Selecting the mechanisms in the SESAR context

Five basic criteria drive the selection process for the investment mechanisms to be considered:

- a range of mechanisms is desired for comparison, covering both advanced and basic types (as defined in Table 1);
- a cross-section of procedural, regulatory and technological types of change is desirable, preferably also addressing different phases of flight;
- both the implementation (strategic) and variable, operational (tactical) costs need to be well-known or amenable to reasonable estimation;
- modelling a realistic differential stakeholder uptake for the mechanism needs to be feasible;
- each mechanism needs to be aligned with the selected disturbances.

In principle, it is also desirable to include at least some paradigm mechanisms that offer new insights into disruption mitigation, e.g. by challenging established conventions and/or practices. However, this combination of selection criteria is ambitious – the cost data alone being difficult to obtain. It is also necessary to control the number of combinations of mechanisms and disturbances modelled, to maintain a manageable and focused set of analyses.

Intending that the stakeholder uptake (discussed in Section 3.4) should broadly reflect near-term ATM operations through the first (earliest) levels modelled, we wished to set a corresponding context for the mechanisms selected, with regard to SESAR maturity.

The SESAR Concept of Operations (henceforth 'ConOps') is mapped into three overlapping steps (SESAR, 2012). The 'Deployment Baseline' comprises operational and technical solutions that have successfully completed the R&D phase and have already been implemented, or are being implemented, and runs up to 2018. ConOps Step 1 (time-based operations) starts from the Deployment Baseline; its deployment phase is from 2014 to 2025. Steps 2 and 3 (trajectory- and performance-based operations, respectively) have deployment targeted for after around 2025. The evolution of six key features (e.g. moving from airspace to 4D trajectory management) are mapped (*ibid.*) from the Deployment Baseline to Step 3, giving a grid of 'SESAR Essential Operational Changes' and associated sub-components (e.g. airport CDM). The deployment of SESAR technology and procedures has been activated by Implementing Regulation (EU) No 409/2013 (European Commission, 2013b) for the Master Plan. The instruments that have been defined to support the deployment include 'common projects' to deploy ATM functionalities (groups of ATM operational functions or services) that are mature for implementation and that have been demonstrated to have a global, positive business case for the European ATM network. The first set of technical and/or operational changes to be implemented in the 2014–2024 timeframe has been defined in the Pilot Common Project (PCP). It is integrated with the SESAR Steps, being the first set of activities between the Deployment Baseline and Step 1, which is where we intend to position most of the ComplexityCosts model. The PCP is the first project that activates this new way for stakeholders and the Commission to deploy this *modus operandi* (European Commission, 2013a), as adopted by Implementing Regulation (EU) No 716/2014 (European Commission, 2014a).

Through literature reviews, consultation of the ATM Master Plan and the SESAR proposal on the content of the PCP and the corresponding ATM functionalities (SESAR, 2013), plus project team suggestions, a list of potential mechanisms was developed. A focus was maintained on fairly discrete and stakeholder-scalable mechanisms, rather than high-level instruments such as Functional Airspace Blocks. Mechanisms likely to be used as market-based responses to air transport evolution were also in scope, even if not explicitly part of the Master Plan. Sources for costs were then sought, with additional consideration of (potential) direct sourcing from industry.

Table 5
Candidate investment mechanisms.

Candidate investment mechanism	Advanced / basic	Cost data
Airlines adding more buffer to schedule	B	✓
(1) Airport CDM*	A	✓
(2) Improved passenger reaccommodation tools	B	✓
(3) Dynamic cost indexing†	A	✓
Enhanced DCB (demand and capacity balancing tools)*	A	
En-route capacity planning tools*	A	✓
Improved flight planning and demand data*	A	
(4) Increasing ATCO¶ hours in selected sectors	B	✓
Investment in new runways	A	✓
Time-based separation*	A	✓

* Explicit correspondence with SESAR Essential Operational Change or sub-component.
† Aircraft variable speed management of delay costs. See Cook et al. (2009), for example.
¶ ATCO = air traffic control officer (/air traffic controller).

Table 5 shows the candidate investment mechanisms initially short-listed, listed alphabetically. The second column indicates whether the change is fundamentally basic or advanced (see Table 1). The final column indicates the availability of stronger cost data. After several rounds of deliberation, the mechanisms shown in bold (numbered (1)–(4)) were selected for final inclusion, offering a selection of basic and advanced types. Each has a robust pathway identified for obtaining the corresponding implementation and running costs (to be reported upon in subsequent publications).

The airport CDM and improved passenger reaccommodation tools mechanisms might be combined into a single, joint mechanism, in view of their complementarity and the current lack of explicit consideration of passengers in A-CDM. Exploring improved airline passenger reaccommodation tools is particularly attractive, as it both extends the framework beyond the SESAR context, is aligned with the model's passenger-centric metrics (see Section 3.6) and allows an exploration of European policy objectives. The first two mechanisms have an airport (at-gate) focus in terms of the point of application. Dynamic cost indexing (DCI) is effected through en-route delay recovery. Increasing ATCO hours will be implemented en-route but with both airborne and at-gate (reduced flow-management slots) impacts. The mechanisms also cover different stakeholder investment foci, primarily: airport and airline (1), airline (2 and 3), and air navigation service provider (ANSP) (4). All the mechanisms include procedural aspects of change. (1)–(3) require supporting technologies, although most of the infrastructure and tools for these already exist.

It is thus hoped that we have demonstrated that a range of interests has been captured through the selection of these mechanisms, as set out in the objectives at the start of this section. (Stakeholder uptake is discussed in the next section.) Table 6 shows the relationship between the disturbance types and the mechanisms selected.

A single tick indicates that the mechanism is expected to mitigate the corresponding disturbance; a double tick indicates a primary expected impact – i.e. a particular focus. Dynamic cost indexing is particularly broad spectrum in its expected impact,

Table 6
Disturbances and mechanisms.

Mechanism	Meteorological – airport localised	ATC strike actions	ATC capacity constraints
(1) Airport CDM (2) Improved passenger reaccommodation tools	✓✓	✓	✓
(3) Dynamic cost indexing	✓	✓	✓
(4) Increasing ATCO hours in selected sectors		(✓)	✓✓

enabling airborne delay recovery irrespective of the underlying cause. The tick shown in parenthesis is to indicate that the increased ATCO hours will *not* be specifically applied to areas where strike action is modelled as disturbance (it is assumed that such action is unresponsive in this respect), although indirect benefits may be realised through increasing capacity in other sectors.

The third disturbance type requires closer definition. It will be necessary not only to exclude ATC capacity constraints due to weather, but to specifically identify such restrictions that may be mitigated through increased ATCO hours. These will naturally include constraints explicitly denoted "ATC staffing" as the regulation cause in the corresponding DDR2 database, and we are currently working on a method[3] to identify other coded constraints that may reasonably be expected to be mitigated by increased human resource. This approach will be conservative in order to avoid over-estimating potential improvements. Simple strategies such as targeting airspace areas with low reported cost efficiencies might not be a robust approach, as the low efficiencies may well be due to relative over-staffing, such that adding extra ATCO resource does not represent a constructive solution.

3.4. Differential stakeholder uptake

As introduced in Section 1, in practice, new technologies and tools are rarely adopted simultaneously by all users or stakeholders. Although high-level roadmaps have been developed within the ATM Master Plan (SESAR, 2012) and the Pilot Common Project (SESAR, 2013) (see previous section), the ComplexityCosts model seeks to refine the relationship between selected mechanisms and stakeholder uptake, in the context of performance assessment.

Useful categorisations following Gaussian uptake distributions for innovation adoption lifecycles have been proposed (Rogers, 1983). Whilst we will adapt this terminology somewhat, we are investigating the modelling effectiveness of, and data availability for, tripartite stakeholder categorisations such as: (i) "early adopters"; (ii) "early majority"; and, (iii) "late majority" (*ibid.*). As mentioned in the previous section, where practical, we aim to reflect near-term uptake through our assignment of the first-level stakeholders, i.e. at level (i).

A-CDM is fully implemented at sixteen airports in Europe,[4] these being dominated by larger/hub airports, which readily suggest themselves for level (i), with several additional airports (almost) ready for full implementation. Indeed, a further twenty airports are identified on the European A-CDM coordination website[5] (managed by EUROCONTROL's Airports Unit), which are also suitable candidates to model at level (ii). It is important in each case to consider the maturity of the A-CDM implementation. Level (iii) will be assigned judgementally, in consultation with EUROCONTROL.

The implementation of improved airline passenger reaccommodation tools at level (i) will be limited to a number of full-service carriers at their hubs (where passenger connectivities are more important). For level (ii), this will be extended to selected non-hubs and also to regional carriers, before finally including a selection of all carrier types at level (iii) – again partly based on judgement regarding the importance of such tools to certain carrier/airport pairings (e.g. excluding certain low-volume carriers operating point-to-point services).

Uptake of dynamic cost indexing will similarly be applied mainly to full-service carriers at hubs first, before being extended to a selection of regional and low-cost carriers, and then a final, fuller uptake scenario at level (iii) (including some charter flights). (Pure cargo operators are out of scope, since we have not yet modelled the corresponding delay cost impacts.) This will be driven by carrier uptake, rather than being airport-focused, and may well echo to some extent the uptake of improved airline passenger reaccommodation tools, as these could indeed support DCI decision-making. A strength of the ComplexityCosts framework is that the *metrics* can also be differentiated by stakeholder sub-types (e.g. types of airline).

The sequential implementation of increasing ATCO hours in selected areas is, *prima facie*, relatively straightforward. This could be achieved partly as a function of ANSP size (as a proxy for staffing flexibility), starting with larger providers at level (i) and moving towards including smaller providers at level (iii), and partly as a function of the frequency at which en-route capacity restrictions are reported as staffing issues (as described in the previous section). However, some evidence suggests (Bujor and Ranieri, 2014) that many larger ANSPs have already exploited such improvement potential, whilst smaller ANSPs may have better remaining flexibility. Furthermore, at least two significant barriers also challenge this simple approach. Firstly, a major issue facing ANSPs is the unpredictability of demand coupled with the fairly long lead time required to train ATCOs (approximately three years), such that the required number of ATCOs might well be unavailable when needed. Secondly, and related to the first issue, is the challenge of ATCO mobility. In the absence of trans-national licencing, there is no common pool of ATCOs in Europe, and forecasting the required number of ATCOs thus remains the task of individual ANSPs operating under strict licencing requirements imposed by the national regulator. Shorter-term resolutions to such problems include flexible rostering, enabled through readily-available software solutions better aligning overall staffing and specific sector allocations with traffic demand. However, social acceptability prevents a number of ANSPs from taking up such solutions and moving away from rigid staffing structures, often resulting in shortages at peak times of the day.

Within the framework, a balance has to be struck between over-investing limited effort available in a necessarily somewhat speculative uptake model, and maintaining focus on the higher objective of assessing the relative impact of increasing ATCO hours. It is also to be borne in mind that this mechanism is intentionally selected as an example of a 'basic' solution, such that bringing higher-level ATCO resource solutions into play (such as virtual centres and dynamic sectorisation) is not appropriate. Nevertheless, some trend analysis of ANSP performance over recent years will be taken into account, along with further expert opinion, in order to build a reasonable uptake model.

[3] See also: L. Delgado, A. Cook, S. Cristóbal and H. Plets, "Controller time and delay costs - a trade-off analysis", D. Schaefer (Ed.), Proceedings of the fifth SESAR Innovation Days, Bologna, 2015.

[4] See: https://www.eurocontrol.int/services/acdm (Accessed July 2015).

[5] See: http://www.euro-cdm.org/airports.php (Accessed July 2015).

3.5. Modelling the cost of airline delay

As part of the framework development, and feeding many of the impact metrics described in the next section, cost of delay values previously published (Cook & Tanner, 2011) by the University of Westminster for 2010, for twelve aircraft types, by phase of flight and delay duration, will be updated to €$_{2014}$ values and extended to include three additional aircraft types.[6] (The new values will be published as independent reference tables, after stakeholder consultation.) These models calculate airline costs separately for strategic delay (planned in advance through the addition of schedule buffer) and tactical delay (incurred on the day of operations). Of these, the tactical costs will be primarily used in the impact metrics described below.

The costs will cover the full range of cost types incurred by airlines – fleet, fuel (and carbon), crew, maintenance, and passenger costs of delay to the airline. Table 7 shows the types of costs that contribute to the strategic, tactical and reactionary (propagated) delay cost calculations. For example, maintenance costs apply in all cases, in contrast to fleet costs that only contribute to the strategic phase. Referring back to the formulations of Section 2.4, summing across the contributing tactical component cost types for assessment units (u) as a function of delay duration (t), furnishes $C_u(t)$. These values are thus not only useful in their own right (such as estimating the cost of delay of a flight) but also in terms of their contribution to the estimation of cost resilience through Equation (3).

'High', 'base' and 'low' cost scenarios are designed to cover the range of costs for European airlines. Combinations of cost scenarios may be used to represent particular airline types. For example, an airline operating long-haul flights with a modern fleet might be assigned 'low' maintenance costs and 'base' fleet, crew and passenger costs. This allows mapping onto the airline types also used in the definition of the differential stakeholder uptake modelling.

These cost updates will reflect market trends and regulatory change – e.g. with respect to Regulation (EC) 261/2004 on passenger duty of care during air transport disruption (European Commission, 2013c) and with respect to driving carbon prices (European Commission, 2014b). Updates to estimates of the passenger cost of delay to the airline will also draw upon a study by Steer Davies Gleave (SDG) in support of a European Commission impact assessment (European Commission, 2013). The objective of the SDG calculation was focused on calculating total network costs. The mapping of certain SDG costs to complement our framework requires further computations to derive aircraft-specific and delay duration-specific costs, in addition to quantified estimates of the passenger uptake of various rights.

3.6. Impact metrics

Widening the discussion beyond dedicated resilience metrics *per se*, in this section we discuss the complementary metrics used to assess the impacts of the mechanisms, to establish model baselines, and to set values of R_C into valuable context, e.g. regarding passenger and flight delays.

Due to the stochastic nature of the model and its soft-computing implementation, its outputs are also of a stochastic nature. For some impact metrics, full probability distribution functions can be estimated, although in general mean values and a range of dispersion measures (e.g. standard deviation, skewness, kurtosis) will be used. The impact metrics can be classified into three basic clusters: (i) departure delay; (ii) arrival delay; and, (iii) reactionary delay.

Table 7
Cost types by operational phase.

Cost to airline	Strategic	Tactical	Reactionary
Fleet	✓		
Fuel (and carbon)	✓	✓	
Crew	✓	✓	✓
Maintenance	✓	✓	✓
Passenger		✓	✓

This apparent simplicity conceals further depths of output, however. For arrival and departure delays, a number of outputs will be produced. These not only include simple counts and averages, but critically include assigned costs, and also conditional values (such as the average departure delay of departure-delayed flights, and values filtered according to commonly used 5- and 15-minute delay thresholds, etc.). Other explicit costs (as discussed in the previous section) can also be isolated and reported, such as the cost of fuel burn, as can estimates of CO_2. Thus, three of the four SESAR key performance areas (environment, cost-efficiency and capacity) will be addressed, whereas safety is out of scope, as mentioned earlier. (We note in passing that assigning costs to safety is currently not matured in European ATM). Reactionary metrics will include basic counts and industry-standard primary/reactionary delay ratios, in addition to measures of back-propagation and tree/branching characteristics, etc.

Moreover, as has been previously established (see Cook et al. (2013) and the review therein) passenger-centric and flight-centric metrics often give different results, and some changes in performance may not be visible using simple flight-centric metrics alone. Our model is thus geared to produce full, corresponding passenger-centric metrics for all the flight-centric metrics, and, indeed, to extend the range of passenger-focused outputs to cover, for example: arrival delay at the *final* destination; extra dwell times measured at different locations (in-flight, at an airport); and, passenger values of time (explicitly differentiated from airline-impacting costs). Other non-cost metrics are also calculated for disrupted passengers, such as counts of missed connections, extra flights required, aborted journeys, and unanticipated overnight stays.

3.7. Test application of cost resilience metric

We here briefly describe an initial test of the resilience metric proposed in Section 2.4 (Equation (3)), using the currently implemented extent of the model, using earlier (2010) delay costs and passenger-traffic data.

The results in Table 8 represent an earlier mechanism investigated (Cook et al., 2013), i.e. an airline at-gate mechanism. Aircraft wait times for missed-connection passengers were estimated on a cost minimisation basis, taking account of prevailing flow management conditions and expected delay propagation. This will form the basis of the improved passenger reaccommodation tools modelling, introduced in Section 3.3. The net cost reduction across all flights afforded by the mechanism corresponds to $R_C = 0.072$ (n = 29 555) for a nominal (typical) day – an average saving of €39 per flight. Imposing additional disturbance (stochastically increasing the average departure delay across the network by one minute), increased the delay costs ($p < 0.01$) and reduced the cost resilience by one percentage point, to $R_C = 0.062$ (n = 29 555). Although these calculations currently assume that the tactical implementation of the mechanism is without cost (i.e. $C_m(t) = 0$), it is clear from Equation (3) that under nominal conditions for

[6] The directly supported aircraft, following stakeholder consultations, are thus: A319, A320, A321, A332, AT43, AT72, B733, B734, B735, B738, B744, B752, B763, DH8D, E190.

Table 8
Airline cost savings with wait rules mechanism.

Scenario modelled	Total network airline delay cost …		Cost resilience
	… without mechanism	… with mechanism	(R_C)
Nominal delays	€ 16.11 m	€ 14.95 m**	7.2%
With disturbance	€ 17.08 m	€ 16.02 m**	6.2%

**$p < 0.01$ for cost reduction relative to no mechanism.

similarly busy days, any network tactical cost of up to €1.16m would still afford some resilience ($R_C > 0$) and offer a net saving. Average traffic figures for the top ten European carriers suggest that a corresponding monthly tactical cost of up to €1.5m of running such a mechanism would be typically worthwhile for such airlines, i.e. offer a net saving in terms of avoided delay costs.

4. Conclusions and advancing the state of the art

We conclude with a reflection on some of the distinguishing features of the model and how it is hoped to develop the state of the art. The model is passenger-centric and event-driven. It is passenger-centric in that the core processes are aligned with full passenger itineraries rather than individual flights, thus better reflecting the true functionality of air transport operations. (To the best of our knowledge, no similar passenger itinerary dataset, with comparable geographical scope, exists.) Flight-centric and passenger-centric metrics will be compared and contrasted in the trade-off analyses to explore the effectiveness of the investment mechanisms. Fully monetised metrics will make essential contributions to the quantification of resilience. Of particular interest will be further investigation of the type of results reported in Section 3.7, particularly comparing these R_C values with those of other mechanisms and under other types of disturbance: we do not yet know if the values of 7.2% and 6.2% are relatively ‘good’, or not, in terms of performance. It would also be insightful to attempt to benchmark such resilience against comparable transport systems presented in Section 2.1, if appropriate data can be sourced. We emphasise again the need to set such results in the context of the (complementary) impact metrics, relating to arrival, departure and reactionary delay.

Instead of a traditional (sequential execution) programming approach, the event-driven model affords better realism in that any given event (subroutine) may trigger one or more dependent events, with the overall flow determined by an event manager. Each actor in the model has associated events, not only individual passengers, but also flights, airlines, airports and ANSPs. A key functional requirement of the programming is to track *causal* links through the events cascade, e.g. using recursive algorithms. This is an important feature, and avoids a much weaker reliance on observed *associations* only, thus enabling significantly better insights into the mechanisms' effectiveness under the disturbance types.

This framework will, it is hoped, advance the state of the art beyond current (synchronous) investment assessment and improve the understanding of complex interdependencies that are often overlooked in trade-off models. With evaluations focusing between the SESAR Deployment Baseline and ConOps Step 1, and by comparing advanced and basic mechanisms, we aim to support improved cost-benefit assessments with regard to costed business cases in ATM and wider European policy objectives.

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