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What Cost 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, will be deployed. A new cost resilience metric is proposed.**

Keywords–complex networks; disturbance; resilience; resilience metrics; stakeholder uptake; strategic investment

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I. INTRODUCTION

The primary objective of the ComplexityCosts project is to better understand 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 disruption, 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 I.

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 or air navigation service provider (ANSP) ownership structure. Although high-level roadmaps have been developed within the ATM Master Plan [1] and associated contexts (such as the Pilot Common Project [2, 3]), the ComplexityCosts model will refine the relationship between selected mechanisms and stakeholder uptake.

TABLE I. MECHANISM CLASSIFICATIONS

Mechanism		*Summary description*	*Example*
Type	Advanced	SESAR Essential Operational Changes* and sub-components thereof (or equivalent advanced or supporting technologies/tools).	Airport collaborative decision making (CDM).
	Basic	Non-advanced, does not centrally involve implementing new technologies/tools.	Airline adding buffer to its schedule.
Disturbance focus	Mitigation[†]	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[†]	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.

* See Section III(C); [†]non-mutually exclusive.

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 II) and on the modelling itself (Section III). 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.

II. RESILIENCE IN CONTEXT

The objective of Section II 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 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 [4, 5]. Many of the roots of complexity science can be traced back to statistical physics, non-linear dynamics and information theory [6]. Moving beyond a definition of resilience, we will conclude the section by examining the particular challenges associated with the design of corresponding metrics in ATM.

A. *Wider perspectives*

TABLE II. 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

Table II 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 [7, 8], ecology [9–10], utilities [11–15], transportation [16–19] and telecommunications [20–22]. 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 a 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 resilience. However, we need to formulate a more precise definition of this within our modelling framework.

B. *What is resilience?*

Regarding an agreed definition of resilience, it has been pointed out in a recent review [23] 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 [24]. A thorough review with numerous ATM examples is in preparation [16]. The first two milestones (see Table III) in the development of the term were its initial introduction in material testing [25] and the later adoption in ecology [9]. The latter led to widespread use of the term in the scientific literature.

TABLE III. THREE MAJOR DEFINITIONS OF RESILIENCE

Terminology	Introduction	Field	State(s)	Key feature
Engineering resilience	Hoffman (1948) [25]	material testing	one stable state	inherent ability of the system to return to its original state
Ecological resilience	Holling (1973) [9]	ecology	multiple states	ability of the system to absorb disturbance
Resilience engineering	Hollnagel (2006) [26]	air transport	multiple states	safety-based design of socio-technical systems

A third important milestone with relevance to air transport was the ‘resilience engineering’ paradigm introduced in 2006 [26], which led to (broader) qualitative modelling of resilience in ATM, from 2009 [27].

TABLE IV. 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

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 [28] across numerous domains, categorised three capacities of resilience, *viz.*: absorptive, adaptive, and restorative. These are summarised in Table IV. The key feature (second column) is taken from [29], 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 II(A) 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 [11], and [15] similarly refers 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.

C. *Resilience metrics*

We are now equipped with sufficient resilience definitions to explore the corresponding metrics. Output metrics measure system performance. They are represented by both cost and non-cost metrics. The latter are briefly discussed in Section II(D). Useful in their own right, the former also play a role in estimations of the cost of resilience. Most of the investment mechanism costs (input metrics) are expected to be paid strategically (i.e. as sunk costs). 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.

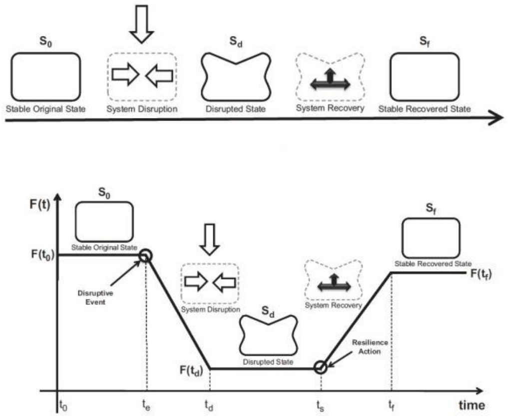

Figure 1. State diagram.
Source: adapted from [23].

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, [23] commences with the formulation (1), where $Я(t)$ 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. [18] uses similar ratios in the urban context: a relatively rare example of work using real estimated costs.

$$Я(t) = \frac{Recovery(t)}{Loss\ (t_d)} \tag{1}$$

The authors [23] 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 metrics 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 illustrated with specific regard to investment mechanisms in Fig. 2, 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 (panel 1(a)).

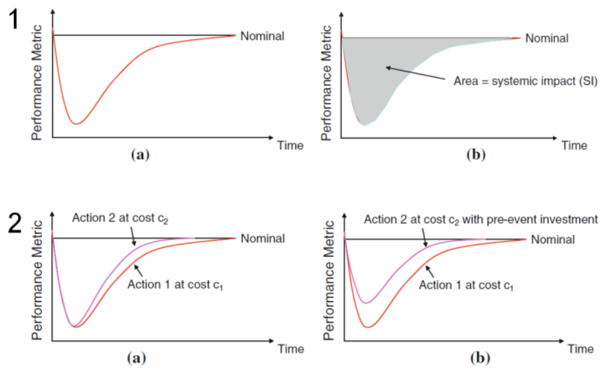

Figure 2. Resilience-enhancing investments.
Source: adapted from [29].

SI is the area of the degraded performance, as shown in panel 1(b). 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 – see panel 2(a). 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 – see panel 2(b). These expenditures are defined [29] as “resilience-enhancing investments”.

As is pointed out (*ibid*.), 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 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 [30] 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.

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

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 [16] and [28]. We next move forward to consider the specific ATM context.

D. *Metrics in the ATM context*

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 measured) and stable (we cannot refine them from one period to another without losing comparability). Let us consider some particularities of dealing with connecting flights in an air transport network, and measuring resilience.

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 required 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 [17], for example. We thus propose to use one operational day in European airspace as the boundary conditions for such 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 casually 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.

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 [20] or a pipe diameter in water distribution [13]. 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 III(C)) and the cost of delay modelling described in Section III(E).

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 $Я = 0.5$, 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. 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, as discussed in Section III(C). (We plan to report on such trade-offs in a subsequent paper, and a large part of ComplexityCosts is dedicated to these analyses). 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 = 1 000)" (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 is denoted $C_u(t)$.

Fourthly, we must 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).

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

Where:

$$\sum_u^d C_u(t) > 0; \quad \sum_u^d \sum_u^m C_u(t), \quad C_m(t) \geq 0 \qquad (4)$$

Such that:

$$R_C \leq 1 \qquad (5)$$

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.) Widening the discussion beyond dedicated resilience metrics, it is necessary to include, and distinguish between, flight-centric and passenger-centric metrics, as these are often uncorrelated – with important implications for cost optimisation assessments [17]. These wider metric classes comprise both cost-based and non-cost-based metrics. Examples of the latter are delay magnitudes, unpredictabilities, and reactionary metrics. Three of the four SESAR key performance areas (environment, cost-efficiency and capacity) will be addressed, whereas safety is out of scope. Such metrics also allow us to put values of R_C into valuable context, e.g. regarding passenger and flight delays. Finally, the models presented in the literature review were deterministic, whereas the ComplexityCosts model will include uncertainty (see Section III(A)). Statistical testing will thus be applied to the metrics and will be used to filter out non-significant R_C ratios, for example.

E. *Example application of cost resilience metric*

Table V shows results from a previous (*ibid.*) network simulation of 199 European Civil Aviation Conference (ECAC) airports plus 50 major airports beyond this region, for a selected day in a busy month (September 2010).

TABLE V. AIRLINE COST SAVINGS WITH WAIT RULES MECHANISM

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

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

Passenger connectivities and airline delay costs were explicitly modelled. An airline decision-making mechanism was applied, whereby 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. 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). Further work will enable us to compare these R_C values with those of other mechanisms. 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 (3) that under nominal conditions for 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. Averaged traffic figures for the top ten carriers suggest that a corresponding monthly tactical cost of up to € 1.5m would be typically worthwhile for such airlines.

III. THE COMPLEXITYCOSTS MODEL

A. *Overview of the model*

The ComplexityCosts model is a stochastic, layered network model that will include interacting elements and feedback loops. 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 of the scenarios. A busy September 2014 traffic day, free of exceptional delays, strikes or adverse weather, will form the baseline, with essentially the same geographic coverage as that outlined in the previous section. EUROCONTROL's DDR2 service 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 output metrics and potential investment mechanisms associated with passenger service delivery. The corresponding algorithms and calibration processes are currently in development.

B. *Differential stakeholder uptake*

As introduced in Section I(A), 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 [1] and the Pilot Common Project [3] (see Section III(C)), the ComplexityCosts model seeks to refine the relationship between selected mechanisms and stakeholder uptake, in the context of performance assessment.

Whilst ANSPs, for example, may be identified by given uptake likelihoods for one mechanism (e.g. based on size (en-route area control centres are classified in [1]) and traffic densities / complexities), a different method of assigning likelihoods might be used for another mechanism (e.g. ownership and regulatory constraints, or position in investment cycle). Developing different stakeholder categorisations for different mechanisms gives us greater freedom in the design of the model and extra power in the usefulness of the outputs.

Airlines are differentiated in the model by their business model into four passenger categories (full-service, low-cost, regional and charter), or as pure cargo operators. The latter are out of scope for ComplexityCosts since we do not have resources to model these delay cost impacts.

Whilst the International Civil Aviation Organization differentiates [31] airports based on ownership, more extensive classifications are needed in ComplexityCosts, with regard to mechanism uptake. These currently extend to: regulatory factors (e.g. controlling expansion); size (e.g. classified in [1] according to movements); number of runways; slot coordination status; and, hub status.

We are exploring such categorisations according to the terminology and Gaussian uptake distribution for innovation adoption lifecycles proposed in [32]. Whilst we will adapt this terminology somewhat, we are currently investigating the modelling effectiveness of, and data availability for, tripartite stakeholder categorisations such as ‘early adopters’, ‘early majority’ and ‘late majority’. A particular strength of the ComplexityCosts framework is that the metrics can also be differentiated by stakeholder sub-types (e.g. types of airline operator).

C. *Selecting the mechanisms*

Four basic criteria drive the selection process for the investment mechanisms to be considered in ComplexityCosts:

- a range of mechanisms is desired for comparison, covering both advanced and basic types (as defined in Table I);
- 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;
- the mechanisms need to be modelled through differential stakeholder uptake.

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 focused set of analyses.

The SESAR Concept of Operations (henceforth ‘ConOps’) is mapped into three overlapping steps [1]. 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 [33] 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* [2], recently adopted by Implementing Regulation (EU) No 716/2014 [34].

Through literature reviews, consultation of the ATM Master Plan and the SESAR proposal on the content of the PCP and the corresponding ATM functionalities [3], 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. Some of the cost data currently remain at a fairly aggregate level (e.g. [3]) and are being investigated further.

Table VI shows the candidate investment mechanisms so far short-listed, in order of appearance in the in-house database (i.e. no order of preference implied). The second column indicates early promise for the differential stakeholder uptake modelling. The final column indicates the availability of stronger cost data. Those in italics are thus less likely to be modelled, based on the data collected to date. Exploring changes to airline passenger reaccommodation policies is particularly attractive, as it is outside the planned SESAR context, and aligned both with the model’s passenger-centric metrics and European policy objectives.

TABLE VI. CANDIDATE INVESTMENT MECHANISMS

Candidate investment mechanism	**Stakeholder modelling**	**Cost data**
Airport CDM*	✓	✓
*En-route capacity planning tools**		✓
*Enhanced DCB (demand and capacity balancing tools)**	✓	
*Improved flight planning and demand data**		
Investment in new runways	✓	✓
*Time-based separation**		✓
Dynamic cost indexing	✓	✓
Changes to airline passenger reaccommodation policies	✓	✓
Airlines adding more buffer to schedule	✓	✓
Increasing ATCO hours in selected sectors	✓	✓

* Explicit correspondence with SESAR Essential Operational Change or sub-component.

D. *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, localisation (spatial scope), duration (temporal scope) and intensity. Notwithstanding qualitative, working classifications of these terms (such as 'rare' or 'unexceptional' frequencies), it is planned to capture a range of disturbances in the model, from volcanic ash clouds to weather disruption at one or more proximal airports. Included in the disturbance types to be modelled are: weather; ash plumes; air traffic flow management capacity restrictions (non-weather); strike actions; technical failures; passenger disruptions; and, military exercises These disruptions will be generically implemented in the model as: en-route capacity decreases; ground capacity decreases (including slot restrictions, increased separation and runway occupation times); airspace / airport closure (and re-routings); flight cancellations and other delays; and, passenger flow disruptions at airports (ground access and/or connecting delays).

Data on the disturbance types, enabling the building of frequency, scope and intensity models, will be sourced from EUROCONTROL (Central Office for Delay Analysis and Network Operations Portals [35]) and METAR (METeorological Aerodrome Report) data. Issues have been identified regarding the resolution of non-unique causal identifications from *basic* IATA delay codes, which may be (partly) resolved through *sub-codes* where available. Some data sources are of course better than others. METAR data furnishes fully sufficient information regarding the temporal and spatial scope of weather events. In contrast, data on strike actions and technical failures are available at rather lower resolution. Where quality thresholds are not met, the disturbance type will not be modelled. However, soft computing (related to fuzzy logic) will also be deployed – enabling the model to work with suboptimal input data in the context of generating higher-level metric estimates. Passenger disruption will be modelled using in-house data. Accidents are not planned for inclusion, due to their rarity. Some of the planned disturbance types will be specifically aligned with given mechanisms, with several one-to-many relationships having been mapped (not shown). No disturbance type is anticipated to be unaffected by all of the short-listed mechanism candidates of Table VI.

E. *ATM cost allocations*

We have already observed that the model's output metrics comprise both cost and non-cost metrics. During the course of the project, cost of delay values previously published [36] 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 two additional aircraft types[1]. These models calculate airline costs separately for strategic delay (planned for in advance through the addition of schedule buffer) and tactical delay (incurred on the day of operations). The former may thus be directly deployed as input costs for the basic investment mechanism of adding buffer to schedule, to increase schedule resilience (see Table VI). The tactical costs will be used in the output metrics. Reactionary (secondary) delays, not absorbed by strategically allocated schedule buffer, for example, will also be assessed.

The costs will cover the full range of cost types incurred by airlines – fleet, fuel (and carbon), crew, maintenance, and passenger costs. Table VII shows the types of costs that contribute to the strategic, tactical and reactionary delay cost calculations. For example, maintenance costs apply in all cases, in contrast to fleet costs that only contribute to the strategic phase. 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 (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 four airline types used for the differential stakeholder uptake modelling.

These cost updates will be published for open-access use as separate tables, along with the supporting literature reviews and summaries of the calculations for 2014. These will reflect market trends and regulatory change – e.g. with respect to Regulation (EC) 261/2004 on passenger duty of care [38] and driving carbon prices [39]. In the published tables, the reactionary costs will be statistical (drawing on network-level data); in the model itself, they will be explicit and causally tracked to the corresponding primary delays (as in [17]).

TABLE VII. COST TYPES BY OPERATIONAL PHASE

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

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[1] A stakeholder consultation is currently in progress regarding this extension. The existing twelve aircraft types [36] continue to account for over 50% of flights in the ECAC region [37].

IV. 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. Also, to the best of our knowledge, no similar passenger itinerary dataset, with comparable geographical scope, exists. Rules already established in the model govern passenger connectivities and recoveries from missed connections during disturbance. 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.

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 will allow us to not only ascertain that a given flight has 30 minutes of reactionary delay, but to identify the cause of the associated primary delay and its relationship with an investment mechanism, scenario-specific disturbance or systemic disturbance. Optimising the event manager processing efficiency is a key challenge, and this is achieved through parallel events execution (whereby events are processed independently and then synchronised) and stochastic approximation (instead of reproducing every process in detail, non-critical processes are replaced by stochastic models).

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. Mechanism assessment will focus between the SESAR Deployment Baseline and ConOps Step 1. Comparing advanced and basic investments, we also aim to further the cost-benefit analysis state of the art with regard to costed business cases in ATM.

REFERENCES

[1] SESAR, European ATM Master Plan, the roadmap for sustainable air traffic management, Ed. 2., 2012.

[2] European Commission, SESAR deployment, targeted stakeholder consultation on the establishment of the “Pilot Common Project” supporting the implementation of the European Air Traffic Management Master Plan, 2013.

[3] SESAR, Proposal on the content of a pilot common project, Ed. 1, 2013.

[4] M.E.J. Newman, “The structure and function of complex networks”, SIAM Review, 45 (2), 167–256, 2003.

[5] S. Boccaletti, V. Latora, Y. Moreno, M. Chavez and D.U. Hwang, “Complex networks: Structure and dynamics”, Physics Reports, 424 (4–5), 175–308, 2006.

[6] P.W. Anderson, “More is different”, Science, 177 (4047), 393–396, 1972.

[7] M. Barthélemy, “Spatial networks”, Physics Reports, 499, 1–101, 2011.

[8] L. Heaton, B. Obara, V. Grau, N. Jones, T. Nakagaki, L. Boddy and M.D. Fricker, “Analysis of fungal networks”, Fungal Biology Reviews, 26(1), 12–29, 2012.

[9] C.S. Holling, “Resilience and stability of ecological systems”, Annual Review of Ecology and Systematics, 4, 1–23, 1973.

[10] A. Zetterberg, U.M. Mörtberg and B. Balfors, “Making graph theory operational for landscape ecological assessments, planning, and design”, Landscape and Urban Planning, 95(4), 181–191, 2010.

[11] K.R. Piratla and S.T. Ariaratnam, “Performance evaluation of resilience metrics for water distribution pipeline networks”, Pipelines 2013: Pipelines and Trenchless Construction and Renewals - A Global Perspective - Proceedings of the Pipelines 2013 Conference, 330–339, 2013.

[12] T.D. Prasad and N.-S.Park, “Multiobjective genetic algorithms for design of water distribution networks”, Journal of Water Resources Planning and Management, 130(1), 73–82, 2004.

[13] J.G. Saldarriaga and M.A. Serna, “Resilience analysis as part of optimal cost design of water distribution networks”, Restoring Our Natural Habitat - Proceedings of the 2007 World Environmental and Water Resources Congress, 1–12, 2007.

[14] E. Todini, “Looped water distribution networks design using a resilience index based heuristic approach”, Urban Water, 2(2), 115–122, 2000.

[15] N. Trifunovic, L. Kanowa, and K. Vairavamoorthy, “Impact of balance between investment and operational costs on resilience of water distribution networks”, 14th Water Distribution Systems Analysis Conference 2012, 1, 579–595, 2012.

[16] H.A.P. Blom, “Resilience”, in: Complexity science in air traffic management, A. Cook and D. Rivas (Eds.), Ashgate Publishing, England, 2015 (in preparation).

[17] A. Cook, G. Tanner, S. Cristóbal and M. Zanin, “New perspectives for air transport performance”, D. Schaefer (Ed.), Proceedings of the third SESAR Innovation Days, Stockholm, 2013.

[18] M. Omer, A. Mostashari and R. Nilchiani, “Assessing resilience in a regional road-based transportation network”, International Journal of Industrial and Systems Engineering, 13(4), 389–408, 2013.

[19] M. Zanin and F. Lillo, “Modelling the air transport with complex networks: A short review”, The European Physical Journal Special Topics, 215 (1), 5–21, 2013.

[20] P. Babarczi, G. Biczók, H. Øverby, J. Tapolcai and P. Soproni, “Realization strategies of dedicated path protection: A bandwidth cost perspective”, Computer Networks, 57(9), 1974–1990, 2013.

[21] R. Bhatia, M. Kodialam and T.V. Lakshman, “Finding disjoint paths with related path costs”, Journal of Combinatorial Optimization, 12, 83–96, 2006.

[22] M. Scheffel, “Optimal topology planning of optical networks with respect to overall design costs”, Optical Switching and Networking, 2(4), 239–248, 2005.

[23] D. Henry and J.E. Ramirez-Marquez, “Generic metrics and quantitative approaches for system resilience as a function of time”, Reliability Engineering & System Safety, 99, 114–122, 2012.

[24] O. Gluchshenko and P. Förster, “Performance based approach to investigate resilience and robustness of an ATM System”, Tenth USA/Europe Air Traffic Management Research and Development Seminar, Chicago, 2013.

[25] R.M. Hoffman, “A generalised concept of resilience”, Textile Research Journal, 18(3), 141–148, 1948.

[26] E. Hollnagel, D.D. Woods and N. Leveson, Resilience engineering: concepts and precepts, Ashgate Publishing , England, 2006.

[27] EUROCONTROL, A white paper on resilience engineering for ATM, 2009. http://www.eurocontrol.int/sites/default/files/article/content/documents/nm/safety/~safety-a-white-paper-resilience-engineering-for-atm.pdf

[28] R. Francis and B. Bekara, “A metric and frameworks for resilience analysis of engineered and infrastructure systems”, Reliability Engineering and System Safety, 121 (2014), 90–103, 2013.

[29] M. Turnquist and E. Vugrin, “Design for resilience in infrastructure distribution networks”, Environmentalist, 33(1), 104–120, 2013.

[30] P. Bocchini and D.M. Frangopol, “Restoration of bridge networks after an earthquake: Multicriteria intervention optimization”, Earthquake Spectra, 28(2), 427–455, 2012.

[31] International Civil Aviation Organization, Doc. 9562, Airport Economics Manual, 3rd Ed., 2013.

[32] M. Rogers, Diffusion of Innovations, 3rd Ed, The Free Press NY, 1983.

[33] European Commission, Commission Implementing Regulation (EU) No 409/2013 of 3 May 2013 on the definition of common projects, the establishment of governance and the identification of incentives supporting the implementation of the European Air Traffic Management Master Plan, Official Journal of the European Union, L123/1–L123/7, 2013.

[34] European Commission, Commission Implementing Regulation (EU) No 716/2014 of 27 June 2014 on the establishment of the Pilot Common Project supporting the implementation of the European Air Traffic Management Master Plan, Official Journal of the European Union, L190/19, 2014.

[35] EUROCONTROL, Network Operations Portal Factsheet, January 2014.

[36] A. Cook and G. Tanner, European airline delay cost reference values, University of Westminster, for EUROCONTROL Performance Unit, March 2011.

[37] EUROCONTROL, Standard Inputs for EUROCONTROL Cost Benefit Analyses, Ed. 6.0, Brussels, 2013.

[38] European Commission, Air passenger rights revision (memo), Brussels, 13 March 2013.

[39] European Commission, Commission Regulation (EU) No 176/2014 of 25 February 2014 amending Regulation (EU) No. 1031/2010 in particular to determine the volumes of greenhouse gas emission allowances to be auctioned in 2013–20, Official Journal of the European Union, L56/11, 2014.