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University of Westminster Fundación Instituto de Investigación Innaxis (Innaxis)	

Abstract

Using traffic and passenger itinerary data for the European network, the cost resilience of four mechanisms, with phased stakeholder uptake, has been assessed under explicit, local and disperse disturbance: industrial action and weather. A novel cost resilience metric has demonstrated logical properties and captured cost impacts sensitively. Of these mechanisms, only A-CDM has been cost-benefit analysed in SESAR, yet the other three each demonstrate particular utility. Flight-, passenger- and cost-centric metrics are deployed to assess the mechanisms, with fully costed results presented, based on extensive industry consultation. Initial work on assessing mechanism payback periods has begun.

Authoring & Approval

Prepared By - *Authors of the document.*		
Name & Company	Position & Title	Date
Luis Delgado / University of Westminster	Consortium Member	26SEP16
Samuel Cristóbal / Innaxis	Consortium Member	26SEP16
Andrew Cook / University of Westminster	Project Leader	26SEP16
Graham Tanner / University of Westminster	Consortium Member	26SEP16

Reviewed By - *Reviewers internal to the project.*		
Name & Company	Position & Title	Date
Graham Tanner / University of Westminster	Consortium Member	27SEP16

Reviewed By - *Other SESAR projects, Airspace Users, staff association, military, Industrial Support, other organisations.*		
Name & Company	Position & Title	Date
N/A		

Approved for submission to the SJU By - *Representatives of the company involved in the project.*		
Name & Company	Position & Title	Date
Andrew Cook / University of Westminster	Project Leader	28SEP16

Rejected By - *Representatives of the company involved in the project.*		
Name & Company	Position & Title	Date
N/A		

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Executive summary

The main objective of ComplexityCosts is to gain deeper insights into ATM performance trade-offs for different stakeholders' investment mechanisms within the context of uncertainty: to what extent do such mechanisms mitigate the impacts of disturbance? This report describes the implementation of the mechanisms and their cost assignments, at the tactical and strategic levels, and the key results from the model simulations.

The ComplexityCosts model is a stochastic, layered network model. It takes into account different stakeholders, according to corresponding tactical and strategic cost structures, and their interactions. The baseline simulation day, 12SEP14, was carefully selected as a busy traffic day, free of exceptional delays, strikes or adverse weather.

Uncertainty (and network performance detriment) is modelled by disturbances introduced into the model: the statistical models for industrial actions and weather are explained. Background ATFM disturbance is also modelled as part of the baseline. The statistical parameters for these disturbances are derived from empirical data, as are the spatial and temporal duration of the disturbances.

The effect of the disturbances is variously mitigated by the mechanisms. Different mechanisms deliver different performance as a function of the spatial distribution of the disturbances. In some cases, a mechanism is better suited for localised disturbances in the network, but provides a lower benefit when disturbances affect the network in a wider manner. Each disturbance is thus modelled with two different spatial scopes: local and disperse. The mechanism mitigation is measured by various metrics: flight-centric, passenger-centric and cost-centric – in addition to a novel cost resilience metric, R_C, for which the derivation is summarised.

The table summarises the mechanism (effectively two for dynamic cost indexing, DCI) and disturbance type combinations. Excluding the baseline (which captures the current operational level of the mechanisms), there are 20 combinations to consider, each with two levels of stakeholder uptake: 'early adopter' and 'follower'. The uptake of the early adopters and followers incorporates the further development of more advanced mechanisms. Each uptake level includes the preceding level(s).

The combination of a disturbance, mechanism and stakeholder uptake level, is referred to as a 'scenario'. The full model thus comprises 40 scenarios in total (each one measured against an appropriate baseline). The table also shows the location focus (physical manifestation of the mechanism) and from where the primary strategic investment in the mechanism originates, noting that for (1) and (3) the main investor is not the airline, although it is the major beneficiary.

Most of the investment mechanism costs are expected to be paid for strategically (i.e. as sunk costs). However, we must also take account of any tactical ('running') costs associated with the mechanisms – such as variable fuel burn during aircraft delay recovery with DCI.

Model scenarios

Mechanism	**Location focus**	**Primary investment**	**AO delay driver**	**Disturbance type**			
				Industrial action		**Weather**	
				Local	Disperse	Local	Disperse
1. Improving sector capacity with ATCO hours	en-route	ANSP	magnitude	✓	✓	✓	✓
2. Dynamic cost indexing[†]	en-route	AO	cost	✓	✓	✓	✓
3. Airport Collaborative Decision Making	airport	airport	magnitude	✓	✓	✓	✓
4. Improved passenger reaccommodation	airport	AO	cost	✓	✓	✓	✓

[†] Plus higher fuel cost scenario.

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 ATM Master Plan. Sources for costs were a primary consideration, as these are limited, and, without them, the metrics cannot be evaluated.

The allocation of passengers to flights, with connecting itineraries and fares, is an important part of the model both with regard to the output metrics and mechanisms associated with passenger service delivery. In-house itineraries for 2010 were used as a starting point. The generation of the passenger itineraries deploys three datasets: individual itineraries for one day in September 2010 (in-house data); aggregated September 2010 International Air Transport Association itineraries (‘PaxIS’ data); and, a sample of anonymised, individual itineraries from September 2014 provided by a global distribution system service provider. In order to calibrate the data to September 2014, aggregated passenger data from Airports Council International EUROPE and Eurostat passenger flows were considered alongside published airline load factors.

In order to be able to assess the scenarios using cost-centric metrics, it is necessary to model the corresponding tactical costs. These are primarily modelled as costs of delay to the airline. The main such costs are comprised of passenger, fuel, maintenance and crew costs. The cost of delay to the airline resulting from passenger delay is applied with a particular focus on the impact of Regulation (EC) No 261/2004. The rules governing such compensation payment entitlements and airline practice, particularly when taking into account associated reactionary delay effects, are highly complex, and legal advice was taken.

Basic model calibration results are presented. Strategic (implementation) and tactical (running) costs of the mechanisms are discussed, contrasting the values in terms of the principles of their operationalisation.

The results of the R_C values calculated for the 40 scenarios are discussed in detail, comparing these across the mechanisms, disturbances and stakeholder uptake levels. These were considered to behave logically and sensitively. Of these mechanisms, only airport collaborative decision making (A-CDM) has been cost-benefit analysed in SESAR, yet the other three each demonstrate particular utility. The improved sector capacities mechanism performed particularly well, and a rationale is presented for this.

The flight-centric, passenger-centric and cost-centric metrics were used to explore the R_C findings in more detail. Flight arrival delay patterns follow departure delays, as expected. Considering the average flight arrival delays, the improved sector capacities mechanism performed best. On average, across all the scenarios and compared with the other mechanisms, it furnished an extra total cost saving to the airlines of approximately €930k during this busy, disturbed traffic day. The two DCI fuel cases are statistically the same in terms of flight arrival delays at the network level, but performed somewhat better than A-CDM. A-CDM, in turn, produced a flight arrival delay significantly lower than the passenger reaccommodation mechanism.

Considering the ratio of arrival-delayed passenger over arrival-delayed flight minutes, the ComplexityCosts model produces values in the range 1.7 – 1.9, in agreement with similar ratios previously reported. This corroborates the need for dedicated, passenger-centric metrics.

For the passenger reaccommodation mechanism, it is likely that the cost-based local rebooking (for the early adopters), subsequently extended to wait rules for passengers (for the followers), suffers from negative impacts further ‘downstream’ (on subsequent rotations) during the operational day. Decisions, as modelled, such as to wait for passengers, are locally good, but globally do not offer the expected benefits, for example due to delays being subsequently compounded by further ATFM regulations being applied. This is partly manifested by the highest reactionary delay ratio (47.4%) occurring for this mechanism. Dynamic cost indexing (under either fuel cost assumption) produced approximately 40 kilotonnes less airborne CO_2 in the network during the busy simulation day relative to improved sector capacities.

Initial work on assessing mechanism payback periods has begun, showing fairly good agreement with published values for A-CDM.

An extensive list of potential future research is presented, identifying opportunities in the short- and medium-term to build on the work completed thus far, to further develop this adaptable method of cost-benefit analysis and cost resilience assessment.

1 Introduction

1.1 Purpose of the document

The primary objective of ComplexityCosts is to better understand ATM network performance trade-offs for different stakeholder investments in the context of uncertainty. A variety of investment mechanisms and disturbance types have been considered. This report presents key background material and the final results.

1.2 Intended readership

This Final Technical Report summarises the ComplexityCosts project for the professional reader and assumes an understanding of air transport and ATM.

1.3 Inputs from other projects

Not applicable.

1.4 Glossary of terms

Not applicable.

1.5 Acronyms and Terminology

Term	Definition
A-CDM	Airport Collaborative Decision Making
ACE	ATM Cost-Effectiveness
ACI	Airports Council International
AEA	Association of European Airlines
AIRAC	Aeronautical Information Regulation and Control
ANSP	Air Navigation Service Provider
AO	Aircraft Operator
APU	Auxiliary Power Unit
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATMAP	ATM Airport Performance Framework
BADA	Base of Aircraft Data (EUROCONTROL)
CODA	Central Office for Delays Analysis (EUROCONTROL)
DCI	Dynamic cost indexing
DDR/DDR2	Demand Data Repository
DPI	Departure Planning Information
ECAC	European Civil Aviation Conference
EFB	Electronic Flight Bag
FTFM	Filed Tactical Flight Model (last-filed flight plan (M1) from Enhanced Tactical Flow Management System from DDR2)
GDS	Global Distribution System (system that distributes inventory on behalf of airlines)
IATA	International Air Transport Association
MCT	Minimum connecting time
METAR	Meteorological Aerodrome Report
MUAC	Maastricht Upper Area Control Centre

Term	Definition
NDA	Non-disclosure agreement
NMOC	Network Manager Operations Centre
SESAR	Single European Sky ATM Research
SIDs	SESAR Innovation Days
SJU	SESAR Joint Undertaking
TOC	Top of climb

1.6 Acknowledgement

We are very grateful to the institutions/individuals identified below, for their invaluable support in the production of this work. (This applies to support in addition to purchased and publicly available data.)

Institution	Support
ACI EUROPE (Brussels)	Passenger throughput data at European airports
Adeline de Montlaur (UPC, Barcelona)	Passenger assignment models (as Visiting Researcher at UoW)
Airlines (numerous, anonymous)	Passenger delay costs, reaccommodation policies & fares rules
Bott & Co Solicitors (Wilmslow, UK)	Passenger compensation claims, application of Regulation 261
CODA (EUROCONTROL, Brussels)	European performance data, especially re. strike actions
DFS Deutsche Flugsicherung GmbH (Langen, Germany)	A-CDM implementation and operation costs
GDS (major, anonymous)	Passenger itinerary data
PACE Aerospace Engineering and Information Technology GmbH (Berlin, Germany)	Assessment of DCI mechanism costs
Performance Review Unit (EUROCONTROL, Brussels)	European performance data, especially re. delays
Sabre Airline Solutions (Sabre Corporation, Delaware, US)	Assessment of passenger reaccommodation mechanism costs

2 Scenarios and metrics

The ComplexityCosts simulation model takes into account different stakeholders, according to their corresponding tactical and strategic cost structures, and their interactions. The aim is to gain deeper insights into ATM performance trade-offs for different stakeholders' investment mechanisms within the context of uncertainty. Uncertainty is modelled by introducing disturbances into the model. Background ATFM disturbance is also modelled as part of the baseline. The effects of the disturbances are variously mitigated by the mechanisms.

Different mechanisms might deliver different performance as a function of the spatial distribution of the disturbances, and the level of uptake by the stakeholders. In some cases, a mechanism might be better suited for localised disturbances in the network, but provide a lower benefit when disturbances affect the network in a wider manner. For this reason, each disturbance is modelled with two different spatial scopes: localised and disperse. The combination of a disturbance, mechanism and stakeholder uptake level, is referred to as a scenario.

This section describes the model scenarios and the metrics used to evaluate them.

2.1 Model scenarios

Table 1 summarises the mechanism (effectively two for dynamic cost indexing, DCI) and disturbance type combinations. Excluding the baseline (which captures the current operational level of the mechanisms), there are 20 combinations to consider, each with two levels of stakeholder uptake: 'early adopter' and 'follower'. The uptake of the early adopters and followers incorporates the further development of more advanced mechanisms. Each uptake level includes the preceding level(s).

This thus comprises **40 scenarios** in total (each one measured against an appropriate baseline). The table also shows the location focus (physical manifestation of the mechanism) and from where the primary strategic investment in the mechanism originates, noting that for (1) and (3) the main investor is not the airline, although it is the major beneficiary. Although airline delay magnitudes and delay costs are intimately related, the mechanisms focus more specifically on either the delay magnitude, or delay cost (fourth column). The latter applies when airline delay costs are (in theory at least) available at the decision-making point during tactical implementation of the mechanism (i.e. airlines applying DCI or controlling passenger reaccommodation tools). Most of the investment mechanism costs are expected to be paid for strategically (i.e. as sunk costs). However, we must also take account of any tactical ('running') costs associated with the mechanisms – such as variable fuel burn during aircraft delay recovery with DCI. Such costs are examined later.

Table 1. Model scenarios

Mechanism	**Location focus**	**Primary investment**	**AO delay driver**	**Disturbance type**			
				Industrial action		**Weather**	
				Local	Disperse	Local	Disperse
1. Improving sector capacity with ATCO hours	en-route	ANSP	magnitude	✓	✓	✓	✓
2. DCI (+ higher fuel cost scenario[†])	en-route	AO	cost	✓	✓	✓	✓
3. A-CDM	airport	airport	magnitude	✓	✓	✓	✓
4. Improved passenger reaccommodation	airport	AO	cost	✓	✓	✓	✓

[†] This qualifier is dropped in subsequent tables.

2.2 Performance metrics

The following tables show the metrics available as model outputs. They are categorised as:

- flight-centric;
- passenger-centric;
- cost-centric.

Strategic and tactical cost metrics are computed individually by stakeholder according to the respective uptake level (baseline, early adopters and followers). Where appropriate, standard deviations are also used to test for statistical differences between means of metrics (see Section 4).

Table 2. Flight-centric metrics

Code	Name	Subcategory	Units	Description	Comments
A.01	Flight departure delay	delay	minutes	actual - scheduled	at-gate
A.02	Flight arrival delay	delay	minutes	actual - scheduled	on-gate
A.03	Number of departure-delayed flights	delay	flights	count if delay > 5 min	threshold may be varied, e.g. to define delays as above 0, 1, 2, … 15, … minutes (according to context required)
A.04	Departure delay of departure-delayed flights	delay	minutes	uses A.03	
A.05	Number of arrival-delayed flights	delay	flights	count if delay > 5 min	
A.06	Arrival delay of arrival-delayed flights	delay	minutes	uses A.05	
A.07	Flight-km	disutility	km	leg length, summed over all flights	classified as “disutility” for comparison with analogue B.07; actually multi-functional
A.08	Reactionary delay	delay	minutes	actual – scheduled (departure delay)	delay caused by late arrival of (other) aircraft or passenger
A.09	Wait at-gate	delay	minutes	waiting time at gate	-
A.10	ATFM delay	delay	minutes	delay due to regulation	imposed at-gate
A.11	Airport reactionary/primary delay ratio	resilience	n/a	reactionary / non-reactionary departure delay	-
A.12*	CO_2 – at-gate	environment	tonnes	CO_2 emitted at-gate	based on MTOW-extrapolated APU data; up to 20 minutes’ fuel burn during turnaround; fuel burn whilst ready but awaiting pushback
A.13*	CO_2 – airborne	environment	tonnes	CO_2 emitted during climb, cruise and descend	based on fuel burn data in Section 3.4.1

* Simple estimation only.

Table 3. Passenger-centric metrics

Code	Name	Subcategory	Units	Description	Comments
B.01	Passenger departure delay	delay	minutes	actual - scheduled	at-gate
B.02	Passenger arrival delay	delay	minutes	actual - scheduled	on-gate
B.03	Number of departure-delayed passengers	delay	pax	passengers affected by departure delay on their first leg only	for delays > 5 minutes; threshold may be varied, e.g. to define delays as above 0, 1, 2, … 15, … minutes (according to context required)
B.04	Departure delay of departure-delayed passengers	delay	minutes	uses B.03	
B.05	Number of arrival-delayed passengers	delay	pax	at final destination	
B.06	Arrival delay of arrival-delayed passengers	delay	minutes	uses B.05	
B.07	Passenger-kilometres	disutility	pax-km	pax X leg length, summed over all flights	analogue of A.07
B.08	Average load factor	resilience	percent	load factors averaged over all flights	-
B.09	Passenger extra time before boarding	wait	minutes	from scheduled to actual boarding time	-
B.10	Passenger arrival extra time / journey time	disutility	ratio	delay on arrival divided by journey length	disturbance perception is related to journey length
B.11	Number of extra flights taken	disutility	flights	passengers re-accommodated	-
B.12	Passenger extra time on aircraft	disutility	minutes	extra time on aircraft, summed over all flights	-
B.13	Passenger missed connections	disutility	pax	disrupted itinerary	due to any reason (including cancellations); only first connection missed is counted
B.14	Passenger re-accommodations	disutility	pax	successfully re-accommodated passengers	-

Table 4. Cost-centric metrics

Code	Name	Subcategory	Description	Comments
Cost of delay				
C.01	Passenger soft costs	indirect	e.g. loss of market share due to unpunctuality	-
C.02	Passenger hard costs	direct	e.g. pax reaccommodation costs	-
C.03	Crew and maintenance costs	direct	crew and maintenance costs due to delays	-
C.04	Fuel costs	direct	fuel cost due to delays	-
C.05	Total cost of delay	direct	C01 + C02 + C03 + C04	-
C.06	Average total cost of delay		C05 / A01 (per flight)	-
C.07	Passenger value of time	indirect	disutility value of delay for passengers	-
Mechanism-related costs				
C.08	Strategic costs	direct	as described in Section 3.2	each mechanism has its own strategic costs, shown by stakeholder uptake level
C.09	Tactical costs	direct	as described in Section 3.2	each mechanism has its own tactical costs, shown by stakeholder uptake level
C.10	Cost resilience	ratio	measures the effect of the investment mechanism with respect to the cost of the disturbance without the mechanism	please refer to text in Section 2.3

All values are costs in 2014-Euros, except C.06 (2014-Euros/flight) and C.10 (cost ratio).

2.3 Quantifying resilience

2.3.1 Qualitative foundations

Before being in a position to quantify resilience, it is first necessary to have a qualitative definition. This section summarises work presented in Cook *et al.* (2016). As pointed out in a recent review (Henry and Ramirez-Marquez, 2012), 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), and a thorough review with numerous ATM examples has recently been published (Blom and Bouarfa, 2016). The first two milestones (see Table 5) 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).

Table 5. 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 (2006)	air transport	multiple states	safety-based design of socio-technical systems

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. The latter is the focus of ComplexityCosts, with safety being out of scope at this stage. 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 6.

Table 6. Three capacities of resilience

Capacity	Key feature	Key associations	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 ‘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. 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 Cook *et al.* (2016), we also discussed (practically) instantaneous recovery, associated with (schedule) buffers and ‘buffer energy’. As will be expanded upon later in this report, ComplexityCosts embraces all three capacities, taking into account both the strategic and tactical phases, with flow (aircraft and passenger) reaccommodation central to the model.

2.3.2 Quantitative developments

We have previously presented (*ibid.*) a quantitative discussion of resilience using state diagrams. Developing a metric for resilience, Henry and Ramirez-Marquez (2012) commences with the formulation (1), where *Я(t)* is the resilience of a system at time *t*. This describes the ratio of recovery at time *t* to loss suffered by the system due to a disruption event at time *td*. 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.)

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

The authors (Henry and Ramirez-Marquez, 2012) go on to define a quantitative 'figure-of-merit' function, which specifies a system-level delivery metric. It is time-dependent and changes as the system state changes. 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 Turnquist and Vugrin (2013). These are implemented strategically and are designed to result in a reduction of the tactical magnitude of the disruption from a given disturbance, in addition to speeding up the system recovery. Such expenditures are defined as "resilience-enhancing investments". An extensive paper (Bocchini and Frangopol, 2012) reporting on an optimisation procedure for the restorative activities associated with the bridges of an urban network severely damaged by an earthquake, cites a normalised integral over time as a "broadly accepted" formulation of resilience. This is dimensionless and takes values in the range [0%, 100%]. For wider reviews of resilience metrics, see Blom and Bouarfa (2016) and Francis and Bekara (2013).

2.3.3 Novel cost resilience metric

In this section, we summarise the derivation of a novel cost resilience metric, R_C, which will be used to characterise the effectiveness of the ComplexityCosts mechanisms, in Section 4. Further details and early evaluations were presented in Cook *et al.* (2016). In order to take account of the time dependency when measuring resilience, causal summations, with specific regard to the mechanism and disturbance applied, are proposed. The precise time over which a given recovery occurs is difficult to assign, since propagation effects persist over many causally linked rotations during the (post disturbance) operational day. One operational day in the European airspace (see Section 3.1) is thus used as the boundary condition for the analyses.

The summation over events causally affected by the mechanism are denoted Σ^m, and as Σ^d for the disturbances. This allows specific assessment of the mechanism, *relative* to the effect of the disturbances. The cost resilience metric, by design, fully comprises *cost-based* components, as a result of the selection only of mechanisms that can be monetised. The tactical 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 $C_u^m(t)$. It is also necessary to take account of any tactical costs associated with 'running' each mechanism, $C_m(t)$. (Such costs are detailed further in Section 0). The final formulation for the cost resilience metric is presented as (2), with constraints (3)[1]. Perfect resilience (complete cost recovery) gives $R_C = 1$; no recovery gives $R_C = 0$. If the mechanism were to induce greater costs than the disturbance alone, $R_C < 0$ obtains.

$$R_C = \frac{\sum_u^d C_u(t) - \sum_u^d \sum_m C_u^m(t) - \sum_m C_m(t)}{\sum_u^d C_u(t)} \tag{2}$$

Where:

$$\sum_u^d C_u(t) > 0; \;\; \sum_u^d \sum_m C_u^m(t), \;\; \sum_m C_m(t) \geq 0 \tag{3}$$

Such that:

$$R_C \leq 1 \tag{4}$$

Whilst simple ratios furnish straightforward metrics, they may also be misleading[2]. The number of assessment units (u, such as flights or passengers) should thus also be cited in their reporting, as with p values in statistical significance testing. The simple discipline of reporting "$R_C = 0.50$ (n = 10)" c.f. "$R_C = 0.50$ (n = 1 000)" ($n = \Sigma\, u$) at least gives immediate insight that the latter had the wider reach.

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[1] The first term in (3), 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.

[2] Take a simple example relating to equation (1): a €50 recovery of a €100 disruption. This would yield the same simple resilience ratio as a €50k recovery of a €100k disruption, i.e. both would give Я = 0.5.

3 Model design, parameterisation and calibration

3.1 Overview of model

The ComplexityCosts model is a stochastic, layered network model that includes interacting elements and feedback loops[3]. The model takes into account different stakeholders, according to corresponding tactical and strategic cost structures, and their interactions. The baseline simulation day, 12SEP14, was carefully selected as a busy traffic day, free of exceptional delays, strikes or adverse weather.

Flights on 12SEP14 were extracted from the DDR2 dataset, cleaned (e.g. to identify circular, positioning, light aircraft, all-cargo, and military flights), and then enhanced with schedule data (from Innovata), airline type identifiers (e.g. full-service) and seating capacities. The resulting clean traffic dataset consisted of 26 860 flights in scope (from a total of 33 810 DDR2 flights), which were then allocated passenger itineraries for the day (outlined in Section 3.4.2).

The stakeholders' mechanism adoption has been modelled according to three uptake levels: baseline (current situation), early adopters (mid-term) and followers (long-term). Uncertainty (and network performance detriment) has been modelled by various disturbances[4], including background disturbance as part of the baseline. The statistical parameters for these disturbances have been derived from empirical data, as were the spatial and temporal duration of the disturbances. The effect of the disturbances has been variously mitigated by the mechanisms.

The model is written in MATLAB (R2016b) using statistical, parallel and simulation packages[5]. Input data from CSV files are transformed into MATLAB-compatible containers to speed-up loading after pre-processing and pre-computations (e.g. passenger cost pre-calculated values). Minimum requirements are at least a quad 2.4 GHz 64-bit core processors and 4 GB of available RAM – with this configuration, a single simulation run can take between 5 and 20 minutes, depending on its complexity. Output storage per simulation run requires up to 500 MB to save a detailed simulation log and a traceable simulation run for further analysis.

In order to perform the combination of simulation runs, an Amazon-cloud grid of five super-computers (EC2 m4.4xlarge) is deployed. Each super-computer can simultaneously execute 11 scenarios using parallel threads, with the grid allowing the super-computers to share their data and simulation results in real-time. A full run, with all scenarios and baselines, takes 12 hours using the grid, whilst generating over 400 GB of simulation output. The final metrics are computed locally.

NB.

Please note that costs indicated as "[C1]", "[C2]", etc. in the following tables have been disclosed (in strict confidence) to the EUROCONTROL Project Officer to demonstrate their sourcing and veracity, but may not be reported here due to NDA / confidentiality restrictions. This restriction is also reflected in reporting some of the results in Section 4.

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[3] This theme is revisited in Section 5.

[4] A disturbance is defined as an event that may potentially cause (or aggravate) a disruption. A disruption is an event where normal operations are significantly degraded.

[5] The model is implemented using GitHub, a fully-featured version control repository, which stores all data source files online (but in a private repository) and can therefore can be accessed by multiple collaborators such that changes in code can be easily tracked, reviewed and commented upon. Since MATLAB is a scripted language, there is no need to compile and build an executable file: any user with access to the repositories is able to run the latest version of the software at any time.

3.2 Mechanisms

3.2.1 Improving sector capacity with ATCO hours

Table 7. Mechanism 1 – cost and implementation summary

Uptake	Costs		Implementation
	Strategic	Tactical	
Baseline	Not applicable		**No mitigation** Delays not mitigated by adding additional ATCO resources.
Early adopters	Not applicable	Full, seven-hour ATCO shifts (i.e. not marginal shifts) are used for mitigating regulations. For each ANSP, the average extra ATCO capacity for its airspace is estimated as the difference between the average number of maximum controllers available for each of the airspaces of the ANSP that have more than one configuration, and the average number of controllers used in these airspaces during the period AIRAC 1313 to AIRAC 1413. (See Table 37 for data.) The ATCO hourly costs are sourced from EUROCONTROL (2016a), and the tactical cost method is based on Delgado *et al*. (2015).	**Extra ATCO hours added** In some cases, ATFM delays may be reduced if ANSPs enhance their operations and manage to avert airspace regulations declared due to staff shortage. This mechanism is similarly implemented as a reduction of ATFM regulation in the airspaces that experience increase in demand due to aircraft re-routing to avoid a disturbance (e.g., traffic circumventing a region affected by industrial action). Delay is typically generated for such flights since such regulations are not averted by the mechanism.
Followers	For this mechanism, the stakeholder making the investment is the ANSP (although this could be (partially) recovered later through airline user charges). The strategic cost is estimated from industry consultation as in the range €1–3M per ANSP, which we have scaled by ANSP size (number of ATCOs). See Figure 1.		

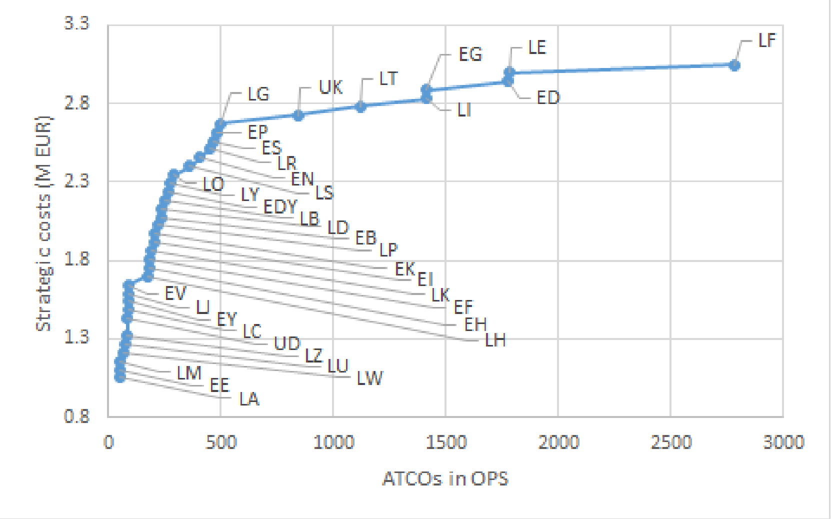

Figure 1. Estimated strategic cost per ANSP for improving sector capacity

Table 8. Mechanism 1 – uptake of improving sector capacity with ATCO hours

Uptake	Actors implementing mechanism
Baseline	None
Early adopters	MUAC, UK (EG)
Followers	Germany (ED), Spain (LE), France (LF), Poland (EP)

Table 9. Mechanism 1 – strategic cost of improving sector capacity with ATCO hours

ANSP	Code	Cost (€m)
MUAC	EDY	2.2
France	LF	3.0
Germany	ED	2.9
UK	EG	2.8
Spain	LE	2.9
Poland	EP	2.6

Table 10. Mechanism 1 – tactical cost of improving sector capacity with ATCO hours

ANSP	Code	Cost per hour* (€)	Average difference between controllers available and maximum	Average tactical cost per hour (€)
MUAC	EDY	215	7.0	1 505
France	LF	99	9.6	950
Germany	ED	197	5.5	1 084
UK	EG	133	2.7	359
Spain	LE	173	6.0	1 038
Poland	EP	96	7.7	739

* Source: EUROCONTROL (2016a).

Table 11. Mechanism 1 – total cost per disruption of improving sector capacity with ATCO hours

Disruption	Uptake	Strategic cost (€k)	Tactical cost (€)
Industrial action, local	Early adopters	5 000	2 500
	Followers	16 400 (11 400)	27 800 (25 300)
Industrial action, disperse	Early adopters	5 000	2 500
	Followers	16 400 (11 400)	25 000 (22 500)
Weather, local	Early adopters	5 000	2 500
	Followers	16 400 (11 400)	10 200 (7 700)
Weather, disperse	Early adopters	5 000	2 500
	Followers	16 400 (11 400)	16 800 (14 300)

Note: strategic cost is the implementation cost; tactical cost is the 'running' cost for one day.

Note: bracketed costs show cost increment compared with previous uptake.

3.2.2 Dynamic cost indexing

Table 12. Mechanism 2 – cost and implementation summary

Uptake	Costs		Implementation
	Strategic	Tactical	
Baseline	Not applicable		**Basic 'rule of thumb'** 10% of flights implement basic 'rules of thumb' to recover as much delay as possible when delay exceeds 15 minutes. This recovery will be bounded by a maximum extra fuel burn, to avoid excessive consumption. This basic rule applies anywhere in the network and for all airlines, except for flights of less than 60 minutes, that don't have the time to recover any significant delay. The implementation will consist of assessing the delay that can be recovered at TOC as with the DCI strategy (i.e. estimate the speed required to recover the maximum delay with the minimum recovery time), then selecting the option which maximises the delay recovery bounded by a maximum extra fuel consumption of 12.5% of the nominal cruise for flights with a flight plan of less than 1 500 NM (average limit of 170 kg with 90 percentile lower than 670kg) and 9% for flights longer than 1 500 NM (average limit of 3 400 kg with 90 percentile lower than 7 300 kg). The limit on fuel is to avoid unrealistic extra fuel usage due to delay recovery.
Early adopters	Cost of crew training regarding new procedures for DCI: cost proportional to the number of pilots per aircraft x aircraft in the fleet that will perform DCI x hours of training required (2 hours) per pilot x cost of crew per hour. It is considered that Class 2 EFBs are required to operate DCI. It is very difficult to estimate market data, but based on expert industry consultation, an even distribution of current EFB uptake by AOs is considered, with 50% of aircraft currently equipped with Class 1 EFBs, 40% with Class 2 and 10% with Class 3. Therefore, for 50% of aircraft that implement DCI, the cost of upgrading to Class 2 EFBs is considered [C2].	[C1]% of the total net saving accrued to the airline.	**Full DCI** For all aircraft implementing the enhanced DCI mechanism: (1) When a flight is delayed, the cost of recovering the delay, totally or partially, by speeding up during cruise, is assessed at the top of climb. (2) Delay is considered for recovery in discrete blocks of minutes using a logarithmic scale, which has greater granularity for smaller values of recovery. (3) Fuel and cost of time (delay) costs will be considered; costs of delay will be considered from historical look-up tables (i.e. will not be tactically updated). (4) Different costs of delay will be considered for inbound and outbound flights from the airlines' hubs. These costs include crew and maintenance costs, passenger costs (reaccommodation, hard and soft) and an estimation of costs due to propagation effects. (5) As reported by SESAR (SESAR, 2016), when the selected Cost Index is modified, not only the cruise speed changes but also the whole trajectory might be modified. In particular, the length of the cruise tends to increase. For this reason, the flights implementing DCI will increase their cruise following a normal distribution (μ=7.60 NM and σ=2.15 NM) bounded in the range [2, 18] NM. The descent duration and fuel will be reduced accordingly ensuring that a minimum descent distance is maintained.
Followers	As with early adopters, the flights considered to operate DCI will require operational training costs and system upgrade costs.		

Table 13. Mechanism 2 – uptake of dynamic cost indexing

Uptake	Actors implementing mechanism
Baseline	All flights greater than 60 minutes eligible to apply basic rules of thumb, as specified above.
Early adopters	Operations by hub carriers at top three ECAC airports (by passengers in 2014): British Airways at EGLL (LHR), Lufthansa at EDDF (FRA), Air France at LFPG (CDG).
Followers	Early adopters will expand DCI operations to their whole network. Other hub operators will consider DCI for flights at their major airports. Aircraft operators at five of the Group 1 ECAC airports, as defined by ACI EUROPE (>25m passengers/year; ACI EUROPE, 2015) in which the aircraft operator operated over 33% of the arrivals and departures on 12SEP14, i.e.: Turkish Airlines at LTBA (IST), KLM at EHAM (AMS), Alitalia at LIRF (FCO), SAS at EKCH (CPH), SWISS at LSZH (ZRH). In addition, a judgemental selection of other carriers: easyJet at EGKK (LGW), Vueling at LEBL (BCN), Iberia at LEMD (MAD).

An estimate of the number of pilots requiring training is based on the total number of pilots per airline and the proportion of operations to/from the hub with respect to the whole network. This ratio has been weighted as a function of the total time of the operations (schedule flight time). Three pilots are considered instead of two for flights scheduled to take over seven hours. The number of aircraft is based on the number of airframes (i.e. unique registrations) used by flights on the day under consideration, differentiating between operations to/from the main hub airport and the rest of the network. (The corresponding full cost table of estimated equipment and training costs for the strategic cost of implementing dynamic cost indexing is available for consultation, in strict confidence, on request by the Project Officer.)

Table 14. Mechanism 2 – strategic and tactical costs of dynamic cost indexing

Uptake	Strategic cost (€k) Total	Tactical cost (€k)
Early adopters **Followers**	[C5]	Charged to the airline as [C1]% of the estimated cost saving

Note: strategic cost is the implementation cost; tactical cost is the 'running' cost for one day.

3.2.3 A-CDM

Table 15. Mechanism 3 – cost and implementation summary

Uptake	Costs* Strategic	 Tactical	Implementation
Baseline	Not applicable	For the airport, agents and ANSP, the annual running cost varies (by airport size) from €50k to €450k. For the airline, the on-going training costs and flow-management role is assigned as an additional cost (compared with no A-CDM) of €50k for the major/'home' carrier (but quasi-nil for small airports: assigned as airports with less than the lower quartile of movements on the day of study, i.e. airports with fewer than 453 movements), and quasi-nil for the other carriers.	**3% average delay saving** Airports implementing A-CDM will have a reduction in the delay propagated, following a distribution centred on a 3% reduction.
Early adopters	Majority of cost invested by airport, agents and ANSP. These implementation costs vary (by airport size) from €550k to €4800k. Airline costs are fixed at €150k for the major / 'home'		**4% average delay saving** For airports that form part of the baseline scenario, a delay distribution will be centred on a 4% reduction. For airports newly implementing A-CDM, a 3% centred reduction will be modelled.
Followers			For airports that form part of the early adopter's scenario, a delay distribution

Uptake	Costs*		Implementation
	carrier, and €50k in total for the other carriers.	The tactical cost computed is yearly, therefore a factor of 0.34% of the cost will be considered as the cost of the day under study. This will allow the comparison of the tactical cost of the day with the other mechanisms. (0.34% is the proportion of traffic of the day under study (12SEP14) over the total yearly traffic.)	will be centred on a 4% reduction. For airports newly implementing A-CDM, a 3% centred reduction will be modelled.

* Sources: EUROCONTROL (2008, 2016c), plus industry consultation.

Table 16. Mechanism 3 – uptake of A-CDM

Uptake*	Actors implementing mechanism
Baseline	Airports with A-CDM implemented in 2014 (DPI operational at NMOC): EDDM, EBBR, LFPG, EDDF, EFHK, EDDL, EGLL, LSZH, ENGM, LIRF, EDDB, LEMD, EDDS, LIMC, EGKK.
Early adopters	Airports with A-CDM implemented by July 2016 (DPI operational at NMOC): LIPZ, LKPR, LEBL, LSGG, LIML.
Followers	Airports at some level of implementation of A-CDM by July 2016: ESSA, LFPO, EKCH, EHAM, LOWW, LTBA, EDDH, LEPA, LFLL, LIRN, ENBR, ENZV, ENVA, EIDW, LPPT, LFMN.

* based on CDM airports – EUROCONTROL - DPI Implementation Progress for CDM Airports. http://www.eurocontrol.int/articles/cdm-airports.

The uptake of the mechanism was based on: airports that were fully A-CDM by 2014 (baseline); those that were fully A-CDM by 2016 (early adopters); those that were at some stage of A-CDM development by 2016 (followers).

Table 17. Mechanism 3 – strategic and tactical costs of A-CDM

Uptake	Strategic cost (€k)	Tactical cost (€)
Early adopters	11 300	3 800
Followers	53 100 (41 800)	17 900 (14 100)

Note: strategic cost is the implementation cost; tactical cost is the 'running' cost for one day.

Note: bracketed costs show cost increment compared with previous uptake.

3.2.4 Improved passenger reaccommodation

Table 18. Mechanism 4 – cost and implementation summary

Uptake	Costs		Implementation
	Strategic	Tactical	
Baseline	Not applicable		**Local, airport-by-airport solutions only** Passengers with disrupted itineraries (missed connections) will be reaccommodated on subsequent flights. The final destination of the passenger is considered during the accommodation process; a different itinerary might be used. The process minimises the cost of reaccommodating the passenger, looking for solutions within the airline and airline alliance, before re-accommodating on competing carriers for high-yield passengers only. The passenger compensation cost (Regulation 261) is considered during this reaccommodation process.
Early adopters	For early adopters, the software is assumed to be an upgrade of existing software, with the cost recuperated through the normal tactical charging regime (see right).	Fixed cost charged to the airlines based on passenger boarded, i.e. [C3].	**Network-wide solutions** For each outbound flight, an assessment is made to analyse how many passengers would miss their connection if the departure is made on-time. Total network costs (including reactionary delays in the network) are calculated for 15-minute increments of wait times (taking into account prevailing ATFM slot conditions). An optimised wait/no-wait rule is implemented, based on the net cost best wait time (which could be zero wait).
Followers	Cost of implementation based on the volume of passengers boarded, i.e. [C4].		

Table 19. Mechanism 4 – uptake of improved passenger reaccommodation

Uptake	Actors implementing mechanism
Baseline	Same airlines as early adopters
Early adopters	Same as in DCI mechanism
Followers	Same as in DCI mechanism

Table 20. Mechanism 4 – total cost of improved passenger reaccommodation

Uptake	Strategic cost (€k)	Tactical cost (€)
Early adopters	0	[C7]
Followers	[C6]	

Note: strategic cost is the implementation cost; tactical cost is the 'running' cost for one day.

3.3 Disturbances

3.3.1 Generic processes

3.3.1.1 Background delays

Background ATFM delay is based on the delay observed for the baseline simulation day (12SEP14), as reported in the corresponding DDR2 data. Figure 2 illustrates the process used to assign ATFM delay to the flights. A pool of potential delays is generated with all the individual ATFM delays reported on 12SEP14. This delay is assigned to flights that operate through the regulated traffic volumes on that day. In this manner, the distribution of delay is similar to that of the baseline.

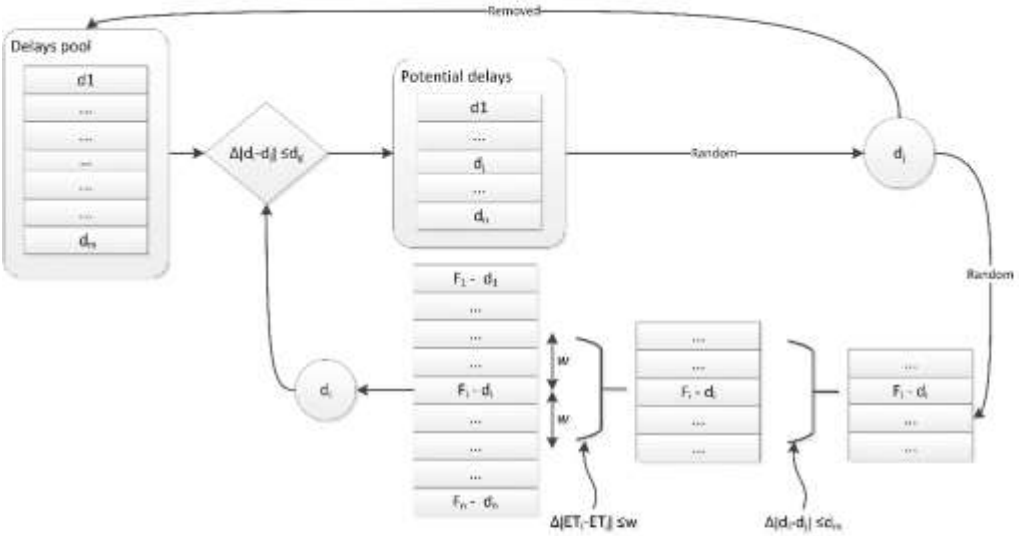

Figure 2. Delay generation concept

1. Delay generation

   A delay is selected for each flight which had ATFM delay assigned in the original data. The delays that are within a given delay window (d_g) from the flight original delay (d_i) are selected from the pool of delays. A delay is randomly selected (d_j) and withdrawn from the pool of delays. The delay which triggers the selection and the delay selected is randomly chosen. The range used to select the flights (d_g) controls the *uncertainty level* in terms of where the delay is generated.

2. Delay assignment

   The next step is to assign the selected delay to an individual flight. The set of flights that enter the traffic volume around the same time as the flight which generated the delay are selected (i.e. flights with an entry time in the traffic volume within a given number of minutes (*w*)). Only flights which originally had a delay with a difference smaller than a given threshold (d_m) with respect to the flight which generated the delay are kept as potential flights to be allocated the assigned delay. These thresholds are also used to control the desired degree of variability with respect to the initial data.

For the assignment of ATFM background delay, the parameters that need to be calibrated in the system are:

- d_g: delay window around delay to be assigned;
- *w*: time window for entry time in regulated traffic volume around the flight that generated the delay;
- d_m: maximum delay difference between original delay in selected flight and generated delay.

Non-ATFM background delay is also modelled, taking account of aggregated (September 2014 (EUROCONTROL, 2014) and full-year 2014 (EUROCONTROL, 2015a)) primary and reactionary delay categorisations.

3.3.1.2 Flights potentially affected by ATFM regulations

ATFM regulations are applied, for a period of time, to traffic volumes that can be defined as airspaces (e.g. a sector or group of sectors), waypoints, airports or sets of airports. For each modelled ATFM regulation, the list of potential flights affected is computed. This estimation of potential flights affected is computed based on the submitted flight plan (FTFM) that has been shifted in time to meet the schedules of the flight.

Only flights departing ECAC airports are affected by ATFM regulation delay. Note that even if a flight crosses a regulated traffic volume it might not be affected by the regulation if the entry and exit time for that traffic volume are outside the regulated period. A flight might be affected by a regulation, entering the traffic volume within the temporal scope of the regulation, due to a temporal shift of its trajectory inflicted by a delay (e.g. due to reactionary delay). For this reason, all the flights that enter the traffic volume during or before the regulation are considered to be potentially affected.

In some cases, a delayed flight might avoid a regulation by entering the traffic volume after the regulation has ended. Thus, for each potentially affected flight, there are two times associated: delay entering the regulation and delay avoiding the regulation. The first is the minutes of delay that a flight has to experience to enter the regulated traffic volume while the regulation is active: this value could be zero for flights that would be regulated if operated according to the schedule. The latter is the delay that a flight experiences for any reason apart from the regulation itself (avoiding the original regulation, after the regulation period).

Regulated traffic volumes are considered without the rules of traffic exclusion-inclusion and the duration of the regulations are as declared in the DDR2 data, i.e. the possibility of extending or cancelling a regulation are not considered.

3.3.1.3 Re-routing

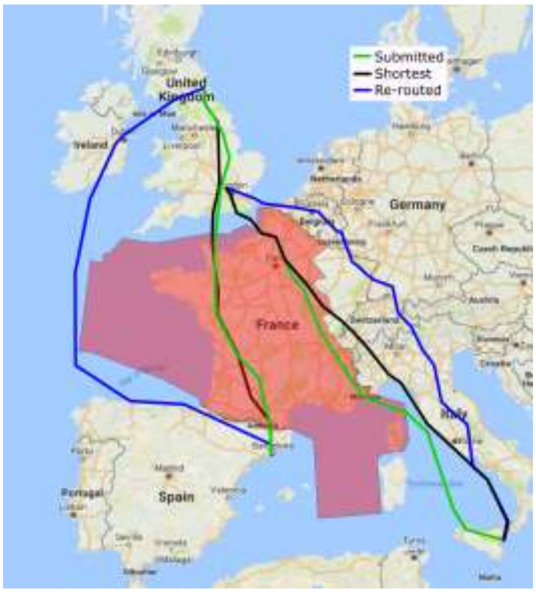

Figure 3. Example of possible re-routings around industrial action

When modelling ATFM regulations due to industrial actions and weather, there is the possibility for the aircraft operator to re-route the flight around the regulated airspace instead of accepting the assigned ATFM delay. A graph of all the possible routes based on the flight plans submitted on the day of study is created. The waypoints used in the flight plans generate the nodes, and the directional edges are added to the graph if a flight plan links two such waypoints. This routes graph consists of over 370 000 nodes and around 600 000 edges. With an A* search algorithm[6], the shortest route between two points in the graph can be computed. To avoid the regulations, the points that are within the boundaries of the ATFM regulations are withdrawn from the graph before computing the trajectory. Figure 3 presents two examples of possible re-routings around an industrial action. For the possible re-routed route, the total new flight plan length is estimated and the distance flown within each ANSP region is computed. This allows us to additionally detect ANSPs that might implement ATFM regulations to manage the extra flow derived from re-routings. This is consistent with *a posteriori* analysis (e.g. EUROCONTROL, 2016d) of industrial action days, whereby delays increase at ANSPs surrounding those implementing such regulations.

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[6] An algorithm widely used in pathfinding between multiple nodes.

3.3.2 Disturbances applied

3.3.2.1 Industrial action

Table 21. Industrial action disturbance – implementation summary

Feature	Parameters			
Probability of delay assigned if regulation entered	25%			
ATFM delay distribution for flights with delay assigned	Burr distribution parameters:	α = 141.474 c = 1.282 k= 4.531		
Cancellation and re-routing probabilities	Cancellation probability:	**5%** (including 1.5% background probability)		
	Re-routing probability:	**7%** (considering extra flight plan distance for re-routing)		
Spatial location and extent	**Local** **One ANSP**		**Disperse** **Five ANSPs**	
	Basis date:	24JUN14	Basis date:	30JAN14
	ANSP(s):	LF	ANSP(s):	LF, LZ, LO, LP, LH
	Regulations:	124	Regulations:	137
Potential re-routing	✓		✓	

For each ATFM regulation, there is a given probability of having an ATFM delay assigned, but for industrial actions re-routings and cancellations represent an important factor to be modelled. The possible re-routing routes are computed as explained in Section 3.3.1.3. To model the probability of an airline cancelling its flights, or re-routing due to industrial action, a number of days affected by industrial action were analysed.

Operational cancellations in 2014 remained stable at 1.5%, with peaks of around 8% on days with industrial action – as shown in Figure 4, these days correspond to airline strikes (EUROCONTROL, 2015b).

Figure 5 presents the average percentage of cancellations for each month in 2014. The peaks observed in April (1.9%) and October (1.8%) are due to strikes at different airlines. In December, there were multiple ATC industrial actions combined with a technical problem at Heathrow, which increased the cancellation rate to 2.4% (*ibid.*).

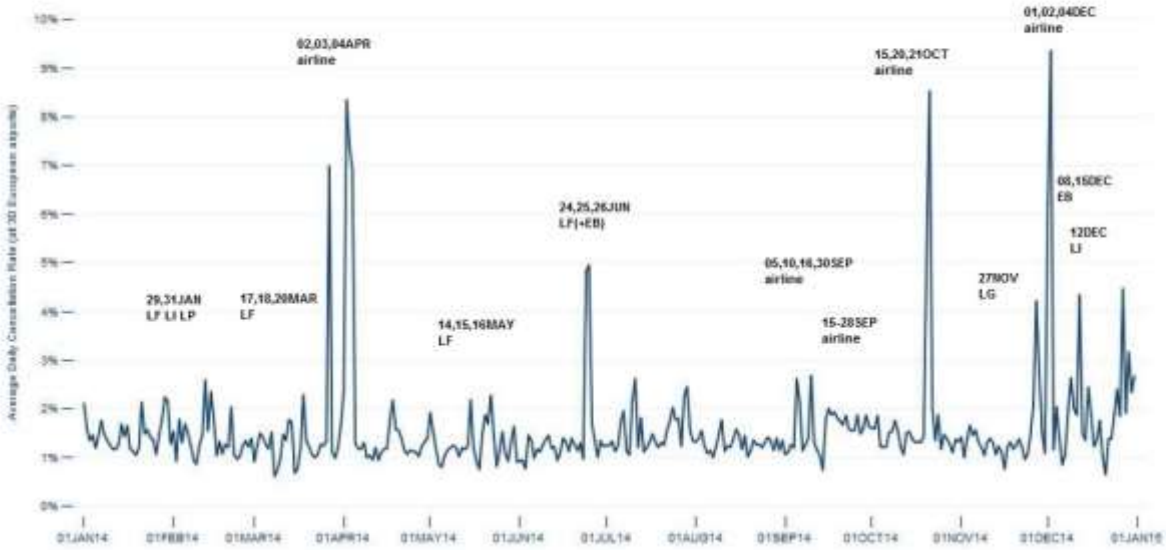


Figure 4. Average daily cancellations 2014

Source: CODA Digest (EUROCONTROL, 2015b).

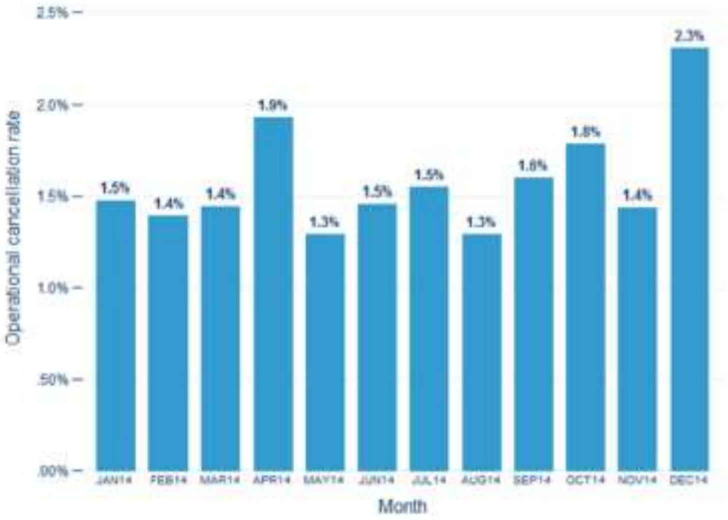


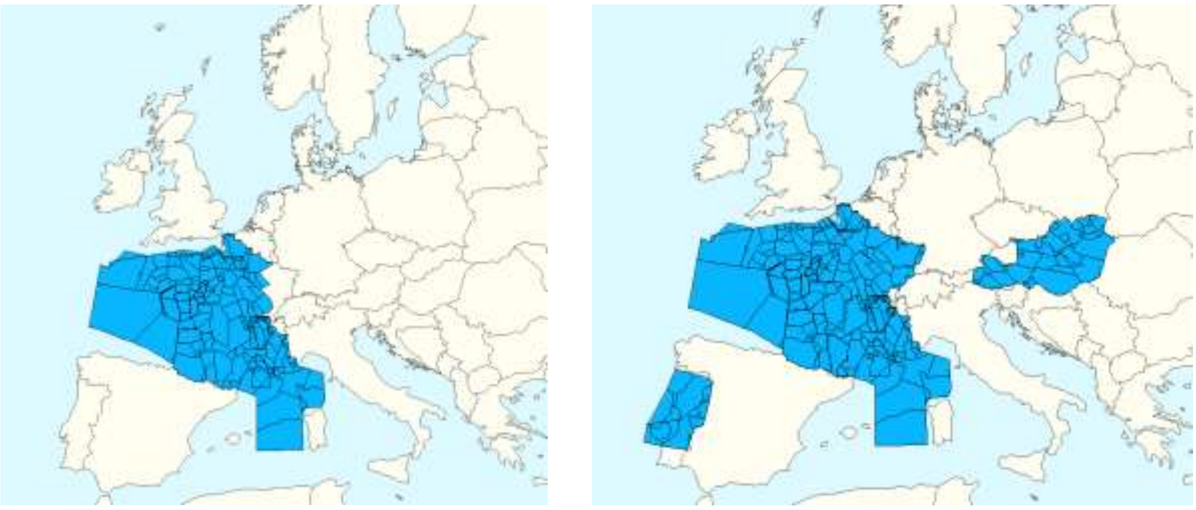
Figure 5. Monthly share of operational cancellations 2014

Source: CODA Digest (EUROCONTROL, 2015b).

Figure 4 shows the cancellation rate experienced on a daily basis, industrial actions are marked at some peaks. In May 2014, French ATC industrial action generated peaks at 2% of cancellations and the industrial actions of 24-26 June increased the cancellation rate up to 5% (EUROCONTROL, 2015b). Traffic data on days where industrial actions were implemented (30JAN14, 15MAY14, 24JUN14, 19MAY16, 26MAY16) have been analysed in detail. A comparison between the total number of flights that operated in the ECAC area with respect to the preceding and following weeks, shows that there is a reduction in the total ECAC traffic ranging between 0.4% and 3.9%. Mindful of all of these considerations, a rate of between 2% and 5% of cancellations is considered for flights affected by ANSP industrial action (note that there is a minimum, baseline level of 1.5% cancellations on a nominal day, for all the flights operating in the ECAC area).

The number of flights that submit a flight plan crossing the regulated airspace on days when industrial actions were active were compared with the traffic expected in the same area for the surrounding weeks, showing that during the regulation there was a reduction of between 7% and 20% of traffic. The percentage of flights that do not use the airspace is higher than the percentage of cancellations, as there are airlines that decide to re-route around the regulated areas. The post-operational report by the Network Manager of regulations implemented on 19MAY16 and 26MAY16 show that there was a reduction of around 8-10% of traffic in the regulated regions (LF). This is consistent with the previous finding. During one of the regulations, the NMOC managed around 2% of the traffic submitting re-route proposals (EUROCONTROL, 2016d). Considering the reduction of traffic in the areas affected by industrial action, and the level of cancellations, the probability of re-routing is established at between 6% and 8% of the traffic going through such a regulation. This probability can be increased as a function of the extra flight plan distance required to re-route around the regulated region.

For the local scope, the airspace regulations due to industrial action on the 'basis' date 24JUN14 are considered. A total of 124 regulations were implemented in French airspace. For the disperse modelling day, the regulations of 30JAN14 are considered, whereby 137 ATFM regulations due to industrial action were implemented in five ANSPs across Europe.



24JUN14 30JAN14

Figure 6. Industrial action regulations for the basis dates

3.3.2.2 Weather

Table 22. Weather-related disturbances – implementation summary

Feature	Parameters	
Probability of delay assigned if regulation entered	Regulations defined at airports: Regulations defined en-route:	51% 32%
ATFM delay distribution for flights with delay assigned	Burr distribution parameters (ATFM airports): Burr distribution parameters (ATFM en-route):	α = 28.809 c = 1.847 k= 1.793 α = 27.309 c = 1.900 k= 1.847
Delay unrelated to ATFM	Arrival and departure delay modelled at 84 airports grouped into three categories by number of IFR annual movements: Burr distributions:	≤50 000 >50 000 >100 000 one distribution applied per airport category, based on the delay observed for that category
	Local **Mostly airports affected**	**Disperse** **Mostly en-route affected**
Spatial location and extent	Basis date: 18OCT14 *ATFM regulations* Airports affected 1 airport (1 regulation) in LS 4 airports (6 regulations) in ED Airspaces affected 1 regulation in EG	Basis date: 25JUL14 *ATFM regulations* Airports affected 6 airports (9 regulations) in ED, EG, EP, LP and LS Airspaces affected 36 regulations in ED, EDY, EG, EP, LE and LF
Potential re-routing	✗ (All the regulations are at airports. Flights to affected airport cannot avoid these regulations by re-routing.)	✓

For weather-related disturbances there are two types of delay that are considered: ATFM regulations (local and disperse, explicitly modelled – see Table 22) and increased 'background' delay due to weather. ATFM regulations are considered at airports and in en-route airspace. These regulations are based on the selected sample days shown ('basis date'). The basis dates were selected such that *airports* were predominantly affected for the local disturbances modelled, with mostly *en-route* airspaces affected for the disperse disturbance day. ATFM regulations of the period AIRAC 1313 to AIRAC 1413 have been analysed. As in the case of industrial actions, for en-route regulations, AOs may opt to re-route.

Delay at airports is often mainly driven by meteorological events. Apart from ATFM delay, weather may also impact system performance (e.g. through lower airport capacities) leading to *'background'* delay (i.e. delay that is not translated into ATFM delay *per se*). For this reason, the total delay experienced, for departures and arrivals is modelled.

For the local scope case, Figure 7 shows the number of ANSPs that declared regulations on each day with respect to the number of regulations declared on that day due to weather at airports. The number of ANSPs provides an indication of the spatial distribution of the disturbances (i.e. generally, more ANSPs declaring regulations implies a wider dispersion of the disturbance through Europe on that day). We use the distribution of ATFM regulations to get an approximation of the distribution of weather-related disturbances at airports. After analysing twelve candidate days, it was found that on 18OCT14, there were numerous regulations due to weather at airports in Germany and Switzerland. This thus suggested itself as a good basis date for localised meteorological disturbance that affected the centre of Europe. The other days were either too localised, or too disperse.

For the disperse scope case, the regulations (also AIRAC 1313 to AIRAC 1413) are based on those implemented on 25JUL14, with 45 regulations due to weather (36 in en-route airspace, 9 at airports; across 8 ANSPs). Similarly to the previous figure, Figure 8 shows the day selected is one with a relatively high number of ANSPs affected by weather regulations (the average delay per delayed flight on that day, due to such regulations, was 9 minutes).

Figure 9 shows the locations of the regulations for the local and disperse case basis days. 18OCT14 (left-hand panel) was selected due to the weather at airports in Germany and Switzerland (shown by blue dots), but there was also, as it happens, a regulation in the UK on that day.

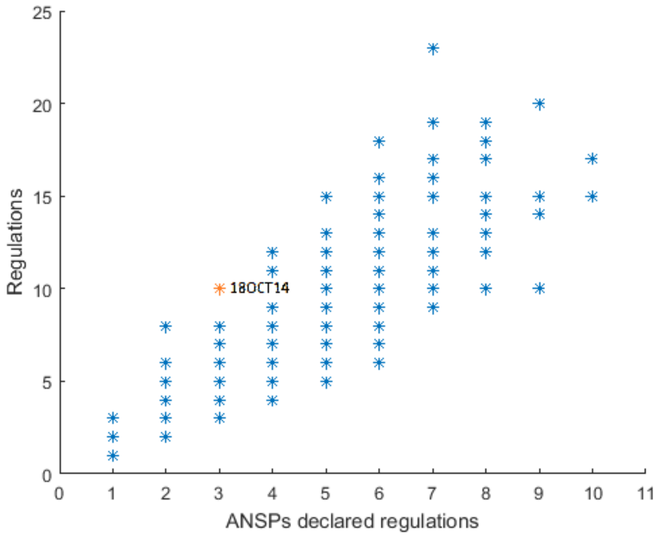


Figure 7. Number of weather regulations and ANSPs – local case selection

Orange marker is local case basis day (18OCT14).

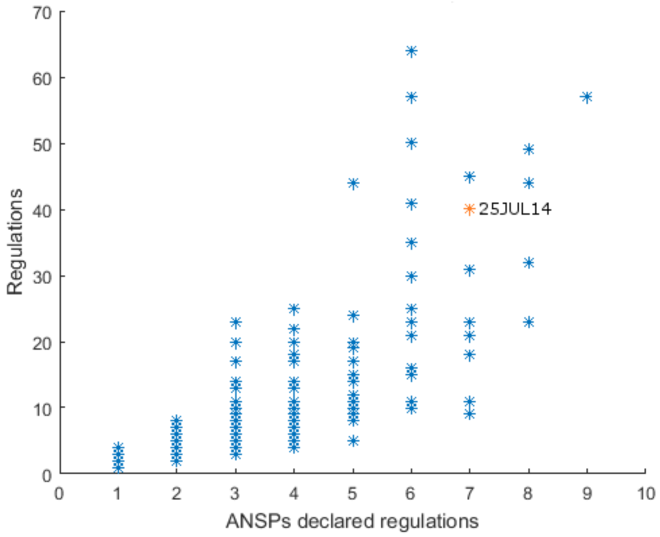


Figure 8. Number of weather regulations and ANSPs – disperse case selection

Orange marker is disperse case basis day (25JUL14).

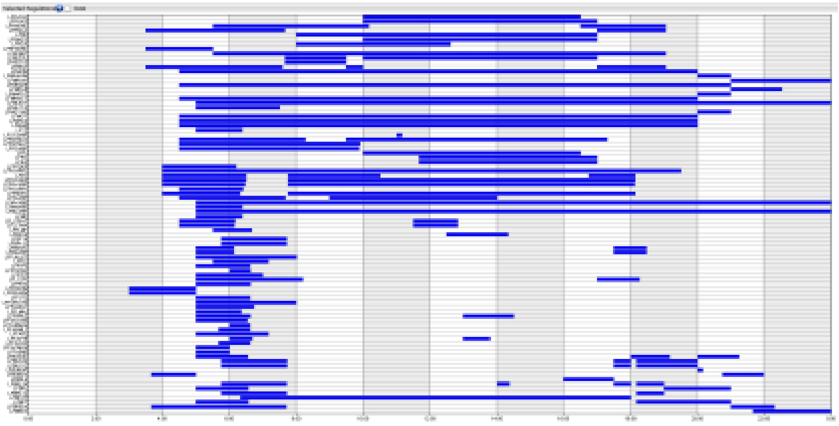
18OCT14 **25JUL14**

Figure 9. Weather-related regulations for the basis dates

3.3.2.3 Capacity shortage due to re-routings (staff shortage)

Due to re-routings, there are regions that might experience more traffic than initially planned. These regions might issue regulations due to capacity shortage that could be averted with more ATC staff.

Regulations location



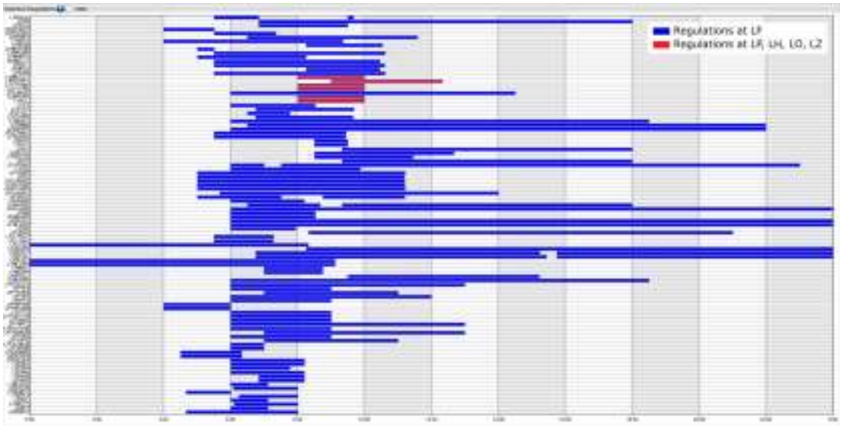
Regulations temporal distribution

ANSPs traffic decreases due to potential re-routing ('000 km)

ANSPs traffic increases due to potential re-routing ('000 km)

Figure 10. Industrial action – local (AIRAC 1406)

Regulations location



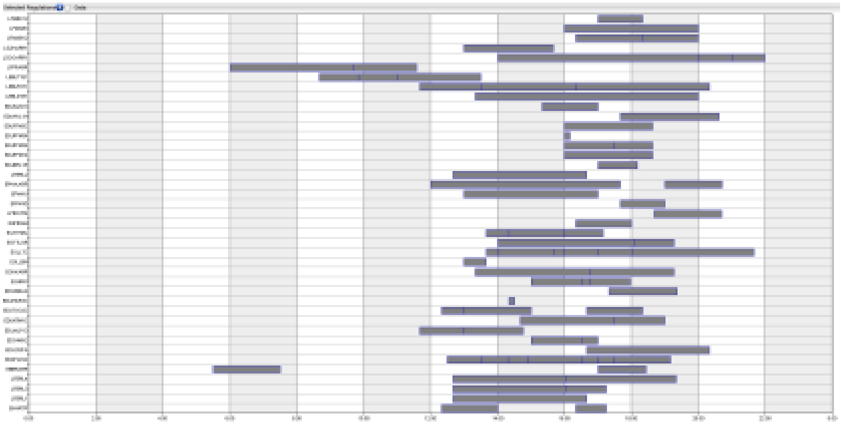
Regulations temporal distribution

ANSPs traffic decreases due to potential re-routing ('000 km)

ANSPs traffic increases due to potential re-routing ('000 km)

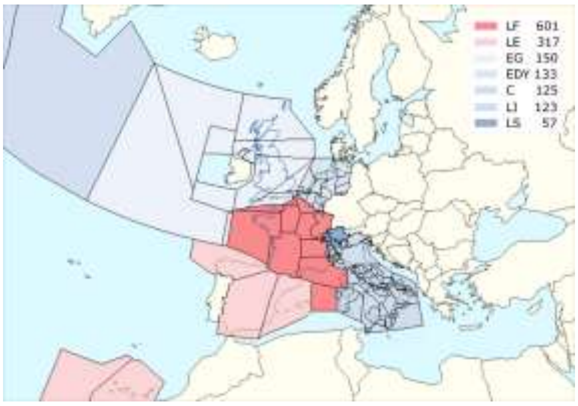
Figure 11. Industrial action – disperse (AIRAC 1401)

Regulations location



Regulations temporal distribution

ANSPs traffic decreases due to potential re-routing ('000 km)



ANSPs traffic increases due to potential re-routing ('000 km)

Figure 12. Weather – disperse (AIRAC 1408)

The preceding figures (Figure 10, Figure 11 and Figure 12) show the locations of the ATFM regulations and their temporal distribution for the days when disturbances are considered. Note that for weather-local there is no re-routing possible as all the regulations are applied at airports. For each flight, the possibility of re-routing to avoid active regulations are computed and, if it is possible to avoid the regulations with this re-routing, the difference in distance flown within each ANSP with and without the re-routed option are estimated. The figures present the ANSPs that account for at least 75% of the changes in distance flown (positive and negatives) if all these flights were to re-route. This analysis gives us an indication of which ANSPs might suffer an increase in demand due to the regulations as flights are re-routing to avoid the airspace congestion. Note that the impact of ANSP industrial action is higher than in the weather scenarios.

With these considerations, Table 23 shows the ANSPs that will increase the ATFM delay due to this extra pressure.

Table 23. ANSPs with reduced capacity due to re-routings avoiding congestion elsewhere

Disturbance	ANSP	Temporal scope
Industrial action, local	EG, LI, LE	0530 - 0900 (period with more active regulations) 1800 - 2000 (period with more active regulations)
Industrial action, disperse	EG, LI, LE	0530 - 1000 (period with more active regulations in French airspace)
	ED	0800 - 1000 (period when active regulations also in LO, LZ and LH)
Weather, disperse	LF	1600 -1800 (period with more active regulations)

The flights that use the airspace of any of the ANSPs shown in Table 23 during the indicated temporal scope might experience ATFM regulations due to the lack of resources and the extra-demand.

Table 24. Capacity shortage due to re-routings disturbance – implementation summary

Feature	Parameters	
Probability of going through a regulation for traffic using the ANSP	2% for industrial action scenarios 6% for weather scenario These probabilities are based on the number of flights that were affected by regulations declared due to ATC capacity or ATC staff shortages with respect to the total number of flights that operated through the different ANSPs that declared such regulations.	
Probability of delay assigned if going through a regulation	42%	
Delay assigned value	Burr distribution parameters:	α = 30.712 c = 1.870 k= 2.916

3.4 Fuel, passenger itinerary and delay cost models

3.4.1 Fuel consumption model

Fuel consumption is estimated by considering BADA performance models. These fuel models are individualised per flight. For each flight, the climb and descent phases are analysed from the FTFM DDR2 data, extracting the time and distance, and estimating the fuel based on nominal BADA performances. For the cruise, the average flight level used for each flight is computed; the average aircraft weight during the cruise is estimated considering the specific range values at the nominal cruise speed (see Figure 13): this average weight will be considered except for flights where the optimal flight level cannot be reached due to short-distance flights. For each flight, the average cruise wind is estimated considering that flights are cruising at their nominal cruise air speed according to BADA. The minimum and maximum cruise speed are computed for each flight and it is ensured that the cruise speed is within the aerodynamic domain of the performances. This cruise model allows us to estimate the fuel consumption under nominal conditions, and also to estimate the cruise time and consumption if the cruising speed is modified (e.g. when using DCI). Figure 14 presents, as an example of the model usage, the cruise fuel estimated for all the flights as a function of their flight plan distance.

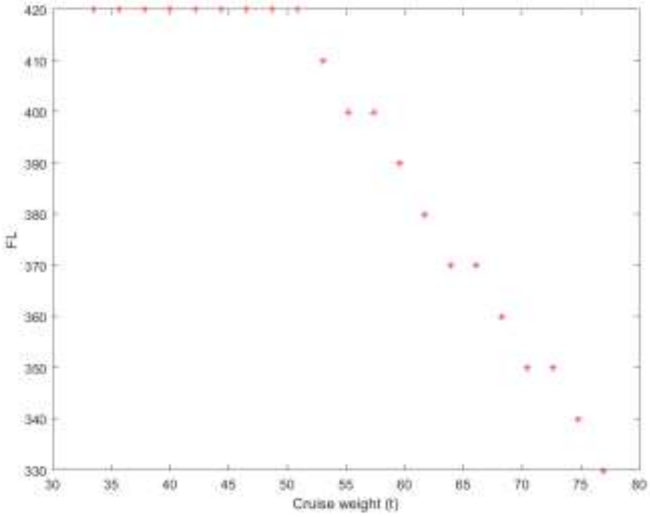


Figure 13. Cruise weight estimation for different FLs (A320)

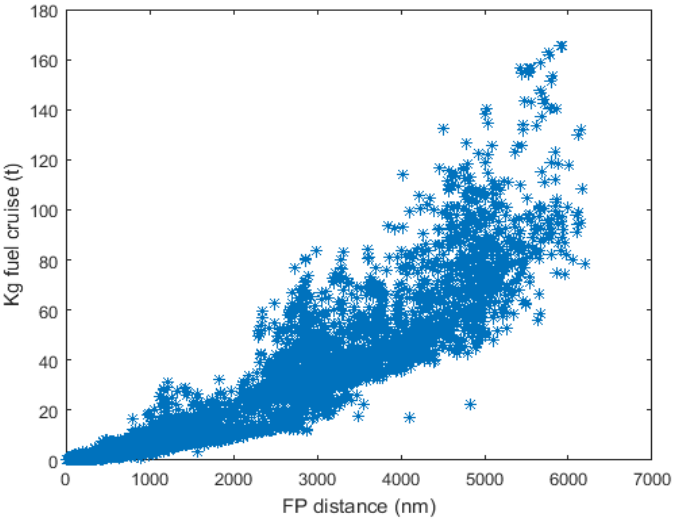


Figure 14. Cruise fuel estimated for flights in model at nominal cruise speed

For each aircraft type, the holding fuel is estimated from BADA as the fuel consumption at FL100 with low reference weight. APU fuel burn allocations are as per Cook and Tanner (2015). The cost of fuel is assigned as 0.8 EUR/kg for the nominal cost scenarios and 0.9 EUR/kg for the high cost scenario used within the DCI mechanism.

3.4.2 Passenger itinerary allocations

The allocation of passengers to flights, with connecting itineraries and fares, is an important part of the model both with regard to the output metrics and mechanisms associated with passenger service delivery.

Flights that submitted flight plans for 12SEP14 to/from 200 ECAC (and 50 non-ECAC) airports, selected based on the highest[7] ACI EUROPE passenger totals in 2014, are considered in ComplexityCosts. Such flights may be disrupted with respect to their published schedules, i.e. delayed, cancelled or diverted. Table 25 shows the treatment of such flights when allocating passengers to them and when modelling them in the system at a tactical level. As shown, flights that were delayed, cancelled or diverted are restored to their original schedule for the passenger allocation process. For the tactical model, for delayed flights, the trajectory of the flight plan is shifted in time restoring them to their original schedule; these flights might then be affected by ATFM delay or disturbances, as explained in Section 3.3. For cancelled and diverted flights, the same cancellation or diversion is maintained in the model (the tactical flight plan either does not exist, or demonstrates the diversion).

Table 25. Treatment of disrupted flights

Disruption to flight	Treatment in allocation of passenger itineraries	Treatment in tactical model
Delayed	Restored to original schedule	Restored to original schedule
Cancelled		Cancelled
Diverted		Diverted

Figure 15 shows the main processes for the generation of the itineraries. This deploys three datasets: individual itineraries for one day in September 2010 (used in the 'POEM' model – Cook *et al*. (2013); aggregated September 2010 International Air Transport Association ('PaxIS') itineraries; and, a sample of anonymised, individual itineraries from September 2014 provided by a global distribution system (GDS) service provider. In order to calibrate the data to September 2014, aggregated passenger data from ACI EUROPE and Eurostat passenger flows were considered alongside published airline load factors. Overall, passenger growth at the selected ECAC airports during the period was between 13% - 16% (according to available Eurostat and ACI EUROPE annual data).

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[7] The 200 selected ECAC airports accounted for 97.6% of passengers at ECAC airports in 2014 (personal communication with ACI EUROPE).

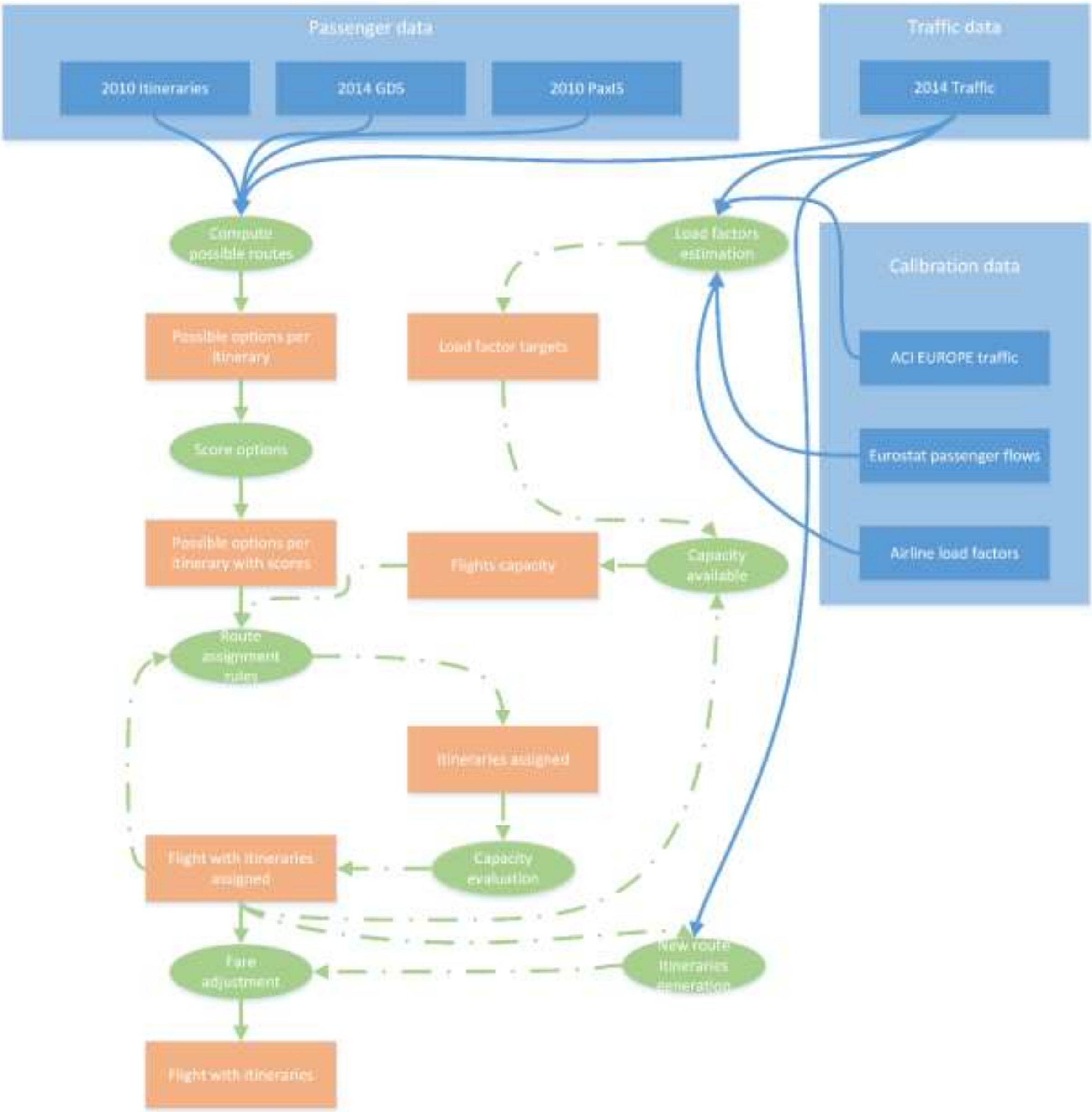

Figure 15. 2014 itineraries generation

For each individual passenger's target itinerary, all possible options were computed considering the available flights on 12SEP14. This computation ensured that passenger itineraries with more than one leg were able to make their connection at the intermediate airport(s), whilst respecting the minimum connecting time (MCT). These options were then preference-scored based on a set of parameters that include the characteristics of the airlines used on multi-leg itineraries (e.g. airlines being members of the same alliance, or partners within an airline group), total itinerary duration and waiting times at connecting airports (where applicable).

Having created a database of viable passenger itineraries for 12SEP14, the next task was to allocate passengers to the individual flights. Previous data cleaning tasks had identified non-commercial passenger flights (i.e. those not requiring passengers), assigned operator name, airline type[8], schedule times and seating capacity. A load factor for each of the four airline types, derived from available SEP14 airline reference values, established an overall passenger target of approximately 3.8 million passengers (see Table 26).

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[8] Four passenger airline types used: full-service, regional, low-cost carrier and charter.

Table 26. 12SEP14 estimated total passengers

Flights in scope	Seating capacity	Load factors	Estimated passengers	Overall load factor
26k	4.5m	Charter: 91% Full-service: 84% Low-cost carrier: 90% Regional: 75%	3.8m	84%

Respecting the available seating capacity on each aircraft, itineraries were assigned iteratively, and probabilistically – to ensure that the final assignment reflected the variability observed in actual operations. After this assignment, there was a capacity evaluation to ensure that all flights were within their targeted load factor: if required, some itineraries were thus (stochastically) removed from flights. After this, process, unallocated, target itineraries were assigned to another flight.

This iterative process ran sequentially for each of the three data sources. At the end of the process, flights still requiring passengers were allocated new itineraries generated based on the characteristics of existing passengers' itineraries. Finally, a fare and passenger type ('premium'/'standard') allocation was made. ('Premium' passengers are highest-yield passengers associated with high-end fares, who were reaccommodated first during disturbances.) In total, there are over 3 million passengers in the modelled day, each with an assigned itinerary.

3.4.3 Delay cost models

In order to be able to assess the scenarios using the cost-centric metrics of Table 4, it is necessary to model the corresponding tactical costs. These are primarily modelled as costs of delay to the airline. The main such costs are comprised of passenger, fuel, maintenance, crew and (strategically) fleet costs. New values have been calculated (Cook and Tanner, 2015) as an update to those published by the University of Westminster for the reference year 2010, extended to fifteen aircraft types, produced partly within the remit of ComplexityCosts, and based on an airline consultation (University of Westminster, 2015) regarding the cost of passenger delay to the AOs. Crew and maintenance costs draw directly on this source. Fuel models were discussed in Section 3.4.1.

The cost of delay to the airline resulting from passenger delay is applied following the principles described in Cook and Tanner (2015) and draws on various sources of evidence, with a particular focus on the impact of Regulation (EC) No 261/2004 (European Commission, 2004), which establishes the rules for compensation and assistance to airline passengers in the event of denied boarding, cancellation or delay. (In addition to these hard costs, the soft costs of passenger delay (associated primarily with market share driven through punctuality) are also applied.)

The rules governing Regulation 261 compensation payment entitlements and airline practice, particularly when taking into account associated reactionary delay effects, are highly complex, and legal advice was taken on this. In summary, the two types of disturbance applied and their associated reactionary delays, do not entitle the passenger to compensation. However, approximately 40% of primary delay, and its associated reactionary delay, does fall within the eligibility of compensation payments. Please see Appendix B for further details.

During disturbance, within airline alliances, flight rebookings for missed connections are calculated using IATA pro-rotation rules. Outside such agreements, following airline consultation and internal calculations, passengers are rebooked at the pro-rated fare plus 75%.

3.5 Model calibration

3.5.1 Delay data

To assess the basic validity of the model's key output metrics, the baseline values (i.e. with baseline mechanisms but without the explicit disturbances) are compared with published values. These are shown to be in good agreement, in Table 27.

Table 27. Delay calibration metrics

Metric	Calibration target	Model baseline
Flight departure delay (mins/flight)	10.7[a]	10.2
Flight arrival delay (mins/flight)	10.0[a]	10.2
Reactionary delay (reactionary/total %)	46.6[a]	42.1
Cost of delay (Euros/flight)	103[b]	104

[a] All European Civil Aviation Conference traffic, September 2014 (EUROCONTROL, 2014).

[b] All European Civil Aviation Conference traffic, full year 2014 (Cook and Tanner, 2015).

(Values to 3 s.f.)

3.5.2 Traffic and passenger assignments

A total of 3 719 364 passengers were allocated to flights on 12SEP14, with no aircraft over capacity and all connections viable. The overall flight-leg proportion targets were based on those used with the POEM project (e.g. 1.25% of passenger movements involving two connections). Although the proportion of allocated connecting passengers on 12SEP14 is slightly lower than the target, overall 16.1% of passenger movements involve at least one connection (see Table 28).

Table 28. 12SEP14 allocated passengers per flight leg compared with targets

Number of flight legs	Passenger itinerary	Passenger proportion targets*	Total allocated passengers	Proportion of passengers per number of flight legs
1	Direct flight	80%	3 120 966	83.9%
2	One connection	18.75%	567 888	15.3%
3	Two connections	1.25%	30 510	0.8%
Totals		100%	3 719 364	100%

* Based on an analysis of SEP10 passenger itineraries (POEM project)

The overall passenger load factor for the baseline traffic day was 83.5%. In the absence of published daily load factors, this compares well with the monthly reference values of two airline associations[9] shown in Table 29. Notwithstanding membership variation, AEA and IATA European load factors in SEP14 ranged between 80.3-83.9%, whilst overall load factors were 80.2-83.6% (IATA, 2015; AEA, 2016).

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[9] SEP14 load factors were not available from other airline associations. Note that since 2016, AEA publishes data covering constant membership, rather than current membership.

Table 29. Airline association load factors (SEP14)

Coverage	Load factor range	Association	12SEP14 overall load factor
Europe	80.3%	AEA Europe total	83.5%
	83.9%	IATA total market - Europe	
Total	80.2%	IATA total market - industry	
	83.6%	AEA total scheduled	

Other calibration checks use ACI EUROPE statistics proportionally reduced to one day using number of flights (12SEP14 approximated as 0.34% of the total passengers in 2014, from DDR2 traffic data). These approximated figures show the total allocated passengers at the busiest ten airports to be slightly higher, but within 6% of official figures, while the top 100 airports were within 11%.

4 Simulation results

4.1 Comparative cost resilience results

Table 30. Strategic costs of mechanisms

Mechanism, by stakeholder uptake	Improved sector capacities	DCI, fuel nominal	DCI, fuel high	A-CDM	Improved passenger reaccommodation
With early adopters	5 000	–		11 300	0
With followers	16 400	–		53 100	–

(Costs in k Euros; 3 s.f.)

Table 31. Tactical costs of mechanisms

Mechanism, by stakeholder uptake	Improved sector capacities*	DCI, fuel nominal	DCI, fuel high	A-CDM	Improved passenger reaccommodation
With early adopters	2 500	–		3 800	–
With followers	20 000	–		17 900	–

* Costs are assigned per disturbance type; values shown in table are averages over disturbance types.

(Costs in Euros; 3 s.f.)

Table 30 shows selected strategic costs of the investment mechanisms. These are the implementation costs of the mechanisms. Note that the 'with followers' costs include the 'early adopters' costs, as these are assessed in the model against the total benefit of the early adopters and followers. Costs indicated '–' cannot be shown due to commercial sensitivity[10]. Those for DCI are comparable with the improved sector capacities and A-CDM values. The improved passenger reaccommodation value for the followers is lower than other values in the same row; the corresponding early adopter value is zero.

Those tactical costs shown in Table 31 are the 'running' costs of the mechanisms for the (single) simulation day. Apart from DCI, the tactical costs for these mechanisms are calculated in advance. In practice, (relatively small) adjustments could be made tactically based on more flexible ATCO payments, to A-CDM costs and passengers' boarded (for the reaccommodation tool costs), but the pre-simulation estimates are believed to be robust. In contrast, the DCI tactical costs are derived directly from the savings made by the airlines, and are thus calculated dynamically. Although, again, costs indicated '–' cannot be shown due to commercial sensitivity[10], the DCI values (in each row) are similar to the improved sector capacity and A-CDM costs, being somewhat lower for the followers (but of the same order of magnitude). The passenger reaccommodation tool running costs are the highest in each row, but remain comparable with the others.

Of note, is that the DCI costs *fall* (averaged over all scenarios) by around 10% between the nominal and high cost fuel cases. This is because fuel burn falls by the same amount, as the number of occasions when it becomes cost effective to speed up to recover delay decreases with the higher fuel cost. The implications for the R_C values will be discussed later.

Table 32 and Table 33 show the results of the R_C values calculated for the 40 scenarios introduced in Section 2. The values are shown in pairs, i.e. for local and disperse disturbances, for each combination of stakeholder uptake and mechanism.

Firstly, we note that the local and disperse values are comparable in each case, demonstrating that the formulation of R_C (2) is effectively capturing the comparative effects of the mechanisms relative to the respective baselines.

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[10] Please see 'NB' in Section 3.1.

Table 32. Cost resilience under industrial action disturbance

Mechanism, by stakeholder uptake & disturbance level	Improved sector capacities	DCI, fuel nominal	DCI, fuel high	A-CDM	Improved passenger reaccommodation
With early adopters					
Local	0.038	0.020	0.019	0.008	0.024
Disperse	0.049	0.017	0.016	0.004	0.021
With followers					
Local	0.237	0.056	0.064	0.007	0.008
Disperse	0.271	0.058	0.067	0.004	0.009

(All values relate to n = 26 860 flights.)

Table 33. Cost resilience under weather disturbance

Mechanism, by stakeholder uptake & disturbance level	Improved sector capacities	DCI, fuel nominal	DCI, fuel high	A-CDM	Improved passenger reaccommodation
With early adopters					
Local	0.027	0.008	0.016	0.002	0.000
Disperse	0.020	0.002	0.010	0.012	0.004
With followers					
Local	0.210	0.053	0.064	0.002	-0.000[a]
Disperse	0.211	0.044	0.057	-0.000[a]	0.005

[a] Adjusted from small negative values statistically equivalent to zero.

(All values relate to n = 26 860 flights.)

Comparing the early adopter values (upper two rows in Table 32 and Table 33) with the corresponding followers (lower two rows in the same tables), it is apparent that the improved sector capacity and DCI mechanisms offer notably increased cost resilience as the scope of the mechanism (stakeholder uptake) is increased. This is not apparent for the A-CDM or improved passenger reaccommodation mechanisms. The rationale for this is likely to be attributable to the relative colocation of the disturbances and mechanisms. The improved sector capacity provisions are typically close to the disturbances, and the DCI mechanism is fairly widespread through the network. Initial analyses suggest that the positive effects of A-CDM are less well colocated with the disturbances in terms of having a notable amelioratory impact. This is less likely to be the reason for the lower values for the passenger reaccommodation tool, since its spatial implementation mimics that of DCI, as explained earlier: we will thus return to these lower values.

By the time the follower stakeholder uptake is incorporated into the model, it is notable that the R_C values for each mechanism are very similar when comparing the industrial action and weather disturbances. This levelling effect is as expected, as the location of the early adopters becomes less of a factor relative to the disturbances (and the delay subsequently propagated more widely through the network as reactionary delay) as the mechanism uptake becomes more widespread.

Also of note is that the R_C values appear overall to be relatively low in magnitude. Further research would be required to investigate these values under different conditions and modelling assumptions, although none of the values is close to the upper limit of unity (perfect cost resilience). It should be borne in mind, however, that the values are summated over a wide network area and many flights, yet they still seem to behave logically and sensitively. Of particular interest in further work, would be to examine more *localised* cost resilience values, for example with widespread disruption in one airspace region (or state), and applying specifically to more highly impacted flights, or flights passing through that region. It would then be expected that the cost resilience values would all increase markedly.

In a similar vein, the higher value of cost resilience observed for the improved sector capacities mechanism can be attributed, in large part, to the fact that this mechanism is only active when a direct benefit is expected, i.e. an ATFM regulation is averted. ATFM regulations due to staff shortage are averted when the mechanism is active, thus furnishing a significant saving on primary delay at a relatively low tactical cost[11].

Before concluding this summary of the R_C results, it is worth being reminded of the fact that the DCI and passenger reaccommodation mechanisms are, to a certain extent, self-determining with respect to their cost resilience, since both mechanisms are charged to the airspace user relative to their efficacy and usage, respectively. The low passenger reaccommodation R_C values are discussed in the next section.

Addressing the DCI values, as observed in the previous section, these costs *fall* by around 10% between the nominal and high cost fuel cases. However, the R_C values are fairly stable across these cases, i.e. within given rows. This is because the mechanism is here actively trading off the cost-benefit of speeding up to recover delay, and there is a consistent fall (of around 5%) in the cost of delay between the nominal and high cost fuel cases.

4.2 Resilience in the context of disaggregated metrics

In this section we explore further the high-level cost resilience (R_C) results, through the use of a small *selection* of the dedicated metrics evaluated for each of the scenario and baseline runs. These include flight-centric and passenger-centric metrics, as it is necessary to differentiate between the two, as established in the literature (see Cook *et al*. (2013) for European examples, and a literature review). The cost-centric metrics also draw on Cook and Tanner (2015).

The selection of results presented in Table 34 are referred to by the corresponding row numbers, and standard z tests are applied to assess the statistical significance of differences (in each case, the minimum number of flights included is 26 860)[12]. These values are also aggregated over all scenarios for each mechanism, to furnish a convenient overview of performance. Some key values of note are highlighted by white-on-black shading. In further reporting, such analyses will be disaggregated by disturbance type and stakeholder uptake, building on the corresponding observations of Section 4.1.

Of initial note is that the key metrics of Table 27 are significantly deteriorated, as expected, in Table 34, i.e. under the influence of the explicit disturbances applied. As is commonly observed in trends in European operations (EUROCONTROL, 2015a), flight arrival delay patterns follow departure delays, as there is not commonly any significant delay recovery (or deterioration) en-route. As expected, the larger recoveries in row (b), relative to row (a), are for the DCI mechanisms (although none of these differences are significant *at the network level*, as reported in the table).

Considering the average flight arrival delays (b), the improved sector capacities mechanism performs better than the other four ($p = 0.00$, x4). The two DCI fuel cases are statistically the same ($p = 0.89$), but perform somewhat better than A-CDM[13]. A-CDM, in turn, produces a flight arrival delay significantly lower than the passenger reaccommodation mechanism ($p = 0.03$). The clear performer here, however, is once again the improved sector capacity mechanism, with the other four producing essentially similar results.

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[11] Furthermore, whilst this mechanism reduces the delay for staff shortage regulations (from the background (ATFM) delay) and the ATFM delay added due to re-routing flights, since the weather-local scenario does not have re-routings, all the delay saved by the mechanism is then only due to the reduction of background delay. In the early adopters, EG implements the mechanism, removing regulation EGTTHM12, which has 1 437 minutes of delay, and in the followers, EP is added, removing regulation EPBD12M, with an additional 240 minutes of ATFM delay at a relatively low tactical cost: €2 500 and €10 200, respectively.

[12] The results shown have been obtained from an average of 25 simulation runs per scenario. Further simulations have since been performed, increasing the average to 46 simulations per scenario. All metrics in Table 34 have been z-tested against the higher-volume simulations, with no significant differences observed (minimum p value 0.93, average p value 0.99), thus confirming the robustness of the values cited.

[13] $p = 0.02$ (nominal fuel price), $p = 0.01$(high fuel price).

Table 34. Summary metric results, aggregated by mechanism

	Metric	Improved sector capacities	DCI, fuel nominal	DCI, fuel high	A-CDM	Improved passenger reaccommodation
(a)	Flight dep. delay (mins/flight)	14.9	17.6	17.6	17.9	18.4
(b)	Flight arrival delay (mins/flight)	14.9	17.3	17.2	17.8	18.4
(c)	Pax arrival delay (mins/pax)	25.1	27.9	27.8	28.3	28.4
(d)	Arr. delay of arr.-delayed pax (mins/pax)	53.4	56.8	56.7	56.6	56.3
(e)	Pax / flight delay (ratio: c / b)	1.69	1.61	1.61	1.59	1.55
(f)	Cost of delay (Euros/flight)	287	318	316	328	328
(g)	Reactionary delay (reactionary/total %)	44.2	44.9	44.8	45.7	47.4
(h)	Airborne fuel burn (tonnes/flight)	8.94	8.45	8.45	8.93	8.93
(i)	Airborne CO_2 (tonnes/flight)	28.3	26.7	26.7	28.2	28.2
(j)	At-gate CO_2 (tonnes/flight)	0.215	0.223	0.223	0.223	0.226

(Values to 3 s.f.)

The average passenger arrival delays (c) are in the same order, across the mechanisms, as the flight arrival delays, although the distribution is a little flatter. However, the standard deviation of these means (not shown) are considerably higher than those of the flight delays, consistent with observations that passenger delay distributions are typically much wider than those of flights (Cook *et al*., 2013). As a consequence of this, there is no significant difference ($p > 0.55$, x6) in performance between any pairs of mechanisms for the four mechanisms in the right-hand side of the table. In other words, only improved sector capacities out-performs other mechanisms in this respect ($p < 0.01$, x4). These statistical significance patterns are exactly reflected for the costs of delay (f), such that the improved sector capacities mechanism offers, on average, across all the scenarios and compared with the other mechanisms, an extra total cost saving to the airlines of approximately **€930k** during this busy traffic day.

The values of the arrival delays for arrival-delayed passengers are fairly flat across the mechanisms (row (d)), although that for improved sector capacities (53.4 mins/pax) is just significantly better than that for passenger reaccommodation (56.3 mins/pax; $p = 0.04$).

In row (e), the ratio of the passenger to flight arrival delay is shown. Lower values indicate relative better performance in managing passenger delay. As might be expected, the passenger reaccommodation mechanism shows the best ratio (1.55). Considering the ratio of arrival-delayed passenger over arrival-delayed flight minutes, the ComplexityCosts model produces values in the range 1.7 – 1.9 (not shown). These values are in agreement with similar ratios previously reported (Cook *et al*., 2013) in the European context of 1.3 – 1.9: these tending to be expectedly higher under greater disturbance.

The reactionary delay values (g) offer some insight into other performance characteristics of the passenger reaccommodation mechanism. Here, it is likely that the cost-based local rebooking (early adopters), then extended wait rules for passengers (followers), suffer from negative impacts further ‘downstream’ (on subsequent rotations) during the operational day. Decisions, as modelled, such as to wait for passengers, are locally good, but globally do not offer the expected benefits, for example due to delays being subsequently compounded by further ATFM regulations being applied. This is partly manifested by the highest reactionary delay ratio (47.4%) occurring for this mechanism.

This presents particular further opportunities for exploring these impacts in the network. Higher reactionary ratios for passenger-oriented solutions were also reported in (Cook *et al*., 2013), as an expected consequence of waiting aircraft. It is also to be noted that this is the major reason for the low R_C values reported earlier for this mechanism: these R_C values are robust with respect to the assumed tactical costs and change relatively little if these are revised significantly downwards.

Regarding the average airborne fuel burn (h), it is interesting to note that the cross-scenario average of 8.45 tonnes/flight increases to 8.82 tonnes/flight (not shown) for both DCI fuel cost cases when only the early adopters are included. In other words, it is the extension to the follower cases that brings the average fuel burn down to below those of the other mechanisms, as we might expect from the mechanism with greatest specific focus on 'smart' fuel consumption. The airborne CO_2 (i) is a linear function of the fuel burn (h), as described earlier, and is included in the table to directly show the comparative outputs. For example, based on the 26 860 flights, DCI (under either cost assumption) produces approximately **40 kilotonnes less airborne CO_2** in the network during the busy simulation day relative to improved sector capacities[14] ($p = 0.00$, x2), yet still performs comparably well in (b) and (c), as discussed. At-gate CO_2 is significantly higher for the passenger reaccommodation mechanism than for the other four[15], which echoes the highest reactionary delay effect for this mechanism, as observed above.

4.3 Taking account of the strategic investments

Table 35. Strategic cost recovery periods

Mechanism, by stakeholder uptake	Improved sector capacities	DCI, fuel nominal	DCI, fuel high	A-CDM	Improved passenger reaccommodation
With early adopters	1	6	5	10 (1[a])	≈ 0
With followers	< 1	4	3	(5[a])	2

[a] Based on airline implementation costs – see main text.

(Cost recovery periods to nearest traffic-adjusted, *high-disturbance* month.)

Table 35 shows indicative cost recovery periods for the mechanisms investigated. These basic values are subject to refinement during further model scenarios, in particular investigating biases introduced due to the colocation, or separation, of the disturbances and mechanisms. These highly simplified payback periods, illustrating the future potential of the model, are calculated by simply dividing the implementation costs of Table 30, by the net cost savings of each mechanism, averaged over all the disturbances. These are not calculated in time-discounted Euros and assume that all the days in which the mechanism applies experience the same high levels of explicit disturbance. The cost recovery periods are cited in high-disturbance months. The values are proportionally corrected, however, for the fact that the sample day had relatively higher traffic than a typical day, such that we might expect recovery over lower-volume traffic days to take longer.

With these several caveats in mind, it is apparent that the improved sector capacities mechanism offers rapid payback, as does the passenger reaccommodation mechanism. For the latter, the cost recovery for the early adopters is of course effectively instantaneous, since the software upgrade was assumed in the model to be made on the basis of tactical recovery costs only. With full implementation costs involved for the followers, and running costs based on passengers boarded, the recovery period (in terms of high-disturbance months, it is again stressed) is still quite low.

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[14] Or any other mechanism, since the non-DCI values in row (i) are practically the same.

[15] From left (improved sector capacities) to right: $p = 0.00, 0.01, 0.01, 0.01$.

DCI recovery periods are comparable in order of magnitude, with the slightly lower values for the *higher* fuel cost case reflecting its corresponding somewhat superior cost efficiency, as reflected in the majority of the R_C values. The A-CDM value of 10 months is artificially high for two reasons. Firstly, it is biased by the colocation issue.

Secondly, the implementation costs are borne largely by non-airline stakeholders, whereas the benefit is calculated only as a delay saving to the airlines (note that this is also the case with the improved sector capacities). The A-CDM values shown in parenthesis are for *airline* strategic (implementation) costs (not shown). These produce payback results comparable with the other mechanisms. (The value for the followers based on Table 30 was excessively large and is not shown.)

The cost-benefit analysis reported in EUROCONTROL (2008) for a generic airport implementing A-CDM shows that for all stakeholders there is a positive payback, and that the payback period is between 1 and 2 years for all partners. However, if only the benefit for airlines and all the strategic implementation costs are considered, that payback period is slightly over 2.5 years; if only airline strategic investment and benefits are considered the payback period for the airlines is approximately 5 months. These values are aligned with the 10 months of disrupted operations recovery period shown in Table 35 and with the 1 month value, if only airline investments are considered.

5 Future research

Key areas for future research are identified in Table 36, as summarised under five categories.

Table 36. Future research

1. Model implementation

Area of coverage	The model currently uses 50 external traffic flows to accommodate traffic outside ECAC. Provided such data were available, it would be possible to improve this extra-ECAC representation and, indeed, to apply the model to other regions.
Stakeholder coverage	The model currently measures impacts on airlines, passengers and the environment. This could be extended to other stakeholder impacts.
Auto-calibration and sensitivity analysis	The calibration and sensitivity analysis are currently performed manually, by running the model, making observations and changing parameters accordingly. It would be possible to automate this process by establishing a set of target calibration values and a ranked parameter space.
Visualisation tool for debugging & validation	There is currently the option to generate full log reports for each simulation run. However, these reports are plain text files of hundreds of megabytes. Alternatively, the model could be improved by adding an interactive visualisation front-end that could allow the user to follow a simulation in a more accessible and interactive way.
Parallel event stack	The current model uses a synchronised event stack to simulate all actors, a further improvement would be to manage independent event stacks for each actor. This would be a major overhaul of the model, but if done properly it could allow the platform to incorporate elements from the agent-based modelling paradigm.
Detailed processes	It would be possible to add more details and modules to the existing collection of events and actor processes, e.g. more detailed passenger movements inside the terminal, detailed aircraft surface movements, airspace conflict resolution, etc.

2. Input data and cost assignments

Improved re-routing	More detailed empirical data on re-routings would be required to have a finer model of the re-routing probabilities.
Passenger fare and preference data	Further information regarding fares and types of passenger would help to further enhance the passengers' itineraries generation. Data / analysis of passenger choices regarding itinerary preferences and decision-making for aborted journeys would also be useful.
Itinerary ensembles	It could be possible to generate a stochastic ensemble of itineraries instead of one specific day of itineraries. This ensemble would add variability to the individual passenger's itineraries. This could be achieved through automation of the current passenger assignment algorithms.

3. Disturbances

Flight-level capping	When dealing with ATFM delay due to disturbances, one of the strategies used by airlines is flight-level capping. This could be modelled by increasing the fuel required for crossing such a regulated region, as performance would be deteriorated with respect to operating at nominal flight levels.
Regulation estimation	Currently, all flights entering an airspace that is regulated might have delay assigned. However, usually, some of the traffic flows that enter the regulated traffic volume are excluded from regulations. This means that, in general, we are slightly over-estimating regulated flights.
Industrial action models	More detailed data on industrial actions may well be available from airline partners and CODA. From the airline perspective, it would be particularly interesting to model the rules behind cancellations and airframe / crew reallocations, on which the literature is not very rich.
Weather model	For weather disturbances, it could be possible to add the temporal dynamic of the disturbance by considering the airports' ATMAP (ATM Airport Performance Framework) scores. These scores are computed based on METAR (Meteorological Aerodrome Report) data, by classifying the METAR information into five categories, and could be historically retrieved at 30-minutes intervals. The delay probabilities due to weather would be airport-type and ATMAP-score dependent. With this methodology, the evolution of 'background' delay (i.e., delay that is not translated into ATFM delay *per se*), would be modelled, as delay at airports is often mainly driven by meteorological events. The main challenge is extracting the component of delay due to weather in order to avoid double counting delay.
Passenger disruption	Other disturbances could be modelled in order to assess the performance of the mechanisms. It would be particularly interesting to consider disruptions that generate compensation for passengers under Regulation 261, as this would likely increase the cost resilience of the passenger reaccommodation mechanism.

4. Mechanisms

A-CDM delay	A different distribution of the reduction of delay, rather than a uniform reduction, could be considered for the A-CDM mechanism. More data on the impact of A-CDM on delay would be required.
A-CDM coordination	For major airports, the coupling with an arrival and departure manager, as with true A-CDM, would be interesting to be modelled as the explicit modelling of slots might lead to improvements due to the mechanism.
DCI flight levels	In DCI the possibility of modifying the flight level could also be modelled.
Improved passenger heuristics	The passenger reaccommodation mechanism could consider further information or heuristics to determine the knock-on effect of the application of wait-for-passenger rules. This would enhance the performance of the mechanism.
Extra ATCO demand	For improved sector capacities, a more precise modelling of the delay

due to the extra demand generated due to re-routings could be implemented.

5. Analyses

Localised resilience values

Of particular interest in further work, would be to examine more *localised* cost resilience values, for example with widespread disruption in one airspace region (or state), and applying specifically to more highly impacted flights, or flights passing through that region. It would then be expected that such cost resilience values would increase markedly.

Disaggregated metrics

It would be possible to disaggregate the metrics by disturbance type and stakeholder uptake, thus allowing deeper insight into the performance of the mechanisms.

Further metrics ready

Other metrics could be considered in order to gain insight into the different trade-offs and performances of the mechanisms. In particular, the consideration of further flight-, passenger- and cost-centric metrics would be of value. Of those deployed in the model, only a small selection has been used in Section 4. For example, consideration of the minutes of delay saved by each mechanism, and not just the cost, would be useful.

Payback periods

The payback period analysis could be extended to include more typical operational days.

Emergence and feedback

Feedback loops in the model could potentially generate new emergent macroscopic behaviour, and analysis thereof is a key next step towards the goal of improved cost-benefit analysis in ATM.

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Appendix A

Table 37. Average number of controllers used, maximum and difference per airspace and ANSP

ANSP	USE	MAX	DIFF	ANSP	USE	MAX	DIFF	ANSP	USE	MAX	DIFF
EB	7.5	12.0	4.5	**EV**	6.6	8.0	1.4	**LJ**	4.3	10.0	5.7
ED	6.3	11.8	5.5	**EY**	4.7	6.0	1.3	**LK**	6.7	12.0	5.3
EDY	5.7	12.7	7.0	**GC**	9.8	16.0	6.2	**LM**	2.0	4.0	2.0
EE	2.6	4.0	1.4	**LA**	4.8	8.0	3.2	**LO**	12.0	24.0	12.0
EF	5.6	10.0	4.4	**LB**	3.2	9.0	5.8	**LP**	13.5	20.0	6.5
EG	7.3	10.0	2.7	**LC**	5.5	10.0	4.5	**LQ**	2.0	4.0	2.0
EH	8.8	12.0	3.2	**LD**	7.1	19.0	11.9	**LS**	4.6	9.0	4.4
EI	7.7	12.0	4.3	**LE**	9.9	15.9	6.0	**LT**	8.5	10.5	2.0
EK	9.4	12.0	2.6	**LF**	10.8	20.4	9.6	**LW**	2.7	6.0	3.3
EN	6.2	10.1	3.8	**LG**	6.0	14.0	8.0	**LY**	6.5	17.5	11.0
EP	10.3	18.0	7.7	**LH**	5.5	9.4	3.9	**LZ**	4.6	10.0	5.4
ES	3.6	6.0	2.4	**LI**	7.2	14.3	7.1	**UK**	6.0	8.5	2.6

KEY

USE:	average number of controllers used in airspace, according to airspace configuration opening schemes.
MAX:	maximum number of controllers, on average, available per airspace.
DIFF:	difference in (maximum) number of controllers available (in principle) and number used.

Source: Internal analysis of DDR2 data for AIRAC 1313 to1413.

Appendix B

Importantly, Annex 1 of Regulation (EC) No 261/2004 sets out a non-exhaustive list of circumstances considered as 'extraordinary circumstances' (which are currently being reviewed by the Commission), whereby passenger compensation payments are exempted:

i. natural disasters rendering impossible the safe operation of the flight;

ii. technical problems which are not inherent in the normal operation of the aircraft, such as the identification of a defect during the flight operation concerned and which prevents the normal continuation of the operation; or a hidden manufacturing defect revealed by the manufacturer or a competent authority and which impinges on flight safety;

iii. security risks, acts of sabotage or terrorism rendering impossible the safe operation of the flight;

iv. life-threatening health risks or medical emergencies necessitating the interruption or deviation of the flight concerned;

v. air traffic management restrictions or closure of airspace or an airport;

vi. meteorological conditions incompatible with flight safety; and

vii. labour disputes at the operating air carrier or at essential service providers such as airports and Air Navigation Service Providers.

2. The following circumstances shall not be considered as extraordinary:

i. technical problems inherent in the normal operation of the aircraft, such as a problem identified during the routine maintenance or during the pre-flight check of the aircraft or which arises due to failure to correctly carry out such maintenance or pre-flight check; and

ii. unavailability of flight crew or cabin crew (unless caused by labour disputes).

We note that passenger assistance (e.g. refreshments and hotel accommodation) is due even if the disruption is caused by extraordinary circumstances, since these only exempt operators from paying *compensation* (Rouissi and Correia, 2014; European Commission, 2013).

Airlines may decide to make payments outside the requirements and scope of Regulation 261, for customer retention purposes.

This raises specific questions regarding compensation payments, particularly with respect to reactionary delays, as a consequence of extraordinary circumstances. Responses were very kindly provided by Bott & Co Solicitors (Wilmslow, UK) who specialise in airline compensation claims and Regulation 261:

Q: When may airlines claim that weather is an 'extraordinary circumstance'? How is reactionary delay treated?

A: It is generally accepted by the courts that not all bad weather is extraordinary. The burden is still on the air carrier to prove that the conditions were 'freakish' or 'wholly exceptional' (e.g. snow in the Middle East). It is also generally accepted that *any* bad weather on a previous flight is *not* an extraordinary circumstance. The courts adopt a strict interpretation that the meteorological condition has to actually affect the flight concerned, and reactionary delays (even for the same aircraft) would not be exempted.

Q: Consider, for example, a strike in France. If an aircraft was due to fly LHR-MAD-FRA-LHR, but the first leg was severely delayed (or cancelled) due to the strike, could the airline apportion disruption on the MAD-FRA and FRA-LHR legs to the French strike also, as an indirect effect, thus avoiding paying compensation?

A: This may indeed be used as a defence. The courts take the view that reactionary effects are still extraordinary – the *only* exception to this is where it concerns bad weather.

Although the weather modelled in ComplexityCosts is neither ‘freakish’ nor ‘wholly exceptional’ (which would thus entitle the passenger to compensation, e.g. due to aircraft unavailability) these disturbance effects are modelled as *consequent ATFM delay* and will thus be assigned as *not* entitling the passenger to compensation. This renders **consistency and comparability across the two disturbance types** (weather-related (ATFM) and industrial action), thus avoiding the situation whereby one type is associated with compensation payments and another is not. The overall assignment is summarised as shown in the table.

Table 38. Summary of compensation payments assigned by delay types

Delay code	Type of delay	Approximate percentage (a)	Compensation paid for primary delay	Compensation paid for reactionary delay
'A'	ANS / ATFM (mostly)	13%	✗	✗
'TW'	Turnaround and (non-ATFM) weather (b)	40%	✓	✓
'R'	Reactionary	47%	If type 'TW'	If type 'TW'

(a) Estimates based on EUROCONTROL (2014) and EUROCONTROL (2015a). (Strikes are subsumed across these categories (data not explicitly shown in reports), probably mostly as 'A'.)

(b) Mostly aircraft turnaround; this will include *some* exempted (exceptional) weather, but this is likely to be a rather low proportion and thus neglected, and even this sub-category still triggers reactionary compensation in any case.

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