Final Project Results Report

Deliverable 1.2

Domino

Grant:	783206
Call:	H2020-SESAR-2016-2
Topic:	SESAR-ER3-06-2016 ATM Operations, Architecture, Performance and Validation
Consortium coordinator:	University of Westminster
Edition date:	28 February 2020
Edition:	01.01.00

Founding Members
EUROPEAN UNION
EUROCONTROL
SESAR
JOINT UNDERTAKING

Authoring & Approval

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Document History

Edition	Date	Status	Author	Justification
01.00.00	20 December 2019	Release	Domino Consortium	New document for review by the SJU
01.01.00	28 February 2020	Updated	Domino Consortium	Updated document considering feedback from SJU review

Domino

NOVEL TOOLS TO EVALUATE ATM SYSTEMS COUPLING UNDER FUTURE DEPLOYMENT SCENARIOS

This document is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 783206 under European Union's Horizon 2020 research and innovation programme.

Abstract

This deliverable summarises the Domino project in terms of objectives, work performed, results obtained, and links with the SESAR programme. It recalls the initial objectives of the project, the study of a methodology to capture architectural changes and their systemic effects. The project defined new metrics able to measure these effects, developed a platform (Mercury) able to simulate changes of architecture and complex network effects, and devised a methodology to systemically study architectural changes, applying it to three examples of mechanisms. This deliverable reports the main findings of the project and shows examples of results obtained with the model. This deliverable explains the links of the project with the rest of the SESAR programme, its maturity and proposes some lines of research for the future.

Notes

Whilst the official status of this deliverable according to Grant Agreement No 783206 is 'Confidential', the consortium has agreed to release it as 'Public'.

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1 Executive Summary

Domino adopts the premise that components of the air transportation system can be tightly interdependent. Hence, any change in its architecture, such as those produced through the implementation and deployment of various SESAR components, is likely to alter how other parts of the system, initially not affected by the change, react. Higher degrees of coordination and information sharing, as well as higher levels of traffic, may further 'tighten' the network, i.e. increase dependencies (such as delay propagation), and the likelihood of systemic disruptions.

In order to study this effect, Domino proposed:

- the definition and review of new metrics able to capture these network effects;
- to build a platform which would serve as a test bed for new mechanisms (procedures, technology or regulatory changes);
- to provide a methodology to study any change of architecture with a better understanding of the effect of changes for flights and passengers.

Domino reviewed relevant existing metrics, both classical (e.g. delays and costs for flights and passengers) and advanced/network metrics. Of importance are two concepts: network centrality and Granger causality. Both have been used in the ATM domain in the past, but Domino has extended them. These metrics have been evaluated in different scenarios and using historical datasets.

The concept of centrality, directly considered from network theory, was used to assess the importance of a node (e.g. an airport) in a network (such as the ATM network composed of airports and flights and passengers linking them). Centrality considers the number paths coming from, or going to, a given node to estimate its importance. Domino extended this concept by incorporating the temporal aspect of a path considering flight schedules, i.e., paths are only available at some temporal instances. These centrality metrics have been further extended by incorporating passenger itineraries in order to compute feasible paths in the network, modifying existing centrality algorithms and metrics to tailor them to the air transportation system. The consideration of flights or passenger itineraries leads to the definition of '**trip centrality**', which measures the potential connectivity of an airport, and '**passenger centrality**', which considers planned passenger itineraries and thus measures the actual connectivity of an airport.

Granger causality based on time series (for instance, hourly averages of delay at different airports) can be used to infer if the state of a node (e.g., congested) can influence the future of the state of another node. In this manner one can establish propagation of delay and cost in the network. In Domino, a new causality metric, '**causality in tail**', has also been suggested. This causality metric captures the propagation of extreme events (e.g., airport congestion in terms of delay or cost) instead of typical ones (average delays).

Domino has re-implemented and augmented an existing tactical mobility model, called 'Mercury', developed over 10 years in various projects. The simulator is a stochastic algorithm able to model a single day of operation down to the passenger level. Mercury focuses on the gate-to-gate component of passengers' itineraries, providing both advanced and classical passenger and flight metrics. Mercury draws on a very extensive dataset merged from various data sources including passenger itineraries, flight schedules, aircraft performance data and the estimation of costs (e.g. fuel, route charges, delays). This model has been re-written in Domino in order to include new important features, namely, it is now fully based on an agent-based modelling (ABM) paradigm. In this version, for Domino, it is particularly easy to implement and evaluate new architecture changes or behaviours.

The simulator has been calibrated on real data and validated through stakeholder consultations. ABM-Mercury, to our knowledge, is the only full European Civil Aviation Conference (ECAC)-wide model able to simulate key stakeholders, such as, passengers, airlines and the network manager, in an integrated simulator. With respect to previous versions, it allows us to inject complex behavioural rules for different agents, in particular airlines.

Domino has shown that this model can be used to inspect, with a high level of detail, different aspects of the system. In particular, it is able to shed light on the inner functioning of different mechanisms (such as flight swapping or dynamic cost indexing), understanding under which conditions they would, or would not, provide benefits for the different stakeholders.

Domino's model sheds light on the role of exogenous and endogenous noise, the behaviours of agents and the initial conditions (passengers, schedules, etc.) on the efficiency of different mechanisms.

Three example mechanisms have been selected to test this methodology: 4D trajectory adjustment (4DTA), a combination of dynamic cost indexing with wait-for-passenger rules; flight arrival coordination (FAC), based on extended arrival managers (E-AMAN) with different scopes and prioritisations; and flight prioritisation (FP) based on the User-Driven Prioritisation Process (UDPP) to allow air traffic flow management (AFTM) slots issued at regulations at arrival airports to be swapped.

Domino has established a methodology to study architecturally induced, systemic effects by running different scenarios. These scenarios include different implementations of the three mechanisms (4DTA, FAC, and FP), and different delay levels. The results showed the relevance of trade-offs between KPIs.

Of the three mechanisms investigated, the 4D trajectory adjustments mechanism seems to have the greatest impact. Its application shows that it has some impact on delays, costs, centrality, and causality metrics and it is efficient at reducing costs for the airlines, mostly through the protection of critical flights and overall arrival delay reduction. However, whilst connecting passengers tend to gain from this mechanism, other passengers have their average arrival delay increased, which highlights an important trade-off that policymakers should consider.

Passenger centrality tends to worsen, which indicates that cost-driven airlines are negatively affecting more (low cost-impacting) itineraries than they improve (high cost-impacting) ones. Overall, the mechanism creates some buffer in the system, as shown by the causality metrics, decreasing the potential delay propagation channels.

The flight prioritisation mechanism has almost no effect at a system level, except for a tendency to decrease delay feedback loops (hence decreasing the probability that a flight is late because previous flights are delayed). This mechanism is, by its nature, limited with regard to which airlines can use it (e.g. having enough flights in an ATFM regulation at an arrival airport with expected costs sufficiently different to benefit from swapping them) and in which circumstances (e.g. at arrival airports which have issued an ATFM regulation). The impact at the network level is thus also rather limited.

The effect of the horizon of the flight arrival coordination mechanism is highly dependent on the exact optimisation algorithm of its queuing process. Overall, the larger the Extended Arrival Manager (E-AMAN) radius, the higher the uncertainty associated with the flights therein. This translates into suboptimal behaviours if the optimiser does not have proper uncertainty computation capabilities. For instance, longer holding times can be assigned to flights that previously had fuel-saving instructions, due to landing sequence-breaking uncertainties.

We consider that Domino has achieved TRL-2 as theory and scientific principles have been applied to a very specific area in order to define this approach to evaluate the ATM system. Looking forward, ABM-Mercury can serve as a test bed for different types of simulations. Different optimisation processes, levels of congestion, levels of compensation and duty of care for passengers are all examples of modifications which can be tested, relying on a realistic representation for the other components of the model. Mercury takes into account behavioural (potentially sub-rational) effects from different agents, realistic, stochastic generation of delays, passenger management, and a highly detailed cost of delay model, driving the most important decisions for airlines.

2 Project overview

2.1 Operational/Technical Context

The European ATM system is evolving and changes in its architecture (e.g., the introduction of new arrival and departure mangers or UDPP) have a potential impact that expands beyond their local applicability. The modifications introduced by SESAR initiatives and wider technological and policy changes might produce that a priori unrelated subsystems impact each other due to the high level of entanglement and coupling in the system. Moreover, the coupling of these subsystems might be distinct from different stakeholders, as propagation effects (such as delay or cost) in the network are not necessarily the same from different stakeholders' perspectives (e.g., how delay is propagated by flights or by passengers). This coupling of the ATM system is expected to increase in the future as more information will be exchanged between the different components of the European ATM leading to a higher coordination, but also to potentially higher network effects which are hard to analyse and understand. A system both resilient (i.e., which reacts optimally to non-nominal situations) and agile (i.e., which is able to update and enhance itself without affecting other parts of the system) thus relies on good predictions of these effects.

At a time of increased traffic, the ATM system can improve its performance by being better tuned for flexibility to exploit the margins laying in operations to the best for stakeholders. For example, understanding the coupling between flights helps understand the margins embedded into the flight schedules designed by the airlines and can lead to better understanding the coupling between stakeholders and processes.

When dealing with architecture design, many approaches start with enterprise architecture tools. The European ATM Architecture (EATMA) meta-model is the most important in Europe and is able to describe in great details the specific interactions coming from the current procedures and the one envisioned by SESAR or the future. EATMA is a precious tool to specify unambiguously the mechanisms of the solutions presented by SESAR. However, this type of model fails, because it is not its role, at forecasting events that could happen when several instances of the entities represented in the model interact. There is a need to go beyond the classic 'study the parts to understand the system', towards a 'study the behaviour of the system to understand the impact of the parts' paradigm.

When different technologies and operational environments are deployed, the possibilities that stakeholders have when managing their operations change. Stakeholders, partially, act to minimise their operating costs and the downstream impact of their decisions. These decisions consider, to a certain degree, the characteristics of the coupling of the network elements, as this coupling is directly linked to the expected propagation effects. Hence, by using these estimations, stakeholders make complex local decisions which will have an impact at a network level. For example, an airline might consider what would be the impact of delaying a given flight for waiting for connecting passengers, or a delayed flight might estimate how much holding is expected at the destination airport and how much buffer is available to decide if it is worth it to try to recover part of the delay to avoid the generation of additional reactionary delay. With this network view of the cost and delay, estimated cost functions for flights based on their perspective of the system will also be generated. This bottom-up approach where the system behaviours is emergent from the interaction of its systems is paramount to capture the network wide effect of modifications in the system.

Domino aims to develop a set of tools, a methodology and a platform to assess this coupling of the ATM systems from a flight and passenger perspective, providing ATM system designers with insight on the impact of applying new mechanisms. Domino defines a set of case studies to test the methodology based on a few mechanisms: Dynamic Cost Indexing (DCI), User-Driven Prioritisation Process (UDPP) and Extended Arrival Manager (E-AMAN). These mechanisms will be modelled with different operational concepts and uptakes and in isolation or in conjunction. These three mechanisms are selected as they apply to different stakeholders (airspace users, ANSPs, airports) and used in different operational context (local at airports, in the whole network of the airlines or when capacity-demand imbalance arise).

In general, the concept of Dynamic Cost Indexing is used to encompass any type of procedure and technology by which the flight is able to adapt its cost index, i.e., its speed and trajectory, to reach some objective based on the available data. In each specific situation, there is a balance between delay recovered and extra fuel required. The use of delay recovery strategies executed in conjunction with wait-for-passenger rules to minimise operating costs and passengers' missed connections at hubs has been studied in the past but at a single hub and without considering its network implications such as in [35, 36] or the CASSIOPEIA project and in its extension DCI-4HD2D (a SESAR WP-E project led by INX with UoW as partner [41]).

E-AMAN tactically sequences the arrival traffic at the airport. By extending the scope of the arrival manager, flights can be considered for their sequencing earlier, improving in this manner how the absorption of delay is achieved [38]. The implementation of E-AMAN requires the interchange of more information on flights and the coordination with different stakeholders, i.e., good early estimation of the arrival time for the flights. Different E-AMAN operational concepts could be envisaged to capture how technological changes with local implementation have an impact at a network level.

The concept of User Driven Prioritisation Process (UDPP) refers to the possibility to consider user priorities during the pre-tactical phase, when ATFM regulations are issued. Instead of 'blindly' assigning delay to flights, the NM, the FMPs or the Airports could instead receive input from the airlines about the importance of the flights for their operations. UDPP allows Airspace Users (AUs) to prioritise their important flights to the detriment of other less important flights of their own fleet involved in a deteriorated situation in order to reduce the impact of the deterioration (most often delays) on their operations along the day and on their costs. Several methods have been proposed to operate with these priorities: AUs can reorder their flights according to a priority number adjustable to the deterioration; AUs can protect flights (on time) at the detriment of other flights that get more delay; AUs can optimise their prioritisation based on margins; other methods have been explored as well, e.g., in the European project UDPP Credits (developed by EUROCONTROL, ALG, UNITS and UoW). Equitable by design, UDPP is an ATM Demand-Capacity Balancing measure applied in collaboration with the other ATM and Airport actors when opportunity and can be seen as a tool to allocate scarce resources in ATM and at Airports [37].

2.2 Project Scope and Objectives

The aims set out in Domino's proposal were to:

1. Identify, test and validate metrics based on **complexity science** to understand the coupling of the elements in the ATM system, creating a **toolbox** to analyse the system and to identify which elements would be, a priori, affected by changes in the system.
2. Provide a **methodology** to gain understanding on the impact in the system of modifying part of its sub-elements.
3. Provide a detailed **agent-based model** capable of capturing the interactions between stakeholders and ATM elements. This model will be generalisable and extendable.
4. By working in close cooperation with stakeholders, generate **behavioural models and cost functions** based on their expectations and on their visions of the characteristics of the system.
5. Define a set of **case studies**, to test the methodology, based on the use of a few mechanisms: Dynamic Cost Indexing (DCI), User-Driven Prioritisation Process (UDPP) and Extended Arrival Manager (E-AMAN).
6. Apply the model, methodology and toolbox to targeted **investigative case studies** that will be modified to generate **adaptive case studies** aiming at mitigating negative network effects.
7. Describe how the methodology and toolbox can be applied on **historical data** to show how this methodology is generalisable to be applied beyond the agent-based model developed in Domino.

Domino focuses on the **high-level feedback** effects between interacting components of the ATM system rather than the details of the interactions. Changes in the ATM architecture, e.g., new arrival and departure managers or the introduction of UDPP, have an impact beyond their local applicability. The European ATM system is evolving, and such changes will accompany SESAR initiatives and wider technological and policy change. These modifications are likely to have an impact on different a priori unrelated subsystems due to the high level of **entanglement and coupling** in the system.

Therefore, the primary objective of Domino is to develop a **set of tools (metrics)**, a **platform (ABM model)** and a **methodology** to assess the coupling of ATM systems from a flight and a passenger perspective.

2.2.1 Metrics

Domino should identify, test and validate metrics based on complexity science to understand the coupling of elements in the ATM systems, creating at toolbox to analyse the system.

2.2.2 Platform

The platform should allow ATM system designers to gain insight on the impact of applying new mechanisms. It should provide a view of the impact of deploying solutions in different manners, e.g., harmonised vs. local/independent deployment, and information on the criticality of elements in the system and how this might be different for different stakeholders. A generalisable and extendable agent-based model, capable of capturing the interactions between stakeholders and ATM elements, should be developed.

Behavioural models should be created to capture the impact of modifying the operational context by introducing new mechanisms.

2.2.3 Methodology

In order to show the capabilities of the model and test the relevance of the metrics, the project defined three mechanisms likely to have some systemic impact on the system: 4D Trajectory Adjustment (4DTA), based on Dynamic Cost Indexing (DCI) and wait-for-passenger rules, Flight Prioritisation (FP), based on the User-Driven Prioritisation Process (UDPP), and Flight Arrival Coordination (FAC), inspired on the Extended Arrival Manager (E-AMAN) principles. These mechanisms are modelled with different operational concepts and uptakes and in isolation or in conjunction.

A key element of Domino is the continuous consultation process through an Advisory Board composed by stakeholders and through interaction with stakeholders with dedicated consultations and targeted workshops.

2.3 Work Performed

The work on Domino has revolved around three tasks:

1. Definition of network metrics
    a. review and evaluation of existing complexity network metrics
    b. definition and evaluation of newly specialised network metrics for centrality and causality considering stakeholders and system particularities
    c. assessing relationship between newly defined network metrics and current operational indicators
2. Development of testing platform
    a. Design and implementation of agent-based model
    b. Definition of behaviour models and complex cost functions
    c. Validation of model with interaction with stakeholders and historical datasets
3. Methodology to evaluate mechanism on platform with network metrics
    a. Definition of case studies with broad approach to evaluate platform and metrics
    b. Targeted case studies to validate platform and evaluate metrics applicability

2.3.1 Classical and advanced/network metrics

Deliverable D5.1 - Metrics and analysis approach [9] compiled a detailed literature review of classical and advanced metrics. One of the important aspects of this work was to highlight the need for cost-driven and passenger-centric metrics. Moreover, this deliverable presented two concepts which can be used to defined to metrics capturing network effects in the entire system: centrality and causality.

'Centrality' comes directly from network theory and is used to assess the importance of a node in a network. One type of centrality takes into account the number of paths coming from, or going to, a given node to estimate its importance. This has been already used in the past in aviation, typically to assess the importance of an airport. In Domino, we developed some new metrics that take into account the temporal aspect of a path on the airport-flight network, i.e., the flight schedule. This allows us to measure the actual loss of connectivity of an airport, in terms of broken itineraries (due to disruptions such as delays or cancellations). Two versions of this metric have been defined in Domino. One is called '**trip centrality**', which measures the potential connectivity of an airport, only based on flight schedules. The second one, called '**passenger centrality**', uses planned passenger itineraries and measures the actual connectivity of an airport.

The second concept used in Domino is called 'Granger causality'. Based on time series (for instance, hourly averages of delay at different airports), one can infer if the state of a node (e.g., congested) can influence the future of the state of another node. This concept has been rarely used in aviation but is very powerful for producing a diagnosis of the network feedback loops which may destabilise the system. In Domino, a new metrics has been used, named '**causality in tail**', which is interested in how rare events (e.g., massive congestions) can propagate through the network, as opposed to 'common states' (e.g., minor delays).

During the project, these metrics have been applied mostly to one kind of network, the common flight-airport network. However, the methods developed during the project can be applied to any network of subsystem having links between them. This opens the way to systematic estimation of the degree of 'tightness' (dependencies regarding, e.g., delay propagation) of the air transportation system at different levels. Moreover, in D5.1 these metrics were applied to historical data, proving how these analyses can be performed beyond the output of the Domino platform [9].

Finally, it is important to assess relationships that new metrics have with already established ones. It particularly important to highlight:

- The redundancies. In this case, the new metric is partially already captured by an existing one, but it helps also to understand the new metrics.
- The differences. In this case, the new metrics capture something that may be new, and may be interesting as a complement to previous ones.

This analysis has been started in the project. The centrality metrics seem to capture something different from standard passenger/connectivity metrics but are related to them. On the other hand, causality brings a completely new concept, but is more difficult to comprehend, as it has little common ground with previous metrics.

2.3.2 Platform (ABM model)

In order to conduct 'experiments', the project developed a platform able to produce some output that can be analysed using the previous metrics. In order to capture intricate network effects, representative agent models are not suited, and Domino used an agent-based paradigm to develop the platform.

The platform is partially a reimplementation of an existing model called Mercury, used and developed over almost ten years by some of the partners in different projects. The pre-existing implementation of Mercury allowed us to simulate a typical day of operation, at a full European scale with an individual passenger tracking. Mercury focuses on the gate-to-gate component of passenger itineraries, providing both advanced and classical passenger and flight metrics. In addition to this airside model, it also deploys a landside mobility model, capturing a number of metrics regarding passenger flows at the door-to-gate/gate-to-door level (with a special focus on travel time and cost metrics). Mercury relies on a very extensive dataset merged from various data sources, among others: information on airport curfew times, European airspaces and airports, estimates of compensation and delay costs under different circumstances, passenger itineraries and flight schedules, and the Base of Aircraft Data (BADA) which provides information on the performance of various aircraft models (thus enabling fuel burn costs to be estimated).

Domino has extended the possibilities of the simulator by using an agent-based model. Agents in the simulation can now take complex actions and communicate with each other with a unified message protocol. Agents have limited access to information outside of their own memory, which impacts their decisions. The definition of the model as an agent-based model following a well-known methodology (Gaia [42]) is reported in D4.1 - Initial model design [7]. This deliverable comprises the specification and design of the model and serves as technical documentation.

The model makes heavy use of various probability distributions to create a stochastic environment. These distributions, as well as other parameters in the simulations, are drawn from various pre-analyses performed on real data, sometimes on an entire year of operations. This means that this new ABM-Mercury model integrated detailed micro-modelling of processes and agents' interactions with more high-level statistical modelling of processes. The model is flexible enough to allow for the inclusion of the level of detail on the processes that are required for future new mechanisms.

Thanks partly do this agent-based paradigm, the code is now more easily modifiable. Agents are more neatly contained, their strategies more easily isolated and thus more easily modified. Defining and including new agents is now easier, as it is mainly a matter of defining communication with other agents and reaction to events.

The simulator has a fine granularity in terms of agents: every flight, every airline, every DMAN, AMAN, every airport has their own agent, which mean that there are around 32.000 in any given simulation. Passengers, even though they are not formally agents (because they don't make decisions during the simulations), are simulated as groups of passengers following the same itinerary, with a further division in terms of fare and ticket type: 'premium' or 'economy'.

This granularity gives access to a huge number of observables in the system. Some of them are observables also in reality, while lots of them are 'hidden' in general, i.e., not recordable or simply not recorded. This access to low-level variables allows modellers to deeply understand the system, in a way that is not always possible in reality. These observables need to be consolidated and analysed, using new and old metrics.

The accuracy and the relevance of models need to be assessed before one can trust their results. Validating an agent-based model is achieved by:

- Performing checks in the internal logic of the model. This is done by checking that the causal links within the model are implemented 1) as the modeller has intended 2) as to be sufficiently close to real processes. The second step is done via validation with experts, which has been done in Domino with experts during workshops.
- Matching the output of the model to expected standard values. This is done by computing similar metrics based on the output of one of several runs of the simulators and based on some external data. In Domino the baseline scenario has been validated using historical DDR data and reported delay reports by CODA.

2.3.3 Methodology to evaluate mechanisms

The model is primarily designed to test the introduction of new procedures, testing their impact on the system as a whole, and on particular subsystems. Domino used three mechanisms as examples, to show how this analysis could be made.

First, the mechanism needs to be defined in terms of:

- relationships (or modifications thereof) between agents and/or;
- the introduction (or modification) of an agent and/or;
- modifications of parameters and/or;
- additional events and/or;
- additional options in the agents' behaviours.

This should be done by mapping closely these to the real modifications of the system. Since Domino's model is quite low-level, it should be easy in general to proceed to the mapping. For instance, in Domino, we used as basis the user-driven prioritisation process (UDPP) to build our Flight Prioritisation (FP) mechanism. We did not use an extensive description of the UDPP for this, but a simplified description of it, keeping only the flight swapping capabilities. Moreover, we used several levels of implementation in order to test different behaviour, here with FP allowing flight swapping between different airlines or not.

Second, the modifications are implemented in the model. The possibility to use the new mechanism or not is thus available. In Domino, we considered three levels of implementation: baseline (level 0), enhanced (level 1) and advanced (level 2).

Third, one must define scenarios, i.e., a set of exogenous parameters for the simulator. This includes choosing a set of schedules for flights and planned itineraries for passengers. In Domino, we focused on a carefully chosen day of operation, the 12th of September 2014, a busy but not disrupted day. The reason for selecting only one day is related to the scarcity of passenger and schedule data, and the time required to prepare new datasets considering the difficulty to merge them with air traffic data.

In addition, other parameters can be finned tuned, for instance the desired level of turnaround delay, the frequency of ATFM regulations, etc. The scale of the simulation can also be chosen, for instance European-wide or focusing on a small number of flights, airports, etc. In Domino, we only considered European-wide simulations, as the main objective was to assess network effects, but the model is able to operate with any given subset of data.

In Domino, we first defined scenarios with system-wide implementation of each level of mechanism. To test how the mechanisms behaved in different environments, we also defined a set of 'stressed' scenarios, where the level of delay is increased with respect to the baseline (mean delay roughly multiplied by 3). Other, more focused scenarios were also defined in the final part of the project. In this case, the idea was to study the mechanisms in more specific environments, for instance defining local disruptions at some airports and study how different mechanisms can mitigate their effects. These case studies were more targeted to show the capabilities of the model to answer these operational questions.

Different realisations of each scenario are then produced, since each run of a stochastic model produces a slightly different output that needs to be analysed statistically. The low-level observables (delay for each flight, cruise distance, fuel etc.) are recorded in a database. The metrics selected previously by the project can then be computed on the output. The possibilities of analyses are very broad, but in Domino we highlighted:

- The necessity to contrast delay indicators and cost indicators, in order to assess the relevance of the first ones with respect to the real objectives of the airlines.
- The necessity to contrast flight-centric metrics and passenger-centric ones, in order to detect trade-offs.
- The necessity to use centrality metrics to capture network-wide effect on the loss of connectivity of airports.
- The necessity to use causality metrics to capture feedback loops and assess the degree of tightness of the system.

2.4 Key Project Results

The key project results are presented grouped by the following categories:

- Results relating to metrics to capture network effects
- Key results from the ABM model
- Key findings from the modelling and analysis of the three selected mechanisms
- How stakeholders and expert feedback has been incorporated in the project

2.4.1 Network metrics

One of the main results of Domino is its successful use and analysis of new metrics. The project showed that the new network metrics could capture important aspects of the air transportation system. With respect to the initial goal of the call, namely the possibility to assess the degree of tightness (or lack thereof, i.e. resilience) of the network, the metrics developed in Domino have proved very relevant.

The centrality metrics have shown to be important to capture the loss of connectivity experienced by passengers. The difference between theoretical connectivity (from schedule) and the actual one (from actual itineraries) shows how the tightness of the network can impair its functioning where uncertainties are present. Airports that are particularly impacted by this loss of connectivity are easy to highlight. The fact that the centrality can be computed in different layers, for instance corresponding to airlines or alliances, opened the possibility to airline-based focused connectivity loss analyses, as well as differential equity analyses.

Causality metrics have proved to be complex but valuable. First, because these metrics are intuitive as concepts, even if their quantitative values are difficult to interpret. Second, because they represent truly network-based metrics, they take implicitly into account cascades of events, buffers, and reactive behaviours from agents to disruptions, which all participate in the propagation (or non-propagation) of disruptions.

Domino has highlighted the behaviours of these metrics in two ways. First, by performing a preliminary analysis, exploring how these new metrics relate to standard ones. This analysis has shown that the metrics had some degree of overlap with other existing metrics, but they capture other aspects of systemic disruptions, thus highlighting their potential future use. Second, Domino explored systematically the variations of the metrics in the numerous scenarios simulated with the model.

2.4.2 Model

2.4.2.1 Model implementation

Domino has achieved the development of a full agent-based model (ABM) of the ATM system considering relevant stakeholders: ABM-Mercury. The simulator developed is a total reimplementation of the previous version of the mobility simulator Mercury. One of the instrumental goals of this reimplementation was to allow a harmonised management of different mechanisms, by supplying an easy interface to the inner logic of the agents. The implementation of three mechanisms at three levels (including baseline, level 0) using the same core code has shown that this implementation is very well suited for the kind of studies carried out in Domino. The code is general enough to be reused in various situations and can be augmented (new agents, events, strategies, etc.) fairly easily.

Some of the main characteristics of the ABM model can be summarised in:

- The specification and design have been done following a well-known methodology (Gaia [42]) which facilitates its documentation, re-usability and future development
- The model comprises a total of eight agent types:
    - Flights,
    - Airline Operating Centre,
    - Ground airport,
    - Network manager,
    - E-AMAN,
    - DMAN,
    - Radar, and
    - Flight swapper

- Approximately 32 000 instances of these agents are executed on each simulation (e.g., one agent per flight)
- The interactions (messages) between these agents are modelled
- Representation of behaviour for the different agents is driven by different estimations of costs functions
- The model can represent a full day of operations in ECAC including flights (with their reactionary delay) and passenger itineraries (with their connections)

The ABM model is executed in an event-driven simulator environment with the following characteristics:

- Developed using standard approaches and libraries (Python Simpy).
- With a total of 10 events:
    - Flight plan submission
    - Generation of non-ATFM delay
    - Push-back ready
    - Wait for passengers
    - Push back
    - Take-off
    - Flight crossing point (the number, location and agents subscribed to these is parameterisable)
    - Landed
    - Flight arrival
- These events have been designed following the needs of the Domino modelling, but the standard development allows for an easy addition/modification of events as future model usage might be required.

Finally, the model has the following technical requirements for its execution:

- Developed in Python version 3.5
- For all traffic in the ECAC region for a full day of operations (around 27k flights) and with all passenger itineraries (around 3.4M passengers) it requires:
    - around 8GB of RAM memory
    - 25 minutes per execution of a baseline scenario in Intel i7-4790 @3.60GHz

Each execution of the model produces individual low-level metrics for the different stakeholders that can be statistically analysed.

2.4.2.2 Model calibration and validation

Large part of the underlying mathematical model has been reused from the previous version of Mercury. As a result, many of the validation processes undertaken for these versions, which were validated with extensive consultations with experts in previous projects, are still valid for this newly re-implemented version. This includes for instance the choice for the main events for a flight or the default behaviours for airlines.

The new parts modelled in Mercury have been thoroughly tested. This includes stakeholder consultations to help to adjust airlines' strategies and to clarify the role or the importance of newly developed concepts (e.g., curfew) (see Section 2.4.4).

The calibration itself is the process by which some parameters in the model are adjusted to ensure reliable quantitative output. In Domino, the calibration has been performed in order to ensure that the baseline scenario produced results which are aligned with key indicators in historical datasets using: historical DDR [32], CODA reports [28,29,30], and calibration activities performed in previous projects [27, 39, 40, 41].

Table 1 presents the model calibration summary for key indicators with respect to historical DDR datasets (most of them are within 1% of their targets); and Table 2 presents the distribution delays with respect to the reasons highlighted by CODA [28].

Table 1: Model calibration summary

Average value of:	Simulations	Historical	Difference (mins)	Error
Departure delay	11.41	11.43	-0.02	-0.15%
Flying delay	-0.05	-0.16	0.11	-70.45%
Taxi delay	-4.78	-4.62	-0.16	3.50%
Arrival delay	6.58	6.65	-0.07	-0.99%
Arrival delay without earlies	11.32	11.57	-0.25	-2.12%
Scheduled G2G time	159.47	159.47	0	0.00%
Actual G2G time	154.65	154.69	-0.04	-0.02%
Scheduled flying time	136.37	137.28	-0.91	-0.66%
Actual flying time	136.33	137.12	-0.78	-0.57%
Scheduled flying distance	965.37	960.57	4.8	0.50%
Actual flying distance	954.33	948.51	5.82	0.61%
Actual taxi-out time	12.14	12.52	-0.38	-3.02%
Actual taxi-in time	5.6	5.73	-0.13	-2.26%

Not only average values but full distributions have been considered during this calibration process such as the gate-to-gate times reported in Figure 1, or departure and arrival delay in Figure 2.

Table 2. Distribution of delays among the main reasons of delay

Type of delay	Proportion in simulations	Proportion in CODA 2017	Minutes needed in simulation to match proportions
Reactionary	27.85%	44.50%	1.94
Turnaround	58.55%	35.80%	-2.52
En-route	7.60%	7.50%	0.00
Capacity	3.67%	7.20%	0.41
Weather	2.32%	1.90%	-0.04

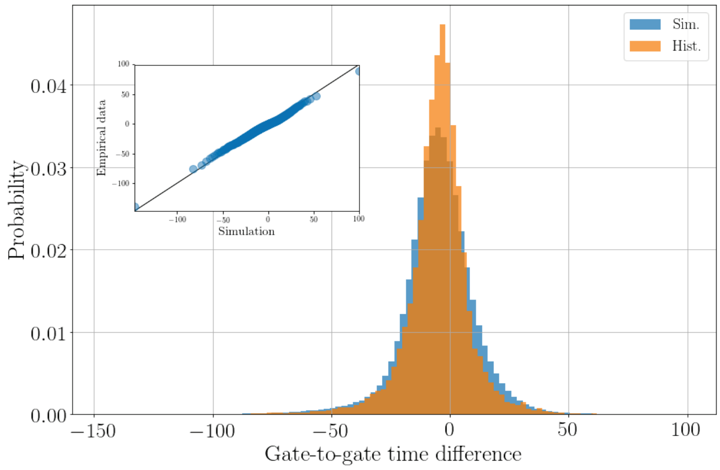
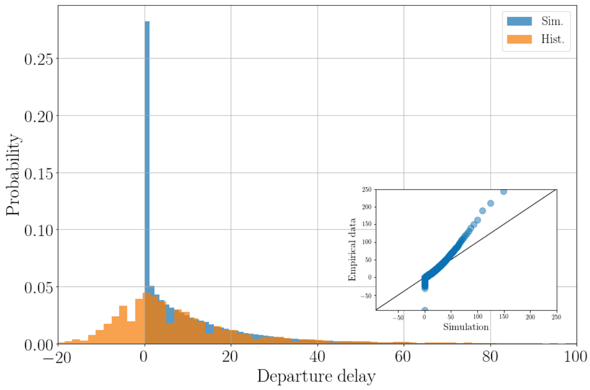


Figure 1: Probability distributions of gate-to-gate differences in simulations and historical data.



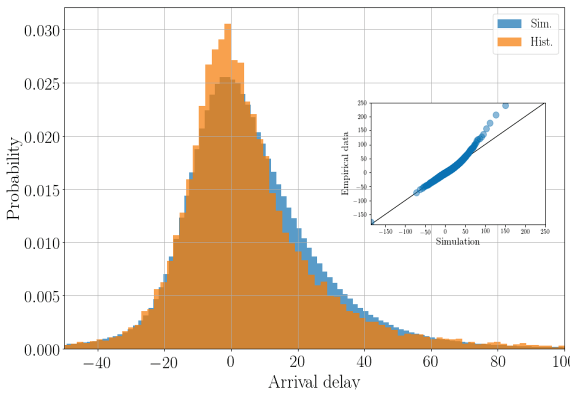


Figure 2: Probability distributions for departure (left) and arrival (right) delay in simulations and historical data. Insets: corresponding QQ-plots.

Whilst the calibration of the model is reasonably good, there are a few known issues which should be addressed in future research:

- The model does not allow for early departures regarding the flight schedule while historical data show that this is a possibility. There is a difficulty to model this due to the lack of reliable datasets which link schedules and historical flights.
- When all flights are considered, the average (and distribution) values of simulated delays are close to historical results, but when flights are classified considering their size there are some discrepancies. The average departure and arrival delay if filtered per aircraft size are not fully as in historical dataset. In particular, the model tends to generate lower departure and arrival delay for larger flights than in the historical data.
- From the analysis of the results, the model presents a high tendency for waiting for delayed passengers at hub in the baseline scenario with values that are higher than what has been reported from the interaction with stakeholders.

2.4.3 Mechanisms

Most of the analyses have been performed by considering 100 simulations of the model for each scenario. For the centrality analyses, we have considered 50 simulations. The results of each metric have been averaged across these, and in the following discussion, we show these averages. Specifically, as in D5.2 – Investigative case studies results [10], we consider the baseline scenario as a reference point, and both for classical and network metrics we show their percentage change with respect to the baseline. As a robustness check, we have considered subsamples of 50 simulations and compared the results (data not shown): thus, most of the results reported are those that have shown consistent results in the subsamples.

In this section, we have collected the most relevant results in three figures, one per mechanism (4DTA, FP, FAC), each of them composed of five panels. The three top panels report the results for classical metrics, namely, from left to right: delay, costs, and passenger-related metrics (delays, missed connections, re-routings, etc.). The two bottom panels show the results of centrality and causality metrics. For centrality metrics, we consider trip centrality, passenger centrality, and trip betweenness. For causality metrics, we define the state of congestion of the airport as the third quartile of the delay distributions of flights departing from a given airport. We then show metrics related to the new causality (BiDAR) approach, with the false discovery rate (FDR) correction.

2.4.3.1 4D Trajectory Adjustment

The top-left panel of Figure 3, shows that the introduction of the 4DTA mechanism improves the airspace system by making it less affected by delays. This is true for all the displayed quantities, namely the average arrival delay for flights with more than 15 minutes of delay, their fraction, and the reactionary delay (number of flights and amount of delay). The detailed analysis shows that this is consistent across different measures of delay. The top-centre panel shows that with 4DTA, there is a sizeable reduction of excess fuel cost (up to almost 20%). This can be understood by the fact that flights use 4DTA to control, in a more efficient way, their total costs, and the cost of fuel is a significant factor driving part of the solution. Other types of cost are only marginally affected by the introduction of 4DTA, some of them are even increasing. Non-passenger delay costs display a small but sizeable decrease. Overall, the costs are reduced by more than 10% when 4DTA is introduced in the system. Also, passenger delays are reduced (see top-right panel). This is much more evident when considering connecting passengers, since they benefit more by the introduction of 4DTA. On the negative side, the fraction of modified itineraries slightly increases, but we can safely affirm that passengers are better off when 4DTA is in operation.

The causality and centrality metrics partly confirm this view. The centrality metrics display a slightly larger loss, possibly in connection with the larger number of modified itineraries. However, the causality metrics show a very significant substantial decrease of density and reciprocity, indicating that the propagation of distress from one airport to the others is much weaker, as well as the two-airport feedback effects. There is, however, a small increase in the feedback triplets. In summary, the introduction of the 4DTA mechanism makes the system better from the point of view of airlines, passengers and the environment (due to reduced fuel consumption). The system is more efficient (from the cost and delay perspective) and more robust to local shocks at airports, which propagate much less.

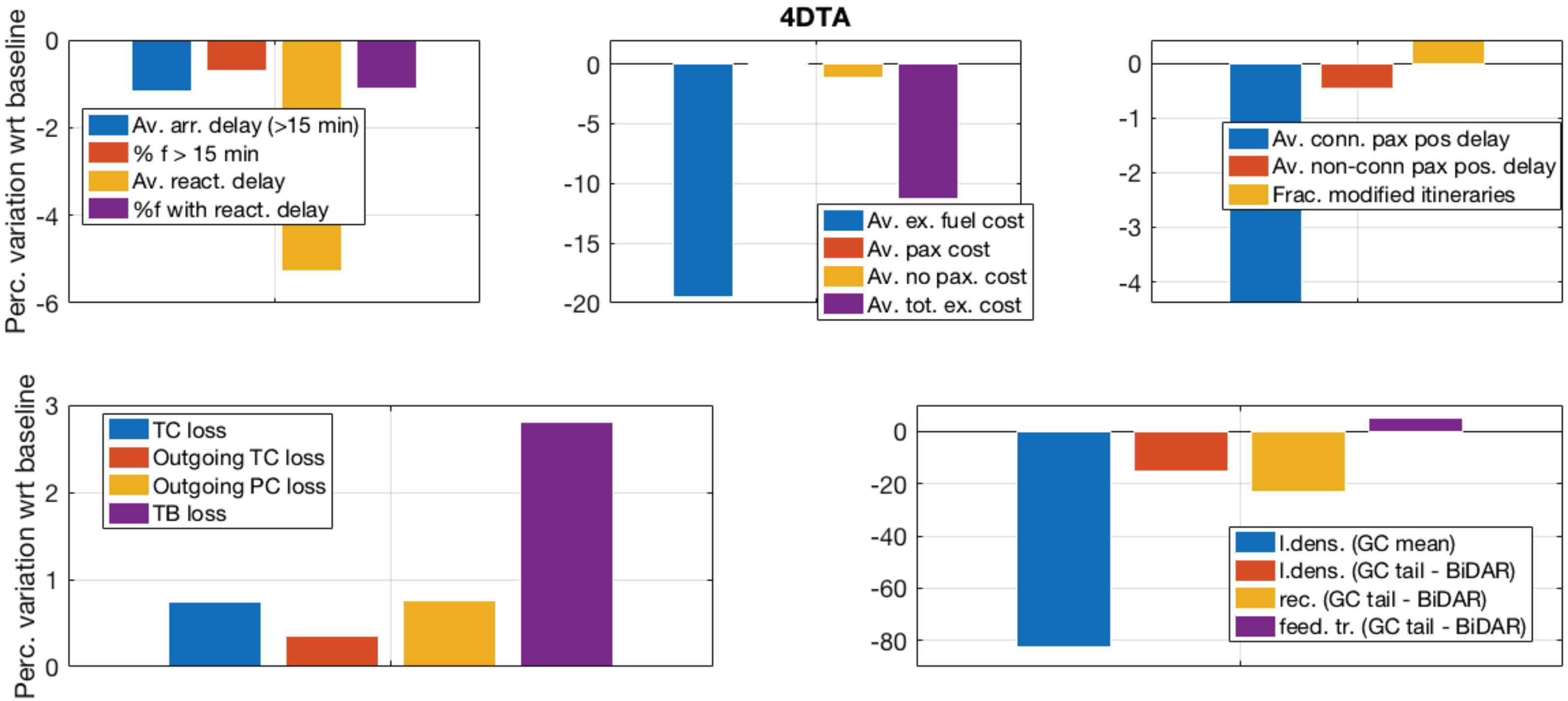


Figure 3: Summary of percentage changes of metrics in 4DTA with respect to the baseline.

2.4.3.2 Flight Prioritisation

The top panels of Figure 4 show the percentage change of classical metrics when FP is implemented at three large airports, namely: LFPG (Paris Charles de Gaulle), EGLL (London Heathrow), EHAM (Amsterdam Schiphol), where ATFM regulations have been manually issued on the morning/early afternoon traffic. Note that the displayed variations are restricted to the three airports where the FP mechanism is applied during the regulation time periods. The overall picture is that the system is worse off, since all but one metric displays a worsening with respect to the baseline. It is important to note, however, that these variations are quite small (never larger than 1.5%, often much smaller). This suggests that the introduction of FP has little or no (or a slightly negative) impact, at least when measured with classical metrics, when FP is in operation.

The bottom panels of Figure 4 show centrality and causality metrics for the three airports where FP is implemented. Again, the variations are very small, and their sign is not common across the airports. Possibly only EHAM displays an overall benefit through the introduction of FP, but, again, the percentage changes are very small. When the analysis is extended to all airports (i.e., not only the three where FP is implemented but all those modelled in the ECAC region), the percentage variation of all metrics becomes extremely small. In summary, the introduction of FP appears to have essentially little or no effect (or maybe slightly negative) on the system, when considering delay, cost, centrality, and causality. More surprisingly, the same conclusion holds when restricting the analysis to the airports where the FP mechanism is implemented.

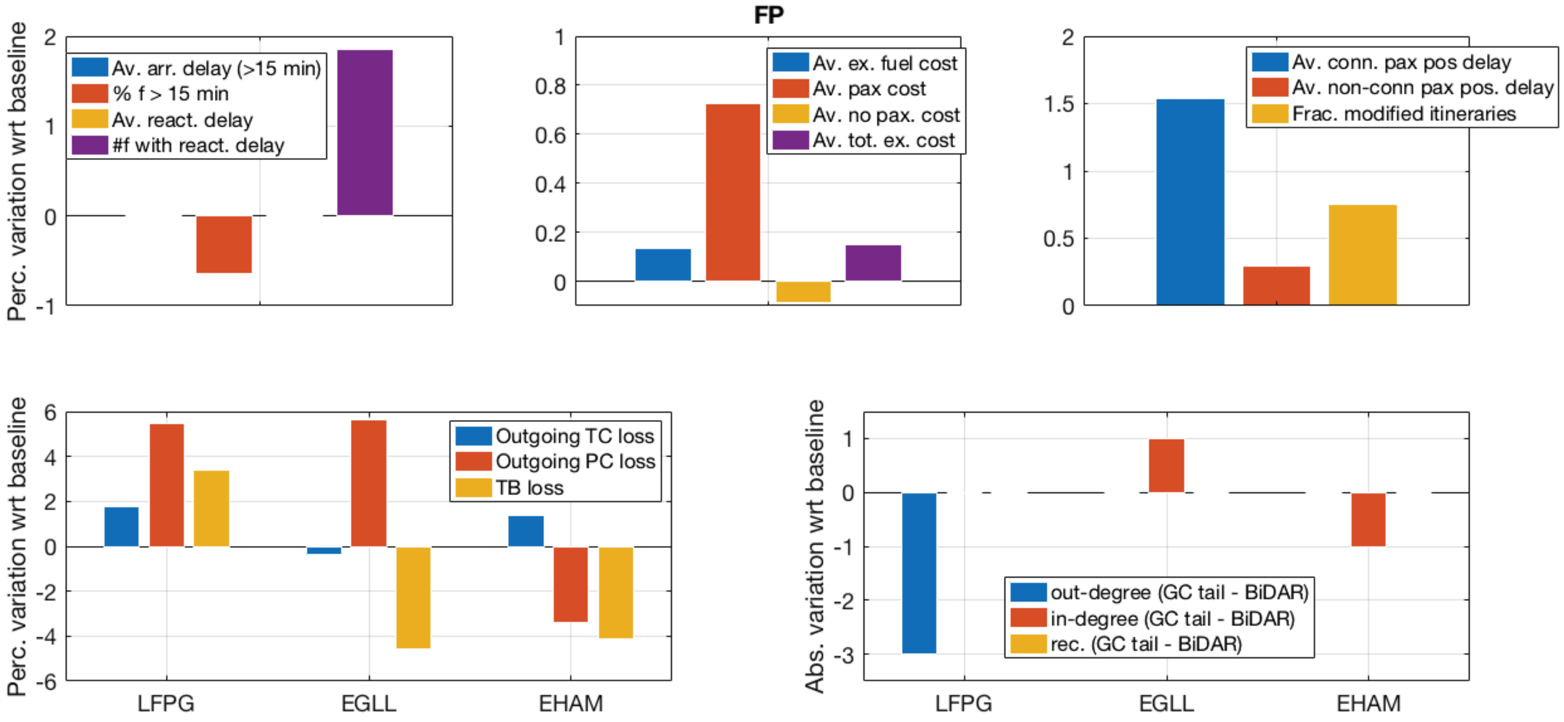


Figure 4: Summary of percentage changes of metrics in FP with respect to the baseline. The percentage variations of the classical delay and cost metrics are restricted to the three airports where the FP mechanisms are applied, and we consider all flights landing at any of the three airports within the time window of active regulation.

2.4.3.3 Flight Arrival Coordination

Flight Arrival Coordination is tested in two different settings, one where the radius of the E-AMAN system is nominal (200 NM), and another, where it is extended (600 NM). Moreover, in the simulations, the FAC is implemented in 24 major airports (as planned according to the Pilot Common Project [33]. Figure 5 shows the results of our analyses. All the displayed results are obtained by restricting the study to the airports where the mechanisms are deployed. In particular, we consider only flights landing at an airport of the restricted sample in computing the delay and cost metrics. The left- and right-hand panels in the top part of Figure 5 clearly show that the introduction of FAC increases the delay of flights and passengers. It appears also that the extended radius of the FAC produces larger delays than the nominal range. Therefore, passenger costs are larger (see the top-central panel). Quite surprisingly, the excess fuel cost is only very slightly smaller (in the nominal radius FAC setting) or even larger (in the extended radius scenario) than in the baseline scenario. Thus, it seems that the introduction of the FAC mechanism makes the system less efficient. This is due to a discrepancy between the E-AMAN planned and actual holding required time, which causes the assignments of additional holding delays to respect the planned landing sequence. This discrepancy is driven by the uncertainty on the traffic and the demand in the implementation of the mechanism in the model. This uncertainty increases as the radius of the mechanism gets larger producing this worsening of the results when the scope of the E-AMAN is increased. These results are highly robust. Generally, the introduction of FAC makes the system worse off for almost all the classical metrics. This conclusion holds even when considering the whole ECAC space, and not only the 24 airports where the mechanism is implemented.

Centrality metrics (bottom-left panel) show small and positive variations, meaning that the introduction of the mechanism makes the centrality loss of these airports larger. This is likely due to the increase of modified itineraries and more generally to the increased delays. The causality metrics are extracted from the network of causal relationships between all the couples of the ECAC airports, but considering only the subgraphs involving at least one airport where the mechanism is implemented. Here the outcome is mixed and not clear: while the introduction of FAC in the nominal radius E-AMAN makes the system slightly worse off, in the extended radius scenario the system becomes significantly less connected, from a causal point of view, both in terms of the number of causal links and of feedback effects (reciprocated links and triplets). This could be explained by the fact that FAC increases the arrival delay of flights independently of their departure delays, thus masking the causal relationships due to network effects. In summary, the introduction of the FAC mechanism appears to make the system worse off from the point of view of airlines and passengers, as well as regarding the environment. Except for causality, all the metrics are worse for the extended range, than for the nominal range.

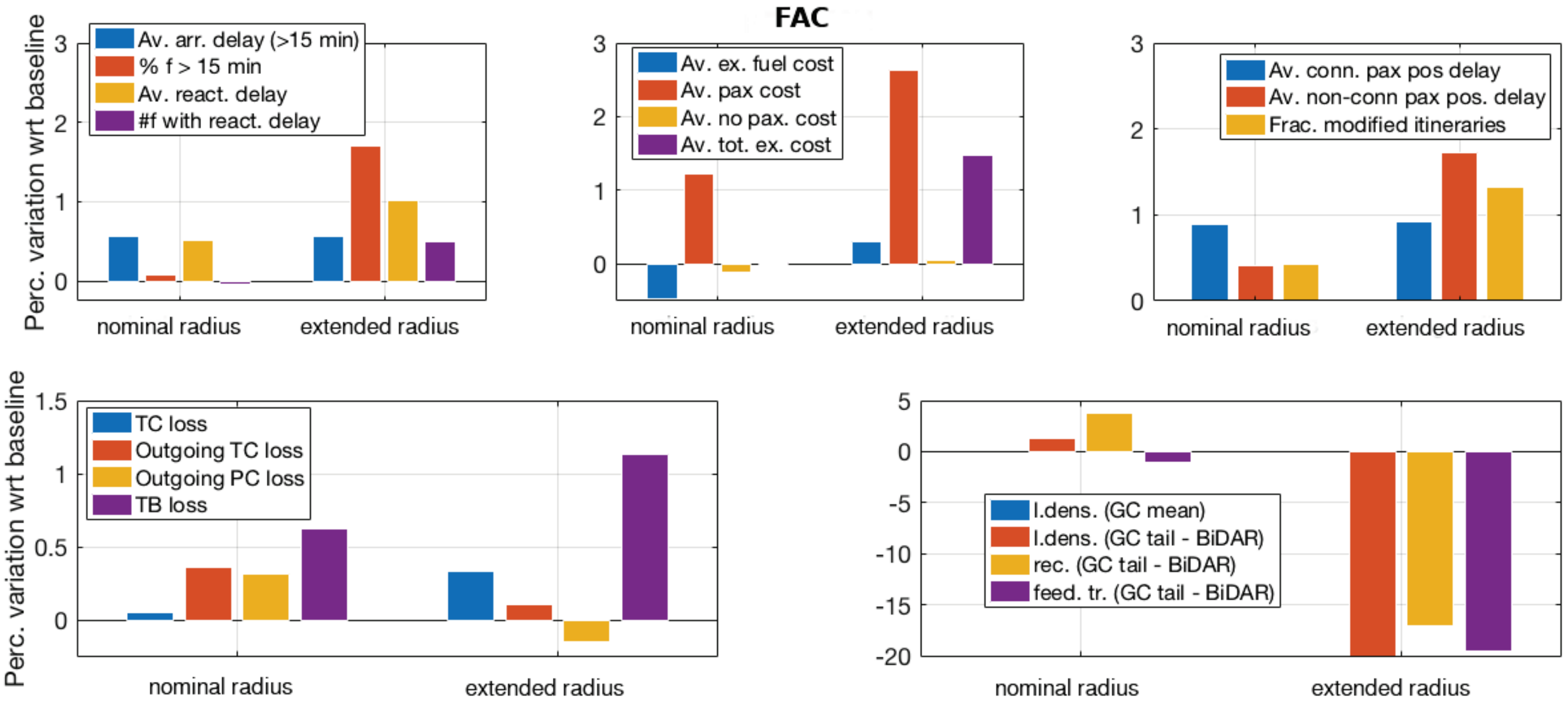


Figure 5: Summary of percentage changes of metrics in FAC with respect to the baseline. The percentage variations of both classical and centrality metrics are restricted to the airports where the FAC mechanisms are applied. In particular, we consider only flights landing at any airport of the restricted sample in computing the delay and cost metrics. The causality metrics are extracted from the network of causal relationships between any couple of the ECAC airports, but considering only the subgraphs, i.e. the reciprocated links or the feedback triangles, involving at least one airport where the FAC mechanism is implemented.

2.4.4 Stakeholder consultation and feedback

Through the development of Domino, consultation and feedback from stakeholders and experts has been conducted. An Advisory Board wad defined in order to have direct contact with industry and stakeholders. Then, dedicated interaction with experts and stakeholders has been strengthen thanks to the relationships available to members of the consortium. These consultation activities have been used on two different stages:

First, once the review of the ATM architecture which was relevant for Domino was conducted, and a first definition of this architecture, potential mechanisms and factors to consider to develop the scenarios were identified, a consultation with experts was carried out (reported in D6.2 – Stakeholders consultation on system and investigative case studies [13]). This consultation was sent to 34 stakeholders and experts (including airlines, airports, ANSPs, network manager, system engineering companies and research institutions). A total of eight responses were obtained, which corresponds to the typical size of a full focus group in market research studies. Their feedback, complemented with interaction with the Advisory Board, was incorporated into D3.1 – Architecture definition [4], and D3.2 – Investigative case studies description [5]. This helped us to define the model and to prioritise the case studies to analyse.

Second, once first results were obtained, two separate workshop activities were performed to gather feedback on Domino's model, metrics and first results on the investigative case studies: one was focused at airspace users, to help us with the validation of the model and to raise awareness of the project; while the other targeted ATM experts to help us to define the final stages of the project. These are reported in D6.3 – Workshop results summary [14].

The first interaction, focused on airspace users, was carried out at the EUROCONTROL Experimental Centre on 7th May 2019. It involved ATM experts from EUROCONTROL and 7 airlines. This was followed up with a dedicated meeting at the University of Westminster with the NM Aircraft Operator Liaison (16th May 2019) to gather further information on airspace users' behaviour. This feedback helped us to adjust some of the behaviour of the agents (including the incorporation of curfews).

Then, a dedicated workshop was organised by Domino at the SJU premises in Brussels on 4th June 2019. This workshop was targeted at ATM and modelling experts. Besides the current model capabilities and results, Domino obtained feedback on the potential future evolution of the project as a tool and from a metrics perspective. Based on the input from this workshop the consortium decided to produce more targeted scenarios for the final part of the project, as described in D3.3 – Adaptive case studies description [6] and in D5.3 – Final tool and model description [11], and case studies results. Some further ideas gathered from this workshop are also described as potential future R&D activities in Section 4.3.1.

2.5 Technical Deliverables

Table 3 presents Domino's deliverables.

Table 3. Project deliverables

Reference	Title	Deliverable Date[1]	Dissemination Level[2]
Description			
D1.1	Project Management Plan	30/04/2018	Confidential
D1.1. is the Project Management Plan (PMP) of the SESAR 2020 Exploratory Research action Domino. The PMP documents the management plan and procedures, complementing the project information provided in the Grant Agreement Description of Action with additional detail.			
D2.1	Data management and resources	14/06/2018	Public
The different data sources considered in Domino and the approach to manage them are detailed in this deliverable.			
D2.2	Database structure	27/09/2018	Public
This is a technical deliverable describing the database used in Domino. The structure of the database along with information on the data sources used are included. This database has been used to store the input and outputs of the executions of the investigative case studies reported in D5.2 – Investigative case studies results and the input for the final case studies reported in D5.3 – Final tool and model description, and case studies results. The deliverable includes a diagram of the relational database and a description of the different tables used with information on the different fields that define these tables. Information on the pre-computation of data to create the required input for the model is also included. Shortcomings of the database are identified and potential solutions highlighted.			
D3.1	Architecture definition	29/06/2018	Public
This deliverable presents the concept of operation of Domino. It includes a description of the systems, subsystems and processes taken into account in the model, as well as the general scope of the model. For each of the mechanisms suggested to be modelled in the project, the deliverable provides a set of possible operational concepts and uptake/scope to be deployed.			
D3.2	Investigative case studies description	16/11/2018	Public
This deliverable presents the scenarios to be simulated by Domino's model. It first describes a list of the parameters and characteristics that are important to take into account to achieve Domino's			

[1] Delivery data of latest edition
[2] Public or Confidential

Reference	Title	Deliverable Date[1]	Dissemination Level[2]
Description			
goals, including the levels of implementation of the mechanisms presented in D3.1. A prioritisation of scenarios is presented, together with its rational.			
D3.3	Adaptive case studies description	17/12/2019	Public
This deliverable presents the improvement planned to be performed until the end of the project at the moment of submitting the deliverable regarding the model (implementation changes, recalibration and the simulation outputs), plus the metrics and scenarios that will be re-run with the model. These changes are based on the insights gathered through the analysis activities performed in the scope of investigative case studies (D3.2 Investigative case studies description and D5.2 Investigative case studies results) and the feedback obtained from experts and stakeholders on the different workshops activities performed (reported in D6.3 Workshop results summary). These insights highlighted missing features of the model and potential improvements, as well as some gaps and shortcomings. The scenarios for this analysis have been chosen highly selectively in order to prioritise the depth of the analysis and methodology development over a large number of scenarios, as these have already been analysed in the scope of the investigative case studies.			
D4.1	Initial model design	08/11/2018	Public
This technical deliverable describes the model design used in Domino. Domino deploys an agent-based model that has been developed following the Gaia methodology. This deliverable contains the requirements, specification and design of the model. This includes the definition of the roles and interactions models as part of the analysis of the system, and the agent, services and acquaintance models as part of the design of the model. Other design issues such as the simulation engine, communication channels and potential parallelisation are described. This deliverable also presents some implementation details such as the programming language and potential libraries that will be used. The changes performed to the model design in the final version can be found in D5.3 – Final tool and model description, and case studies results.			
D4.2	Model source code	31/10/2019	Confidential
This deliverable comprises the technical documentation with information on system requirements, model installation and execution, and parameters file and the model source code which was provided to the Project Officer.			
D5.1	Metrics and analysis approach	21/12/2018	Public
This deliverable presents the metrics proposed to assess the impact of innovations in the ATM system and a stylized ABM model, called a ‘toy model’, to be used as a test ground for the metrics. Existing network metrics are reviewed and their limitations are highlighted by applying them to real data. New metrics are then suggested to overcome these limitations. Their better results in measuring interconnections and causal relationships between the elements of the ATM system are shown for empirical case studies. The design of the toy model is presented and preliminary results of its			

Reference	Title	Deliverable Date[1]	Dissemination Level[2]
Description			
baseline implementation are shown.			
D5.2	Investigative case studies results	31/07/2019	Public
This deliverable presents the results from the analysis of the model executing the investigative case studies. The document focuses on the validation activities and the results for the three mechanisms modelled in Domino in the unitary case studies (considering the three mechanism, their level of implementation and the level of stress/delay in the system). In total 14 scenarios have been modelled and analysed. This deliverable presents the use of classical and network metrics (centrality and causality) on the outcome of the whole European level agent-based model.			
D5.3	Final tool and model description, and case studies results	19/12/2019Error! ookmark not defined.	Public
This deliverable presents the final results obtained from the Domino project. It presents the corresponding metrics, the model, and a detailed analysis of two case studies. The main modifications to the model with respect to the previous version are highlighted, including curfew management. The calibration of the model is presented, which is similar to the previous version, with more in-depth analyses and further effort dedicated to the calibration process. Two case studies are defined in this deliverable, using previous definitions of the three base mechanisms: 4D trajectory adjustments, flight prioritisation, and flight arrival coordination. The case studies are defined to have a focused insight into the efficiency of the mechanisms in specific environments. The two case studies are run by the model and analysed using metrics previously defined, including centrality and causality metrics. The results show different levels of efficiency for the three mechanisms, highlight the degree of robustness to the propagation of negative effects (such as delay) in the system, demonstrate various trade-offs between the indicators, and support a discussion of the limit of the mechanisms.			
D6.1	Dissemination plan and project visual identity	15/06/2018	Confidential
The purpose of Deliverable 6.1 is to describe the dissemination plan, dissemination policy and initial dissemination products of the SESAR 2020 Exploratory Research action Domino, taking into account its specifications and the target audience.			
D6.2	Stakeholders consultation systems and investigative case studies	24/08/2019	Public
This deliverable presents the consultation questionnaire and a summary of the consultation results on the system architecture and the investigative case studies to be modelled in Domino: the feedback has already been incorporated into deliverables D3.1 (Architecture definition) and D3.2 (Investigative case studies description).			
D6.3	Workshop results summary	28/06/2019	Public
This deliverable summarises two workshop activities carried out with stakeholders to provide feedback on the modelling, metrics and first results of Domino. How the feedback will be used in the			

Reference	Title	Deliverable Date[1]	Dissemination Level[2]
Description			
project is also highlighted.			
D6.4	Project dissemination report	31/10/2019	Confidential
This deliverable presents the dissemination activities over the duration of the Domino project, documenting relevant dissemination statistics that relate to attendance at events, conference and journal publications, project website visits, blog posts and other activities. It also gives an overview of the tools and methodology used by the members of the Domino team during the project execution to ensure the dissemination of the results and findings. Copies of the dissemination material used in the project are also included.			

3 Links to SESAR Programme

3.1 Contributions to the ATM Master Plan

Domino has developed an agent-based model able to capture the interaction of different stakeholders and systems at the ECAC level, producing metrics for flights and passengers. Moreover, new network metrics based on centrality and causality have been defined and tested. This model, and its metrics, have proven to be a valid approach to capture the effects of the implementation of various ATM mechanisms. This novel approach to evaluate these systemic, network-wide effects are transversal to SESAR activities, and provide a solid basis for a (future) framework for the evaluation of SESAR Solutions[3]. As a result, Domino is relevant to content integration (PJ19), more specifically to PJ19.04, and performance review activities. The metrics can also be applied to historical data, gaining insight into the effect of these Solutions[3], network-wide.

The objective of Domino was not to evaluate specific SESAR Solutions, but to show the capabilities of the approach, model and metrics. Nevertheless, three mechanisms (flight prioritisation, 4D trajectory adjustment and flight arrival coordination) have been implemented and assessed in Domino. These mechanisms variously relate to some SESAR Solutions and therefore offer contributions to better understanding the corresponding implementation effects. The applicability to selected Solutions is captured in Table 4.

Table 4. Project Maturity

Code	Name	Project contribution	Maturity at project start	Maturity at project end
PJ07.02	AU Fleet Prioritisation and Preferences (UDPP)	Evaluation of the use of UDPP at arrival ATFM regulations at network level with different levels of implementation.	TRL-1	TRL-2
Solution #56	Enhanced ATFM Slot Swapping	Evaluation of swapping of slots among different airlines for arrival ATFM regulations at network level.	TRL-1	TRL-2
Solution #05	Extended Arrival Management (AMAN) horizon	Evaluation of different scopes of the E-AMAN with different prioritisations.	TRL-0	TRL-1
Solution #54	Flow based Integration of Arrival and Departure Management	Evaluation of different scopes for the E-AMAN system with different prioritisations.	TRL-0	TRL-1

[3] Also of Essential Operational Changes and ATM Functionalities.

Furthermore, Domino lays significant foundations for performance assessment that are already well beyond the state of the art. Notably, these include the incorporation of passenger-centric and cost-centric metrics (classical and network, as defined above). These may serve to inform the on-going development of the 'Performance View' in the ATM Master Plan (Chapter 3) and the corresponding work in the SESAR Performance Framework, continuing in Wave 2. Some of the Domino metrics could be used as investigative metrics, quantified using historical / current / exploratory (test/validation) data, and evaluated for future adoption with SESAR Solutions[3]. Such adoption (as a (compulsory) PI or KPI) should be reserved for cases where such new metrics are demonstrably and consensually better suited to measure the required performance, and/or for closing, understanding and better modelling the gap between the SESAR Performance Framework and the SES Performance Scheme (e.g. regarding E-AMAN horizons) – although it may often be more appropriate to maintain separate metrics in these contexts.

3.2 Maturity Assessment

Domino aimed at reaching a TRL-2: technology concept formulated. The assessment of Domino's results' maturity is presented in Table 5. This indicates the maturity of the project to evolve from exploratory to industrial research (ER to IR).

Table 5. ER Application-Oriented Research Maturity Assessment

Thread	ID	Criteria	Satisfaction	Rationale – Link to deliverables – Comments
OPS	**OPS.ER.1**	Has a potential new idea or concept been identified that employs a new scientific fact/principle?	Achieved	• New definition of network metrics adapted to the ATM domain: trip centrality, passenger centrality, causality in tail. • Metrics presented and tested in D5.1 - Metrics and analysis approach, evolved and further described and evolved in D5.3 - Final tool and model description, and case studies results. These were also published in: Zaoli, S., Mazzarisi, P. & Lillo, F. Trip Centrality: walking on a temporal multiplex with non-instantaneous link travel time. *Scientific Reports*, 9, 10570 (2019) • Use of a full agent-based model to simulate the entire ATM network; incorporation of a comprehensive cost of delay model. • Description of the ABM model in D4.1 - Initial model design, with updates on modelling/design reported in D5.3 - Final tool and model description, and case studies results.
OPS	**OPS.ER.2**	Have the basic scientific principles underpinning the idea/concept been identified?	Achieved	• Advance network metrics based on complexity and network science have been reviewed and analysed in D5.1 - Metrics and analysis approach. • Description of the ABM model in D4.1 - Initial model design, with updates on modelling/design reported in D5.3 - Final tool and model description, and case studies results (as previous cell)

Thread	ID	Criteria	Satisfaction	Rationale – Link to deliverables – Comments
OPS	OPS.ER.3	Does the analysis of the 'state of the art' show that the new concept / idea / technology fills a need?	Achieved	• State of the art forecasts a vast increase in interdependencies between components of the air transportation management • To the best of our knowledge, the ABM-Mercury model is the only full agent-based model able to represent the whole of the ATM system from a flight and passenger perspective. • State of the art on metrics (classical, and network metrics – centrality and causality) was reviewed in D5.1 - Metrics and analysis approach. • Consultation with stakeholders with a dedicated experts' workshop was conducted to validate the potential usage of this approach and reported in D6.3 - Workshop results summary. • The relationship between network metrics and operational ones is further analysed in D5.3 - Final tool and model description, and case studies results.
OPS	OPS.ER.4	Has the new concept or technology been described with sufficient detail? Does it describe a potentially useful new capability for the ATM system?	Achieved	• The ABM model has been specified and developed following a standard methodology (Gaia) and reported in D4.1 - Initial model design. • The network metrics have been described in detail in D.1 - Metrics and analysis approach, in: Zaoli, S., Mazzarisi, P. & Lillo, F. Trip Centrality: walking on a temporal multiplex with non-instantaneous link travel time. *Scientific Reports*, 9, 10570 (2019) and in D5.3 - Final tool and model description, and case studies results. • The description on how to use the model and the metrics to analyse new concepts and mechanisms has been included in D5.3 - Final tool and model description, and case studies results.

Thread	ID	Criteria	Satisfaction	Rationale – Link to deliverables – Comments
OPS	OPS.ER.5	Are the relevant stakeholders and their expectations identified?	Achieved	• Stakeholders and experts have been involved in the validation of the project from the beginning, in various activities: ○ setting up and consulting a dedicated Advisory Board, ○ a consultation to identify relevant systems and case studies to be modelled (reported in D6.2 - Stakeholders consultation on systems and investigative case studies) ○ participation in an Airspace Users workshop organised by EUROCONTROL to present first results and validate modelling assumptions (reported in D6.3 - Workshop results summary). ○ organising a dedicated workshop with ATM experts and consulting with EUROCONTROL experts to validate model assumptions and identify requirements by the community to define and use new network metrics, case studies and further lines of research (reported in D6.3 - Workshop results summary).
OPS	OPS.ER.6	Are there potential (sub)operating environments identified where, if deployed, the concept would bring performance benefits?	Achieved	• The model developed in Domino is able to capture the interaction of different ATM elements in the current and future operational concept. • Mechanisms related to the operational concepts of User-Driven Prioritisation Process (UDPP), 4D Trajectory management related to Trajectory Based Operations (TBO) and Extended Arrival Manager (E-AMAN) have already been tested. • The network metrics have been evaluated on historical data to prove their utility beyond the Domino's model (reported in D5.1 - Metrics and analysis approach).

Thread	ID	Criteria	Satisfaction	Rationale – Link to deliverables – Comments
SYS	SYS.ER.1	Has the potential impact of the concept/idea on the target architecture been identified and described?	Partial – Non Blocking	• Relationship between the systems modelled in Domino and EATMA were highlighted in D3.1 - Architecture definition. Further work is required to further describe these relationships. • However, Domino provides a platform to assess high-level interactions between systems, and in that regard, is independent of a specific architecture and able to model current and future operational concepts.
SYS	SYS.ER.2	Have automation needs e.g. tools required to support the concept/idea been identified and described?	Achieved	• Domino has identified the tools needed to develop and execute the model and to compute the network metrics.
SYS	SYS.ER.3	Have initial functional requirements been documented?	Partial – Non Blocking	• The requirements for the model have been captured in D4.1 - Initial model design and updated in D5.3 - Final tool and model description, and case studies results. • The documented code of the model was delivered in D4.1 - Model source code. • The definition of the network metrics is also described in D5.1 - Metrics and analysis approach and D5.3 - Final tool and model description, and case studies results. • Further work is required to update and consolidate the documentation of the model description.
PER	PER.ER.1	Has a feasibility study been performed to confirm the potential feasibility and usefulness of the new concept / idea / Technology being identified?	Partial – Non Blocking	• The feasibility and usefulness of the concepts proposed in Domino has been qualitatively assessed with the interaction with stakeholders and experts in the different consultation activities (reported in D6.3 - Workshop results summary). • Additional consultations should be performed once the relationship with network metrics and operational indicators is further developed.
PER	PER.ER.2	Is there a documented analysis and description of the benefit and costs mechanisms and associated Influence Factors?	Not Applicable	Not Applicable

Thread	ID	Criteria	Satisfaction	Rationale – Link to deliverables – Comments
PER	PER.ER.3	Has an initial cost / benefit assessment been produced?	Partial – Non Blocking	• The benefits of using the suggested network metrics have been highlighted in D5.3 - Final tool and model description, and case studies results, but a comprehensive economical analysis of these benefits should be further developed. • The Domino model is able to capture not only classical metrics in terms of delay but also as cost for airspace users. The network metrics are able to represent how disruption (in terms of delay and cost) propagates through the ATM network.
PER	PER.ER.4	Have the conceptual safety benefits and risks been identified?	Not Applicable	Not Applicable
PER	PER.ER.5	Have the conceptual security risks and benefits been identified?	Not Applicable	Not Applicable
PER	PER.ER.6	Have the conceptual environmental impacts been identified?	Not Applicable	Not Applicable
PER	PER.ER.7	Have the conceptual Human Performance aspects been identified?	Not Applicable	Not Applicable

Thread	ID	Criteria	Satisfaction	Rationale – Link to deliverables – Comments
VAL	VAL.ER.1	Are the relevant R&D needs identified and documented? Note: R&D needs state major questions and open issues to be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution once Exploratory Research activities have been completed, and the definition of validation exercises and validation objectives in following maturity phases.	Achieved	• Further research and development needs are reported in D1.2. • D5.3 - Final tool and model description, and case studies results also identifies new lines of research and activities that could be performed after Domino.
TRA	TRA.ER.1	Are there recommendations proposed for completing V1 (TRL-2)?	Achieved	• Further research and development needs are reported in D1.2. • D5.3 - Final tool and model description, and case studies results also identifies new lines of research and activities that could be performed after Domino.

4 Conclusions and Lessons Learned

4.1 Conclusions

Domino aimed at defining and evaluating network metrics able to capture the relationship between the elements of the ATM system, to provide a platform to assess these metrics and to evaluate new mechanisms, and to develop a methodology to use these metrics and to further assess new mechanisms or regulatory environments. These objectives have been achieved by reviewing classical and advanced metrics and further tailoring network metrics (centrality and causality) to the needs and characteristics of the ATM system. A dedicated ABM model has been designed, documented and developed. These metrics and model have been successfully applied to different scenarios considering a range of mechanisms and historical datasets.

The metrics have proven to be of interest to the community and able to capture complex interactions between the elements of the ATM system (airports) from a flight and passenger perspective. They have been successfully evaluated on historical datasets and on the output of the model and effort has been devoted to relating them to operational indicators.

The ABM model captures the interaction of relevant stakeholders such as airlines, flights, departure and arrival managers, and the Network Manager, *inter alia*. It has been calibrated and validated with feedback from stakeholders and historical datasets. The model is designed following a flexible architecture and with a standard and documented methodology (Gaia [42]). This ensures that the platform is easily reconfigurable and adaptable for future evaluations. Moreover, basing the model on an agent paradigm, the behaviour of the actors can be modelled, based on complex cost functions, quantifying the associated system performance emerging from the evolving interactions of its parts.

A methodology has been used to test different mechanisms based on different operational concepts. They have been selected to show the capabilities of the model and the metrics to capture emergent phenomena as responses to different changes in the system. These mechanisms include local modifications, such as the application of E-AMAN in some airports, and global changes such as the usage of dynamic cost indexing and wait-for-passenger rules by airlines.

4.2 Technical Lessons Learned

The following points summarise the technical lessons learned that may be of benefit to other projects.

1. Domino has stored the input for the model in a MySQL database hosted on a virtual machine at the University of Westminster. This set up was already used in previous projects and therefore the Domino project benefited from this deployment. However, the model produces a large quantity of low-level results, which resulted in very large outputs from each model execution. This led to some limitations in terms of simulation time (the different executions were held by the slow and concurrent writing of the results in the database) and

then data access (the loading of the results was thus relatively slow). This was resolved in the final version of the model by producing output in the format that the team analysing them could directly use (without requiring data pre-processing) and storing them in files. This solution has its own limitations, as files are harder to maintain and their versioning could be challenging. Moreover, this raised some difficulties regarding the analysis, when data needed to be related to the input sources. We recognise that the use of a relational database for the input of the model seems beneficial as it ensures the data consistency, however, for the output of the model, other solutions such as NoSQL databases could be explored, in order to trade the required writing speed with data management.

2. Data availability continues to be an issue when producing research projects in the ATM environment. The access to DDR datasets has been restricted and information required to generate new inputs for the model (e.g. schedules) is not always available. Moreover, the model tries to capture the behaviour of agents, therefore, information on data on the airline's intentions (i.e., first submitted flight plan) would be useful. (Several such issues are being attempted to be resolved for the wider research community by the Engage KTN.)
3. The model has executed a large range of scenarios and more time would be required to further understand how these mechanisms are behaving in even fuller detail. Whilst the project, *by design*, took time to review, at an interim stage, the status of the results through the investigative case studies results (as reported in D5.2 [10] and D6.3 [14]), intensive, yet short, projects within the novel scope of SESAR Exploratory Research inevitably often still raise further issues at the conclusion of the project, which are of value to investigate further. This is notwithstanding the significant extra effort invested by the team to close as many of these as possible in the final reporting cycle.
4. Limiting the scope of the analysis to a subset of mechanism configurations would be beneficial regarding the trade-off between in-depth analyses and showcasing the model's capabilities.
5. More time is required for updating the documentation of the model to ensure that it is re-usable for further research activities. The technical Deliverable 4.1 presents the specification and design of the model. Whilst the actual implementation is very close to this, some changes have been needed. These are reported in later deliverables such as D5.3 [11]. However, it would be convenient to consolidate the model specification and design in an updated document or wiki. This is particularly relevant for design/modelling decisions and for the calibration activities.

4.3 Plan for next R&D phase; next steps; dissemination

4.3.1 Future R&D activities

As highlighted in Section 2.4.2.2 Model calibration and validation, further work is required to improve the calibration of the system, in particular adjusting the delay experienced by different aircraft types in the baseline scenario and some mechanism parameters such as the behaviour of flights waiting for passengers. This validation should include two processes. The model, Mercury, would need to undergo some systematic comparisons with other available models. These include, for instance, the tool from EUROCONTROL, RNEST, outputs from which could be compared with Mercury, where these are similar in scope and depth. The validation of Mercury lies as much in this comparison itself, as in the understanding of the differences between the models. Expert interviews on some detailed aspects of the models are also needed. Furthermore, using additional data to test the model in different environments is paramount to assessing its generalisability. Domino has developed an agent-based architecture which allows the model to capture the behaviour of stakeholders such as airline operating centres. This, linked with passenger itineraries and expected costs, are key capabilities needed to model the behaviour of the ATM system as a whole. However, other tools provide a more detailed modelling of some of the operational phases, for instance the flight phase, which would allow the computation of other metrics such as ATC conflicts. The integration of this agent-based behaviour into a simulation platform such as BlueSky [34] could be an interesting path of research.

Exploring the possibility of using a NoSQL database, such as Apache Cassandra, to store the output of the model is also an interesting route to trade the required speed to store the results and the database capabilities for accessing data.

Further work is needed in order to fully understand the relevance of the network metrics developed (centrality and causality) with respect to operational indicators, and effort is required to render them more intuitive and/or understandable, and thus being candidates to be used as future (key) performance indicators. It is important to note that these metrics may be good proxies for others, and/or add further dimensionality and usefulness. This can only be understood via statistical analyses and additional case studies. It is also worth noting that these metrics are independent of the model.

4.3.2 Next steps

The specific next steps regarding potential further development and wider application of the Domino metrics and model in the research and development contexts include the use of the Domino model in future research projects such as Clean Sky 2 Innovation Action PiLot3 (www.pilot3.eu, https://cordis.europa.eu/project/id/863802) where ABM-Mercury will be considered as part of the validation of new support decision tools for pilots.

The model will be also considered as a candidate for its use and expansion in future ER projects, if some proposals submitted to the SESAR ER4 Call are granted to members of the consortium.

A new updated version of D4.1 - Initial model design [7], will be internally produced in order to have a consolidated specification and design of the ABM system.

The consortium plans to take the developed method forward to analyse network effects closer to a real application in the future. Firstly, by generalising the analysis, allowing complex metrics to be used at different levels. For instance, various subsystems can be considered instead of airports, to infer causality links or central nodes. Flights, routes, sectors are all possibilities of subsystems that could be considered, and whose relationships may thus be analysed. This will allow the consideration of adequate measures to avoid the propagation of disruption in the system. Secondly, the partners plan to test more extensively the method, considering other days of operations or specific environments. This will allow us to provide some improvements to the method, and also to improve the extent of the validation.

Some of the ideas used during the project regarding the three mechanisms (4DTA, FAC and FP) can be further developed. Whilst studies on 4DTA and its impact appeal to airlines regarding their operations, FP is more important to assess for the network manager. The possible introduction of further variations of UDPP (e.g., credits for low-volume users) can be studied with the method presented in Domino. The way in which FAC impacts operations at airports and at the network level, is both important for airports and the network manager. Various optimisation algorithms could be tested with the method presented in Domino.

Domino could also contribute to the assessment of the future architecture of the European airspace, for example as published in [43]. Several recommendations captured in this document require the implementation of new operational concepts such as the 'flow-centric redesign of the airspace sectors' or 'the implementation of a framework for on-demand cross-border use of services for capacity demand'. The impact of these concepts could be assessed with Domino by modelling them as inputs into the platform. Domino could provide the expected (output) performance across different stakeholders and the network. It is also stated (*sic*.) that 'higher levels of resilience' are required in the ATM system, and Domino could support the definition and estimation of such resilience, not least through its new metrics. Since the Domino platform is an agent-based system, it is a natural environment to evaluate the impact of changes that go beyond simple operational modifications, such as the reaction of stakeholders to new legal and financial frameworks where rewards to early movers can be envisaged. It is to be stressed that these are example contributions from Domino. A systematic review could be made in future, requiring a few days of effort from the project team.

4.3.3 Dissemination

It is also planned that the members of the consortium will submit several articles to peer-reviewed journals (e.g. Journal of Air Transport Management; Journal of Transport Economics and Policy; Transportation Research (due to the broad scope of Domino, all of the following parts could be appropriate – Part B: Methodological; Part C: Emerging Technologies; Part D: Transport and Environment)) and participate in conferences and workshops where Domino's approach and/or results are apposite (see Table 6). This will be subject to the availability of alternative funds for these activities, after the project closure. Domino may also present at selected Engage (SESAR KTN) thematic challenge workshops, but only if this is deemed appropriate by the KTN consortium members and if such a presentation would be specifically aligned with the objectives of the thematic challenges and corresponding workshop(s).

Table 6: Potential events for future Domino dissemination

Event	Date	Location	Description	Comments
SESAR Innovation Days (SIDs)	December 2020	Budapest	Forum for ATM exploratory research	Target event for Domino
International Conference on Research in Air Transportation (ICRAT)	June/July 2021	Europe (TBC)	FAA/EUROCONTROL jointly organised event, alternating with ATM Seminar	
ART Agency Research Team (ART) meetings and workshops	April/October 2020	TBC	Regular EUROCONTROL advisory body workshop	

USA/Europe Air Traffic Management (ATM) Research and Development (R&D) Seminar (ATM Seminar)	June/July 2022	Europe (TBC)	FAA/EUROCONTROL jointly organised event, alternating with ICRAT	Target event for Domino
Engage KTN workshops and summer schools	July 2020	Luxemburg	Summer school organised by the Engage KTN network	
World ATM congress	March 2020	Madrid	International air traffic management (ATM) exhibition and conference	
Air Transport Research Society World Conference	July 2021	TBC	Air transport related conference	
CCS – Conference on Complex Systems	October 2020	Palma de Mallorca	Complex systems research community conference	Target event for Domino
NetSci and/or NetSciX – Conference on Network Theory	July 2020	Rome	Network science conference	Target event for Domino

5 References

5.1 Project Deliverables

Please note that public deliverables are available from the project website (http://domino-eu.com/) and the University of Westminster's on-line repository of research outputs (https://westminsterresearch.westminster.ac.uk/).

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6 Acronyms

4DTA: 4D Trajectory Adjustment

ABM: Agent Based Model

AMAN: Arrival Manager

ANSP: Air Navigation Service Provider

ATC: Air Traffic Control

ATFM: Air Traffic Flow Management

ATM: Air Traffic Management

AU: Airspace User

BiDAR: Bivariate Discrete Auto-Regression

CODA: Central Office for Delay Analysis

DCI: Dynamic Cost Indexing

DDR2: Demand Data Repository (second phase)

DMAN: Departure Manger

DX.Y: Deliverable number (X=workpackage, Y=deliverable numbering within workpackage)

E-AMAN: Extended Arrival Manager

EATMA: European Air Traffic Management Architecture

ECAC: European Civil Aviation Conference

ER: Exploratory Research

FAA: Federal Aviation Administration

FAC: Flight Arrival Coordination

FDR: False Discovery Rate

FMP: Flow Management Position

FP: Flight Prioritisation

GA: Grant Agreement

H2020: Horizon 2020 research programme

INX: Short name of Domino partner: Innaxis

NM: Network Manager / Nautical Mile

NoSQL: Not Only SQL (see SQL)

PMP: Project Management Plan

QQ: Quantile-Quantile

R&D: Research and Development

RNEST: Research Network Strategic Tool

RAM: Random Access Memory

SESAR: Single European Sky ATM Research

SID: SESAR Innovation Days

SJU: SESAR Joint Undertaking

SQL: Structured Query Language

TRL: Technology Readiness Level

UDPP: User-Driven Prioritisation Process

UniBo: Short name of Domino partner: Univesità di Bologna

UNITS: Short name of Domino partner: Università degli studi di Trieste

UoW: Short name of Domino coordinator: University of Westminster

WBS: Work breakdown structure

WP: Workpackage

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