E.02.28-D08-TREE-Final Project Report

Document information	
Project Title	Final Project Report
Project Number	0E.02.28
Project Manager	Isdefe
Deliverable Name	Final Report
Deliverable ID	D08 (D0.11 in contract)
Edition	01.00.00
Template Version	03.00.00
Task contributors	
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Abstract

The final report of the TREE project provides a publishable summary of the results. In addition it lists all deliverables, dissemination activities, eligible costs, deviations, bills and lessons learned.

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Rational for rejection
None.

Document History

Edition	Date	Status	Author	Justification
00.00.01	18/01/2016	Draft version	TREE Consortium	New Document
00.00.02	03/02/2016	Final version	TREE Consortium	Revised document

Intellectual Property Rights (foreground)

This deliverable consists of foreground generated as a result of the activities conducted by Isdefe and IFISC within the framework of the project and co-funded with Isdefe/IFISC resources. The foreground is therefore, according to the project contract[1], owned by Isdefe/IFISC.

[1] EUROCONTROL Contract reference 12-120610-C11, Part II General Conditions, Article II.8.

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Publishable Summary

Air transportation systems display a rich phenomenology connected with several key topics in Complexity Science, such as complex networks, cascading failures and percolation. Another feature of these systems is that performing experiments on them is potentially extremely expensive. Thus, the approach of agent based modeling is a compelling alternative to assess the impact of new measures and study in depth different global aspects. Network and airline managers, passengers, crews and airport staffs are involved in the daily operations and may suffer the consequences when failures in the system such as delays appear. In the SESAR WP-E project TREE (Data-driven modelling of the network-wide extension of the Tree of REactionary delays in ECAC area) a model for characterizing and forecasting the spreading of reactionary delays through the European Network has been developed. The results show a good level of precision and accuracy.

Overall Strategy: The modelling approach in TREE consists in tracking the state of each aircraft and airport as the aircraft attempt to perform the scheduled flights in their daily rotations. Limited airport capacities (the maximum numbers of aircraft movements which can take place in an hour) and flight connections (through aircraft, passengers and crew) are the considered mechanisms for delay propagation. The model is data-driven in the sense that as many details of the simulated system as possible are reconstructed from empirical data, namely airport capacities, passenger connectivity patterns and flight schedules with their primary delays.

Connectivity: The connectivity in the model is defined at three levels; aircraft, passenger and crew.

- The flight connectivity is entirely determined by and intrinsic to the flight schedules. It is based on the aircraft rotation, if the actual arrival time of the previous flight (increased by a minimum service time) is higher than the next flight's scheduled departure time, the latter will have to be delayed. Unlike the other kinds cannot be "turned off" in the simulations.
- Passengers on one flight might connect to another at the destination airport, and the latter might need to wait for them if the airline determines it economically convenient. In our model, this process is represented in a stochastic way due to the lack of specific information on each passenger connections. The *simulated* connections are selected randomly between the flights operated by companies in the same alliance with probabilities for the passenger connections as observed in the market sector data and assuming an average of 100 passengers per flight. We introduce an effective parameter $\alpha \in [-1; 1]$, so that there are no connections for $\alpha = -1$, all passenger connect for $\alpha = 1$, and connection probabilities are as in the sector data for $\alpha = 0$.
- Crew members may also connect from one flight to another. The probability of a two-flight crew connection is approximated by the fraction of connecting passengers of the airline in the particular airport multiplied by a tuning parameter γ. Point-to-point airlines are also included in this mechanism applying it to their logistic hubs.

Re-scheduling: When processing a flight (F) that has lost its ATFM slots, the model first tries to negotiate with the departure and arrival airports a new pair of slots. F has a "proposed departure time", given by the earliest time at which, having waited for all the other flights to which it is connected, having dealt with its own primary delay and complying the minimum turnaround time, F can depart. The possible departure/arrival pairs are those such that the departure slot begins at the proposed departure time or later, and no later than the flight's scheduled departure plus a fixed "re-scheduling threshold time". The first pair of available slots is given to the delayed flight. If there is no eligible pair, the re-scheduling procedure fails, and slot swapping is tried.
Through slot swapping, the simulation tries to avoid a flight being cancelled by giving it the slot of other less important flight of the same airline. If this strategy also fails the flight and all the other flights in the aircraft rotation will be cancelled.

Input Data: The TREE model is data-driven. This means that the quality of the results and predictions depends on the quality of the input data. The input data are:

- **Nominal capacity of the airports per hour,** extracted from Eurocontrol information. (Airport Corner, DDR2, etc)
- **Performance data with the daily schedule and the primary delays**: Two sources have been used here: CODA data and Flightradar24. CODA data is more complete including the cause of delays, which allows for the separation of primary (inputs to the model) and

reactionary (outputs) delays. However, the number of days of data available was insufficient while Flightradar was accessed via API (with the site permission) and a continuous flow of data was obtained.

- **Passenger connectivity data**: These data were purchased to SABRE. Market sector data is mostly compiled from travel agencies, airlines and booking services. It includes tickets from a certain origin to a certain final destination with middle stops. This information was used to calculate the probability of passengers in a flight to connect to another one.

Validation of the model: In nominal conditions, the model shows high accuracy to predict flights with reactionary delays and congested airports. The validation exercise was performed with one day of CODA data, June 20 2013, and with 140 days of data obtained from Flightradar24 in 2015. Calibrating α around 0 for the model to fit the global congestion level, one can get a notable agreement between the evolution of the reactionary delay in the data and the model predictions (see Figure 1 with α = -0.02).
The next step was to separate the flights in two groups: those with reactionary delay and those with no delay. The flights with primary delay are in the input of the model and were not used for the validation. The model output after 1000 realizations of the stochastic simulation is a probability for every flight to have reactionary delay. The confusion matrix formalism was used comparing the flights with reactionary delay in the data and those with the highest probability of delay in the model. With CODA data, the agreement is good with an accuracy of 0.83 and a precision of 0.56. The same exercise day by day with the Flightradar data renders slightly lower values with an accuracy stable around 0.7 and a precision over 0.5. Furthermore, if the ROC curve formalism with the CODA data is used the area under the curve or AUROC yields 0.71, which is considered a fair result for a stochastic algorithm. Beyond the flights, this operation was repeated for the airports and the probability for them to belong to the largest congested cluster. The results were better, since it is easier to predict the events at a larger scale. The confusion matrix analysis with the CODA data produced an accuracy of 0.9 and a precision of 0.57.
With Flightradar, the accuracy was also stable around 0.9 and the precision fluctuated around 0.5. Finally, the capacity of the model to predict major network congestion (a size of the largest congested cluster of airports over the median of the period) was tested day by day with Flightradar data. The accuracy turned out to be 0.86 and the precision 0.83. All this values prove the validity of the TREE approach and the possibility to overcome data uncertainty by the use of stochastic algorithms for the ATM in the ECAC area.

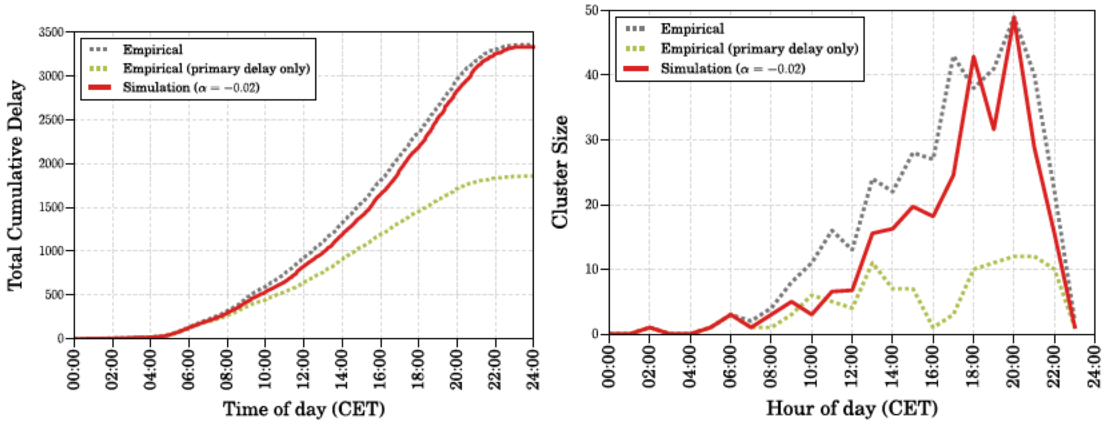

Figure 1 Comparison between model and data for the temporal evolution of the total delay (left) and the size of the largest congested cluster. CODA data for June 20, 2013

Bad weather conditions: The analysis with bad weather reveals the limitations of the TREE model with present mechanisms to simulate the network under severe external disturbances. The model was run with CODA data in the days ranging from January 18 to 21, 2013, in which a major snowstorm affected many airports across Europe including the large hubs in London, Paris, Frankfurt, Munich and Vienna. The overall delay level is well reproduced by the model, but it fails to predict intra-day dynamics as the peaks in congestion observed in the early hours of the day.

Network resilience and weak points: The potential of the model to explore different aspects of the network has also been analyzed. The networks weak points in terms of flights and airports that may impact more strongly the system in case of the delay have been identified and characterized. They correspond to early flights typically run in airports of Scandinavia. The schedule of these flights is normally tight, with very short turnaround times, and their delay can propagate through the main hubs of the continent. In single realizations of the model is possible to visualize directly the trees of reactionary delays that give name to the project (see Figure 2 for examples of trees including the largest in number of affected flights). The picture is similar concerning the airports; the most delicate are those from Scandinavia where these problematic flights are initially operated

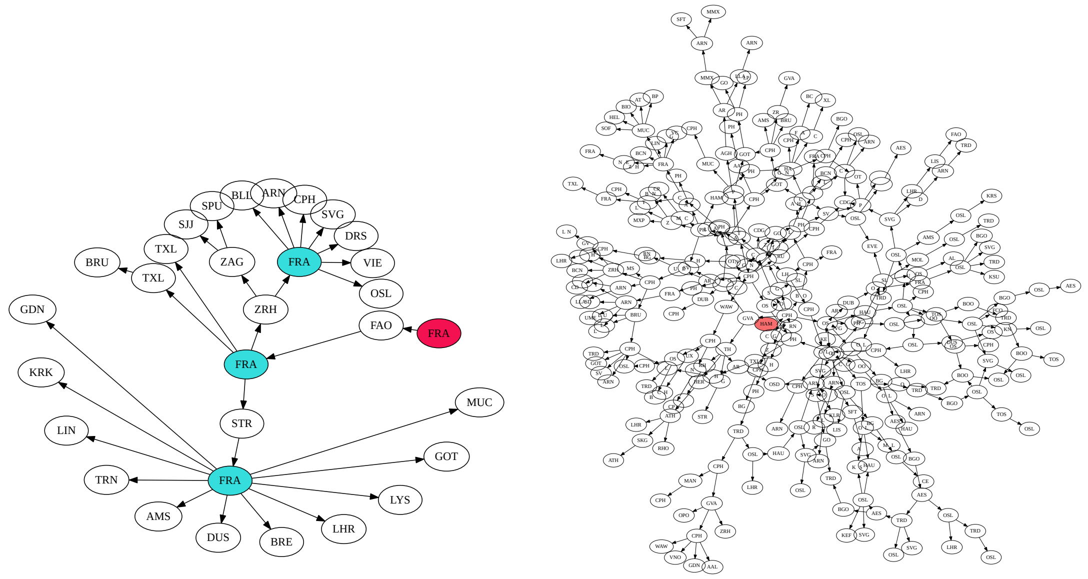

Figure 2 Trees of delay. Every node represents an airport and each link a flight

Beside the network weak points, the model has been used to assess the impact of the out-ECAC traffic in the European network. The impact is high mainly due to the arrival of the intercontinental flights from America early in the morning at the main continental hubs. Generalized delays in these flights may generate large network-wide congestion. The model needs, however, some further adjustment to cope with passenger connections from/to outside ECAC.

Model modifications & what-if scenarios: One of the most delicate model assumptions is the duration of the flights as in schedule. In practice, the pilots may recover some delay on route. This mechanism has been included in the model and its impact on the network-wide congestion tested. The effect was not major but its inclusion may represent an interesting update of the model. Similarly, two different minimum service times in the airports for small and medium size aircrafts, on one hand, and large aircrafts on the other were tested. Since most of the internal traffic in ECAC is carried out with small and medium size aircraft, the effect on these simulations was not relevant.
Finally, the flexibility and capability of the TREE model to analyze what-if scenarios have been tested by considering four cases and running the model on the CODA data of June 20, 2013.

- The first is the reduction of passenger connections guaranteeing only those of first/business class. This has a considerable effect in the delay propagation in the network reducing the total delay in 25%. Of course, implementing this measure has associated important costs but the airlines may want to ponder the implantation of mixed policies waiting for some passengers and not for others.
- The second exercise extends the same idea considering a situation in which only passengers' connections inducing delays lower than a certain threshold of τ minutes would be granted. This policy could have an important impact and the model shows that it is possible to estimate an optimal value of τ searching for a balance between the cost of the delay avoided and that of the missing connections.
- The third scenario refers to a change of business model of a major airline, in this case KLM, which passes from a hub-and-spoke operational configuration to a point-to-point one. The TREE model allows quantifying the impact of this measure for the delay in the full network and for the Skyteam alliance.

- The last scenario contemplates a change in the airport operations that would reduce the minimum service times for aircraft and passengers depending on the arrival flight delay. The TREE model is able to assess the impact of this measure in terms of delay saved with different thresholds Δ. Adding the costs and savings of the different options, it could allow for the search of the optimal value of Δ that could render this policy sustainable.

Conclusions and further lines of research*:* The TREE project has developed a model able to reproduce the propagation of reactionary delay in the ECAC Area and to predict if a flight is going to be delayed or if an airport is going to be congested based on the daily plan. The model is validated and its applications can be of interests to a wide range of stakeholders involved in the area from researchers, to airlines or network managers.

Further research is needed to understand which are the ingredients missing in the model to improve its behavior in the reproduction of extreme cases scenarios. Still the most likely is that the preventive measures applied the day before and during morning by airline and network managers need to be taken into account in an explicit way in order to reproduce the empirical delay patterns.

More features can still be added to the model, as the airspace structure modelling, that will increase the predictability and allow the simulation of a wider range of what if scenarios.

1 Introduction

1.1 Purpose of the document

The purpose of this document is to:

- Summarise the technical results and conclusions of the project (Publishable Summary);
- Provide a complete overview of all deliverables;
- Provide a complete overview of all dissemination activities (past and in progress). Where appropriate, provide feedback from presentations. Describe exploitation plans;
- Provide a complete overview of the billing status, eligible costs, planned and actual effort (incl. an explanation of the discrepancies);
- Analyse the lessons learnt at project level.

1.2 Intended readership

The target readers of the document are:

- Members of SESAR WP-E network “Mastering Complex Systems Safely”, interested in feedback about usability of a modelling approach integrating ideas from complexity science.
- ATM operational researchers and SESAR participants: they will found simulation feedback about innovative strategies potentially contributing to reach performance goals;
- ATM simulation and modelling experts, interested in the state of the art of modelling approaches applied to ATM;
- Complexity Science researchers, since TREE applies an innovative perspective of approaches from complexity to manage the future Air Transport Scenario.
- SESAR Airspace User Group, they will find specific topics/phases where their support is required in the project.
- Airlines traffic forecast units

1.3 Inputs from other projects

This work partially relies on concepts and results of other SESAR projects such Pablo Fleurquin’s PhD work under the Complex World Network. Any other particular source is properly cited across the text, with references listed in Section 7.

1.4 Glossary of terms

N/A

1.5 Acronyms and Terminology

Term	Definition
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CODA	Central Office for Delay Analysis
ECAC	European Civil Aviation Conference
IATA	International Air Transport Association
ICRAT	International Conference on Research in Air Transportation
KLM	Koninklijke Luchtvaart Maatschappij N.V. (Royal Dutch Airlines)
NEWO	emerging NEtwork-Wide Effects of inventive Operational approaches in ATM
SESAR	Single European Sky ATM Research Programme
SID	SESAR Innovation Days
SJU	SESAR Joint Undertaking (Agency of the European Commission)
TREE	Data-driven modelling of the network-wide extension of the Tree of REactionary delays in ECAC area
US	United States
WP	Work Package

2 Technical Project Deliverables

Number	Title	Short Description	Approval status
D1.1	Problem Statement and Conceptual Framework	Definition of the conceptual framework based on both SESAR and TREE modelling approach related concepts.	Approved
D2.1	Modelling Approach and Traffic Data acquisition	Description of modelling mechanisms to be incorporated in the tool, advanced information about previously proposed metrics test and data acquisition and treatment. IATA Data 70000 Euros	Approved
D5.1	Report on Stakeholders (Scientific, ATM community and industry) expectations	Definition of the project Stakeholder needs and expectations about the model, case studies and scenarios to be studied in TREE through a Workshop	Approved
D4.1	Modelling Scenarios and Exercise Plan	Description of the set of Scenarios and exercises plan for each scenario	Approved
D3.1 (part I)	Model Structure and Functionalities	Description of main functionalities and verification and validation activities.	Approved
D3.1 (part II)	Model Structure and Functionalities	Description of main functionalities and verification and validation activities.	Approved
D4.2	Exercise Report	Results gathered from simulation runs together with a preliminary analysis of the results	Approved
D5.2	Report on feedback from Scientific, ATM community and industry	Feedback from ATM community, industry…simulation results will be validated through Expert Group sessions. The aim is to check whether the stakeholder expectations have been fulfilled.	Submitted
D6.1	Final Report on Conclusions and recommendations	Conclusions of the project based on the simulation results and the feedback on ATM and Scientific Community	Submitted

Table 1 - List of Project Deliverables

3 Dissemination Activities

3.1 Presentations/publications at ATM conferences/journals

The dissemination activities under this section have been to date:

- Poster for the Third SESAR Innovations Days (26th November 2013, Stockholm, Sweden), introducing the project, the importance of the reactionary delays and the airlines strategies impact.
- Paper for the International Conference on Research in Air Transportation (ICRAT) (26th May 2014, Istanbul, Turkey), with description of the project motivation, modelling technique, experimental plan and next steps.
- Presentation at the Fourth SESAR Innovations Days (25th November 2014, Madrid, Spain) of the paper "Data-driven modelling of the tree of reactionary delays" [1], describing the modelling approach, as well as the current model development detailing the different connections (aircraft, passengers and crew) and the ATFM Slots Management. A poster was also presented to show preliminary results.
- Presentation at the ATM Seminar (23rd June 2015, Lisbon, Portugal) of the paper "Modelling Delay Propagation Trees for Scheduled Flights" [2], describing all the project since the beginning: motivation, modelling approach, aircraft rotations treatment, connectivity, ATFM Slots management and slot swapping and the results in nominal conditions.
- The SID 2014 paper was selected for further consideration in a Special Issue of the Journal of Air Transport Management. The final article was in set with other one from the UIB: 'Trees of Reactionary Delay: Addressing the Dynamical Robustness of the US Air Transportation Network' [3].
- Presentation at the Fifth SESAR Innovations Days (1st December 2015, Bologna, Italy) of the paper "TREE Model: A Tool to Explore Delay Reduction Scenarios in the ECAC Area" [4], describing the model validation and some simulation scenario results. A poster was also presented to show more scenario results.

3.2 Demonstrations

Two demonstrations sessions with experts have been held over the TREE project.

- In February 2015 a Demonstration Session was held in Palma de Mallorca with the aim of show the tool development, and validates the ATM daily operations modelation. At that point, it was interesting to get the sector experts' opinion about the project, its approach and the next steps. This last point was especially important because some airlines strategies were being selected to be tested. The workshop was structured in 4 parts. The first one was oriented to the presentation of the project, session objectives and TREE model description.

The other three were oriented to show the model capabilities and capture the Experts' opinion.

- During the TREE final dissemination workshop (6th October 2015, Madrid, Spain), some demonstrations of the TREE simulation tool were performed, the first one in nominal conditions and the other were different simulation scenarios. The aim was to provide a hint of the configuration options and the computational speed to the workshop attendees.

3.3 Exploitation plans

The following results and lessons learnt from the project are very valuable outputs that benefit directly the project members or the research community:

- The focussed literature review performed at the initial stages of the project constitutes a structured baseline for further research, not only for topics directly related to TREE scope, but also for more ample research topics like complex systems;
- The set of simulation strategies gathered from the experts over the project life remains useful for future projects;
- The public data treatment remains as a guideline for future projects that would need to deal with this data sources;
- The weight of the passengers connections on the propagation of reactionary delays have been measured and can be used as an input for future projects;
- Simulation results are obviously an indispensable input for future studies exploring network response to some airlines and network manager strategies.
- Finally, the project has allowed deepening into the understanding of the potential of the modelling technique used. The main benefit is the new tool developed for the project members but also for the community that will have access to the conclusions in terms of modelling approach usability. A more accurate awareness of the tool exploitation possibilities paves the way for enlarging the scope of the TREE research in lines such as:
    - React pre-emptively in case of knowing in advance disruptions;
    - Model the air space and take it into account in the delay propagation patterns;
    - Reduce some of the model assumptions and simplifications;
    - Define specific indicators oriented to measure benefits for airlines;
    - Model other operational concepts that are being developed in SESAR projects.

4 Total Eligible Costs

Date	Deliverables on Bill	Contribution for Effort	Contribution for Other Costs (specify)	Status
23/07/2014	D0.1, D1.1, D0.2, D7.1, D2.1, D0.3	74.171,21 €	Travel costs: 877,75 €	Paid
27/08/2015	D0.4, D0.5, D0.6, D0.7, D5.1, D4.1, D3.1 (part I), D7.2	82.314,76 €	Travel costs: 6.999,89 € Data Purchasing: 30.613,07 € Other costs: 112 €	Paid
25/11/2015	D0.8, D0.9, D0.10, D3.1 (part II), D5.2, D7.3	106.826,79 €	Travel costs: 4.118,28 € Other costs: 373,86 €	Submitted
TBD	D0.11, D4.2, D6.1	73.612,24 € (estimated)	Travel costs pending	Not submitted
GRAND TOTAL		336.925 €		

Table 2 - Overview of Billing

Company	Planned man-days	Actual man-days	Total Cost	Total Contribution	Reason for Deviation
ISDEFE	535	869,125	294.250 €	147.125 €	TBC after close-out meeting. Deviations are expected mainly because of the following reasons: • The planned costs per day per engineer are lower than the ones estimated at the beginning of the project; • The initial estimations of man-days were based on the specific number of hours per profile. As the profiles of the engineers has changed during the lifecycle, the number of actual man-days were also changing;
UIB	730	750	189.800 €	189.800 €	TBC after close-out meeting. Deviations are minimal and mostly due to similar reasons as above: • Bruno Campanelli has got extra funding from the Government of the Balearic Islands to pay his salary so part of the effort has gone at zero cost. • More effort than expected was needed for data collection and cleaning. • The initial numbers were an estimation, reaching the promised goals has taken a little more effort than planned, but at the same cost for the project and without significant deviations.
GRAND TOTAL	1265	1619,25	484.050 €	336.925 €	

Table 3 - Overview of Effort and Costs per project participant

5 Project Lessons Learnt

What worked well?
The project established **clear scope and objectives** from the start, ambitious enough given the innovative nature of the project, but not too wide. This, together with planned slots for addressing topics that could arise in the course of the research, provided a good framework for delivering concrete answers and conclusions.
The **suitability of the mesoscopic modelling framework** used for analysing the multi-component air transport network and, in particular, for obtaining straightforward performance results associated to specific prioritisation rules applied to flights.
The establishment of **contact with transport operational experts** (such as airlines, slots managers or airports operators) resulted in realistic inputs to the project, which contributed to fulfil the objective of identifying real strategies to be simulated. Also being able to engage them to the project field of study was very positive in terms of the quality and depth of feedback received.
The **small/ two-company team size**, not requiring great managerial workload, perfectly fitted the project size, objectives and technical challenges.
On the side of **project external supervision**, the level of control was a well-fitted combination of firmness and flexibility, allowing adaption to the unexpected particularities that arise in innovative research projects and to better focus on delivering valuable results. **Continuous and open communication with EUROCONTROL Project Officer**, receiving real-time feedback and suggestions during the project execution, was valuable by itself, and also helped to ensure that the SJU expectations with regard to the project performance were met.
What should be improved?
The main problem within the TREE project has been the **traffic data availability**, the original intention of the project was to simulate one year of operations, finally only one day of data in nominal conditions and four days with extreme disturbances were provided by CODA. That forced the project team to acquire data from public sources with an extra work for data conditioning.
For the particular operational focus of TREE project, the **airlines inputs** would have been very valuable for defining specific strategies to manage delays. But the airlines are not willing to share their own strategies and in consequence, the simulated strategies have been based in high level strategies.
The **connecting passengers' data** are not public and the cost of acquiring them is high. A potential solution for SJU WPE projects would be to acquire these data in a centralised manner so that acquisition costs are reduced and information is better managed.
The **crew rotations' data** are not public and the airlines refuse to share strategic information so that source of delay propagation has finally had a small impact in the model.
The use of TREE webpage as dissemination or communication mean was not satisfactory, neither the LinkedIn group. The trade-off "cost of effort"/ "usefulness" was poor.

Table 4 - Project Lessons Learnt

6 References

[1] A. Arranz, I. Etxebarria, C. Ciruelos, B. Campanelli, P. Fleurquin, V.M. Eguiluz and J. J. Ramasco "Data-driven modelling of the tree of reactionary delays", ISDEFE & IFISC, November 2014, 4th SESAR Innovations Days.

[2] A. Arranz, S. Peces, I. Etxebarria, C. Ciruelos, B. Campanelli, P. Fleurquin, V.M. Eguiluz and J. J. Ramasco, "Modelling Delay Propagation Trees for Scheduled Flights", ISDEFE & IFISC, June 2015, ATM Seminar.

[3] A. Arranz, I. Etxebarria, C. Ciruelos, B. Campanelli, P. Fleurquin, V.M. Eguiluz and J. J. Ramasco, "Trees of Reactionary Delay: Addressing the Dynamical Robustness of the US Air Transportation Network", ISDEFE & IFISC, 2015, Special Issue of the Journal of Air Transport Management.

[4] A. Arranz, C. Ciruelos, B. Campanelli, P. Fleurquin, V.M. Eguiluz and J. J. Ramasco, "TREE Model: A Tool to Explore Delay Reduction Scenarios in the ECAC Area", ISDEFE & IFISC, December 2015, 5th SESAR Innovations Days.

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