





















boarded, the recovery period (in terms of high-disturbance months, it is again stressed) is still quite low.

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 V was excessively large and is not shown.)

## V. CONCLUSIONS AND FUTURE RESEARCH

Using traffic and passenger itinerary data for the whole European network, the cost resilience of four mechanisms, with phased stakeholder uptake, has been assessed under local and disperse disturbance. In the only model of its kind, as far as the authors are aware, a novel cost resilience metric has demonstrated logical properties and captured cost impacts sensitively. We have compared and contrasted the cost benefits of the four diverse mechanisms. Of these, only A-CDM has been assessed within the SESAR context, yet each of the other three demonstrates particular strengths. It would be instructive to explore these further.

Several features of the model may be improved upon, particularly the downstream behaviour of the passenger reaccommodation mechanism, and colocation effects. In addition, higher specification of the disturbances and the construction of a wider sample of traffic and passenger itinerary inputs would be useful. Enhanced airline behaviours (e.g. tactical responses to industrial action and strategic responses to changes in Regulation 261) could also be included. As mentioned, of particular value would be to explore more localised cost resilience values, and to examine the results to date in more detail using further flight-, passenger- and cost-centric metrics: of those deployed in the model, only a small selection has been used here. There is also an opportunity, probably a necessity, to use advanced data visualisation tools to more comprehensively map the large data outputs from each scenario. Initially promising work on payback periods has begun, with opportunities to broaden the included stakeholder costs and to assess cost recovery periods over more typical operational days. Despite uncertainty being one of the main factors generating reduced performance, behaviours are often driven by complex interactions and feedback loops that render it difficult to assess second-order impacts at a network level. Feedback loops in the model could thus potentially generate new emergent macroscopic behaviour, and analysis thereof is a key next step towards the goal of improved cost-benefit analysis in ATM.

## ACKNOWLEDGMENT

The Deutsches Zentrum für Luft- und Raumfahrt (DLR) is project partner with the University of Westminster and Innaxis. We are very grateful to the following institutions/individuals identified, for their invaluable support in the production of this work: ACI EUROPE (Brussels), passenger throughput data at European airports; Adeline de Montlaur (UPC, Barcelona), passenger assignment models (as Visiting Researcher at the University of Westminster); airlines (numerous, anonymous), passenger delay costs, reaccommodation policies and 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.

## REFERENCES

- [1] A. Cook, L. Delgado, G. Tanner and S. Cristóbal, "Measuring the cost of resilience", *Journal of Air Transport Management*, 56, 38–47, 2016.
- [2] EUROCONTROL, 2008. Airport CDM Cost Benefit Analysis. Ed. 1.4.
- [3] EUROCONTROL, 2016. A-CDM Impact Assessment, Final Report.
- [4] SESAR, Proposal on the content of a pilot common project, Ed. 1, 2013.
- [5] H.A.P. Blom and S. Bouarfa, "Resilience", Chapter 5 in: *Complexity science in air traffic management*, A. Cook and D. Rivas (Eds.), Routledge, England, 2016.
- [6] A. Cook, G. Tanner, S. Cristóbal and M. Zanin, "New perspectives for air transport performance", D. Schaefer (Ed.), *Proceedings of the third SESAR Innovation Days*, Stockholm, 2013.
- [7] M. Omer, A. Mostashari and R. Nilchiani, "Assessing resilience in a regional road-based transportation network", *International Journal of Industrial and Systems Engineering*, 13(4), 389–408, 2013.
- [8] D. Henry and J.E. Ramirez-Marquez, "Generic metrics and quantitative approaches for system resilience as a function of time", *Reliability Engineering & System Safety*, 99, 114–122, 2012.
- [9] O. Gluchshenko and P. Förster, "Performance based approach to investigate resilience and robustness of an ATM System", Tenth USA/Europe Air Traffic Management Research and Development Seminar, Chicago, 2013.
- [10] R.M. Hoffman, "A generalised concept of resilience", *Textile Research Journal*, 18(3), 141–148, 1948.
- [11] E. Hollnagel, D.D. Woods and N. Leveson, *Resilience engineering: concepts and precepts*, Ashgate Publishing, England, 2006.
- [12] EUROCONTROL, A white paper on resilience engineering for ATM, 2009.
- [13] R. Francis and B. Bekara, "A metric and frameworks for resilience analysis of engineered and infrastructure systems", *Reliability Engineering and System Safety*, 121 (2014), 90–103, 2013.
- [14] M. Turnquist and E. Vugrin, "Design for resilience in infrastructure distribution networks", *Environmentalist*, 33(1), 104–120, 2013.
- [15] P. Bocchini and D.M. Frangopol, "Restoration of bridge networks after an earthquake: Multicriteria intervention optimization", *Earthquake Spectra*, 28(2), 427–455, 2012.
- [16] L. Delgado, A. Cook, S. Cristóbal and H. Plets, 2015. Controller time and delay costs - a trade-off analysis. Schaefer, D. (Ed.) *Proceedings of the fifth SESAR Innovation Days*, Bologna.
- [17] A. Cook and G. Tanner, 2015. European airline delay cost reference values, updated and extended values, Version 4.1.
- [18] European ATM Master Plan, Edition 2015. SESAR JU, Brussels; 2015.
- [19] C.S. Holling, "Resilience and stability of ecological systems", *Annual Review of Ecology and Systematics*, 4, 1–23, 1973.
- [20] EUROCONTROL, ATM Cost-Effectiveness (ACE) 2014 benchmarking report with 2015-2019 outlook, May 2016.
- [21] EUROCONTROL, CODA Digest, all-causes delay and cancellations to air transport in Europe – Quarter 3, 2014.
- [22] EUROCONTROL, Performance Review Report - An Assessment of Air Traffic Management in Europe during the Calendar Year 2014 - PRR 2014, 2015.
- [23] European Commission, Regulation (EC) No 261/2004 of the European Parliament and of the Council of 11 February 2004 establishing common rules on compensation and assistance to passengers in the event of denied boarding and of cancellation or long delay of flights, and repealing Regulation (EEC) No 295/91, 17 February 2004, 1-7, 2004.
- [24] Association of European Airlines. Monthly Traffic Update, accessed August 2016.