Modeling Reactionary Delays in the European Air Transport Network

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***Abstract*—Complex Systems are those in which a very large number of elements interact, usually in a non-linear fashion, producing emergent behaviors that are typically difficult to predict. Air transportation systems fall in this category, with a large number of aircraft following a pre-scheduled program. 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. It has been shown that it is possible to understand and forecast delays propagation in these systems. In the framework of SESAR WP-E TREE project, we have developed a model for characterizing and forecasting the spreading of reactionary delays through the European Network. Our results are preliminary, but show a promising agreement with empirical flight performance data.**

Keywords–Reactionary Delays; Complexity Science; Distruption Management; Network Performance

I. Introduction

Direct costs originated by flight delays amounted in Europe to 1,250 million euros during 2010 according to the European airline delay cost reference values report from the Westminster University [1]. A similar study for the US found that the costs imputable directly or indirectly to delays were around 40,700 million dollars [4]. Understanding how delays propagate in the airport network starting from primary events is thus of high economic relevance. When facing an initial disruption, airline managers try to minimize the impact by getting back on schedule as quickly as possible. Several factors such as cancellations, flight holds, aircraft swaps, crew rotation and passenger connections can influence delay propagation. Since airlines operate in an interconnected network, they are subject to propagation effects. A disruption in one airport can quickly spread and multiply affecting other parts of the air transport network.

Here we introduce a model developed within the framework SESAR WP-E TREE project. The model follows an agent-based approach, with aircraft as basic units, and includes mechanisms for simulating aircraft rotations, passenger connections, slot reallocation and swapping. We have now preliminary simulation results, which show a promising agreement with the flight performance data obtained from CODA.

II. Literature Survey On Delays Propagation

In this survey we focus on works studying delay propagation, both at the level of characterizing the patterns in which delays appear and of investigating the relevant factors. These works can be loosely grouped in two categories: mathematical static studies and modelling and simulation attempts to reproduce flight operations. In both cases, literature is typically focused on the US system, even when the investigation is carried out by European organizations and researchers. Several studies analysed static data to find cause-effect relations between air transport schedules and the reactionary delays distributions in the network. A prolific field of study is the algorithmic optimization of airline schedules where the general objective is to mitigate the spreading of delays. A model developed in [1] produced robust crew schedules, minimizing the crew cost and maximizing the number of move-up crews, i.e. the crews that can potentially be swapped in operations. Algorithmic approaches were also used in [4] for airline scheduling, with focus on maintenance routing constraints, redistribution of existing slack in the planning process and multi-objective optimization respectively. All these theoretical studies showed promising results in reducing propagated delays and improving the robustness of the network. Propagation trees are a useful tool for tracking the propagation originated in a single flight through the network and studying the impact of airline schedules on delay propagation. While pioneering study [7] identified the early reduction of primary delays as a key to control delay propagation, [8] took the tree analysis further, concluding that even with root delays of up to three hours, a large (nearly 40%) fraction of the flights have no propagating effect, and identifying the key buffers limiting the propagation of delays in crews going off-duty, crews and aircraft remaining together (preventing one delay from causing downstream delays to two different flights), and periods of decreased activity in the network. One of the few attempts to analyse European airline planning and traffic data in search of delay propagation patterns was the thesis by Jetzki [9] In the four seasons assessed, results demonstrated that approximately 50% of the delays in low cost operations were reactionary, in the other hand, regular airlines accounts for 40% of reactionary delays and, surprisingly, in point-to-point (charter) operations 45% of the delays were due to reactionary causes. In [10], data mining was performed as a previous step to develop a model that reproduces delay propagation in the USA airport network. The complexity of the mechanisms that produce delay propagation motivates that different modelling techniques were used for modelling delay spreading. One example is [11] where the air traffic system is represented as a network of queues. Using as metric the propagated delay profile per flight and hop at each airport, the proposed model was used to estimate slack and flight time allowance needed to compensate for the root delays at airports and en-route. A strategic departure delay prediction model for a single airport is developed in [12], taking into account the stochastic nature of the air transport network performance. Departure delays are split in three components: seasonal trend, daily propagation pattern and random residuals, addressing in this way the uncertainty in flight's departure time. Complex network theory has been used to assess the propagation of delays in the European air traffic network, describing the system as a graph formed with vertices representing commercial airports and edges direct flights between them. NeCo 2030 project [13] proposed a high level assessment of the behaviour and stability of the highly congested network in 2030. The tool used was a macroscopic model conceived to capture the emergence of network properties such as performance degradation, behaviour predictability, amplified impact of external events and geographical stability. An evolution of the tool was later on used to analyse the impact in terms of network-wide performance and delay propagation of local departure prioritization strategies. After studying a number of innovative departure strategies used in other science domains, the better performance at a global level was obtained with the First Come First Served criterion [14]. As general conclusion, it was proved the suitability of the mesoscopic modelling framework for analysing the multi-component air transport network and, in particular, for obtaining straightforward performance results associated to specific prioritization rules applied to flights. In [15], a stochastic and dynamic queuing model based on the Approximate Network Delays concept (AND-concept) was used to analyse the USA airport network. The macroscopic model computed the propagation of delays within a network of airports, based on scheduled itineraries of individual aircraft and a First Come First Served queuing system for each airport. The metrics were local and of system-wide (propagated) delays over a 24 hour period. The models results were sensitive to different parameters, such as the setting of the slacks in ground turnaround times and promising results were obtained in reproducing trends and behaviours that are observed in practice in the USA system. The impact of disruptions in the air traffic network is inevitable, but the effects on terms of delay propagations depends very much on the strategies the airlines use to face them, [16] offers a good description of the key factors to assess in response to a disruption. Finally, [17] motivated and explored an approach based on metrics focused on passengers rather than aircraft.

III. Model Description

A. *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, accounting for airport capacities, monthly passenger connectivity patterns and flight schedules with their primary delays. At the time of writing, although all the functionalities described below have been implemented, not all such data is available to us; therefore, we only present preliminary results in section IV. We expect to be able to improve on such results in the following months as the data become available. Flight schedules will be provided by the Central Office for Delay Analysis (CODA) of EUROCONTROL [18] and Flightradar24.com [19] could be used as an alternative data source, while passenger connectivity data have been recently purchased from Sabre [20] and are being analysed at the time of writing. It is possible to obtain airport capacities from empirical data, e.g. from the EUROCONTROL Public Airport Corner website [21] or the DDR2 data repository [22]. For the preliminary results shown below and for timings sake, we estimated the capacities using the number of scheduled movements per hour (see section IV for details) multiplied by a factor 1.5. We recognize that this preliminary approach is likely oversimplified and it will be improved in future versions of the model. Simulating more problematic scenarios will require the use of empirical capacity values. For instance, in case of airports using separate runways for arrivals and departures, separate capacities must be used in the simulations.

One run of the simulation consists of processing a queue of events, which can be of two types; the first requires a flight to be processed to deal with its delay (if it has any), while the second models the reaction of the system to an external perturbation. The events are processed in chronological order, with the scheduled departure time being used to sort flights. When a flight is being processed, the proper actions to take are determined according to its state. If it has no delay, no measure is necessary, i.e. the flight will depart and land as scheduled. If the flight is delayed, but still able to depart and arrive within its currently assigned ATFM slots, delay needs to be propagated to the next leg in the aircrafts rotation and the passenger/crew connections (if any). Through this process, the affected connections may accumulate enough delay to miss their slots - for simplicity, we assume that slots are always assigned or lost in pairs. Aside from reactionary delays, a flight might also lose its slots because of its primary delay. When a flight that has lost its slots is processed, the simulation tries to find a new suitable pair of slots (first through re-scheduling, then through slot swapping), which also may cause delay to be propagated. If the process fails, the flight and all the successive legs in the same aircrafts rotation are cancelled.

Two further simplifying assumptions must be noted here:

- flight duration is fixed, and equal to the scheduled duration of the flight found in the data (from scheduled off-block time to scheduled in-block time), so that it is not possible to recover delay en-route. This is likely to introduce an overestimation of delays, but since flights within the ECAC area dont have long durations, as compared to e.g. intercontinental flights, we expect the impact of this assumption to be modest.
- A flight cannot affect other flights scheduled to depart before it.

At the end of each simulation run, the final state of each flight is returned as output, including whether it was re-scheduled or cancelled, its amount of reactionary delay, and the flights to which it has propagated delay. From this, macroscopic quantities such as the daily distribution of delays or the temporal evolution of the cluster of congested airports can be calculated.

B. Flight Connectivity

Aircraft connectivity is the most basic kind of connectivity: if the actual arrival time of the previous flight in the same rotation (increased by a minimum fixed amount to account for aircraft servicing) is higher than the next flights scheduled departure time, the latter will have to be delayed so that the two times are equal. This connectivity is entirely determined by and intrinsic to the flight schedules, so unlike the other kinds cannot be turned off in the simulations. The minimum servicing time is a simulation parameter and is considered the same for all aircraft. Further developments of the model could include different minimum servicing times, dependent by airline policies and aircraft types. The latter information can, for example, be obtained from DDR2.

For the other kinds of connectivity, connections are established randomly at the beginning of each simulation run between eligible pairs of flights, i.e. pair of flights $\mathbf{F}$, $\mathbf{G}$ such that $\mathbf{F}$ and $\mathbf{G}$ are not served by the same aircraft (otherwise there would automatically be a tail connection), the origin of $\mathbf{G}$ coincides with the destination of $\mathbf{F}$, and the scheduled departure of $\mathbf{G}$ falls in a time window starting at $t_{\mathbf{A}} + T_{\text{trans}}$ and ending in $t_{\mathbf{A}} + T_{\text{C}}$, where $t_{\mathbf{A}}$ is the scheduled arrival time of $\mathbf{F}$, T_{trans} is the minimum buffer time that must pass between one flight and the other to allow the eventual transfer of passenger or crew members, and $T_{\mathbf{C}}$ is the horizon time for allowing connections between flights; each of these two parameters has a single value for all flight pairs.

Passenger connectivity data include the monthly number of passengers and flights between any pair $\boldsymbol{i}$, $\boldsymbol{j}$ of airports for each airline, as well as the number of passengers who connect to further flights in $\boldsymbol{j}$ and to which flights they connect. We take the monthly fractions of passengers remaining at $\boldsymbol{j}$ or connecting to extra flights as the probabilities of a stochastic multinomial process - the average number of incoming passengers determining the number of extractions - which outputs the number of passengers remaining in $\boldsymbol{j}$, the connections of those who continue to travel and how many of them follow each connection - this process is necessary since the connections change from day to day.

Crew connectivity is related to which airports are the hubs of the different airlines. Such information can be partially acquired using market sector data as a proxy: if $\phi_{\boldsymbol{jA}}$ is the fraction of passengers travelling with airline $\boldsymbol{A}$ and connecting to further flights in $\boldsymbol{j}$, then $\phi_{\boldsymbol{jA}}$ is different from zero if and only if $\boldsymbol{j}$ is a hub of $\boldsymbol{A}$. We assume that crew connectivity $c_{\boldsymbol{jA}}$, i.e. the probability that two flights owned by $\boldsymbol{A}$ and eligible for connection in $\boldsymbol{j}$ are actually connected, is given by $c_{\boldsymbol{jA}} = \alpha\phi_{\boldsymbol{jA}}$, where α is an effective parameter to be calibrated by comparing the model's output with empirical data. All the flights must wait for all of their connections, regardless of the impact on the airline.

C. Re-scheduling

When processing a flight $\mathbf{F}$ that lost its ATFM slots, the simulation first tries to negotiate with the departure and arrival airports a new pair of slots. $\mathbf{F}$ has a proposed departure time, given by the earliest time at which, having waited for all the other flights to which it is connected and dealt with its own primary delay, $\mathbf{F}$ can depart. Note that it is assumed that a delayed flight will depart as soon as possible, i.e. unlike normal on-time flights where the slot goes from -5 to 10 minutes after the scheduled departure time, in reallocated slots the departure is established at the first minute of the new slot. 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 flights scheduled departure plus a fixed re-scheduling threshold time parameter $T_{\boldsymbol{R}}$, taken to be equal across all flights, and a pair can only

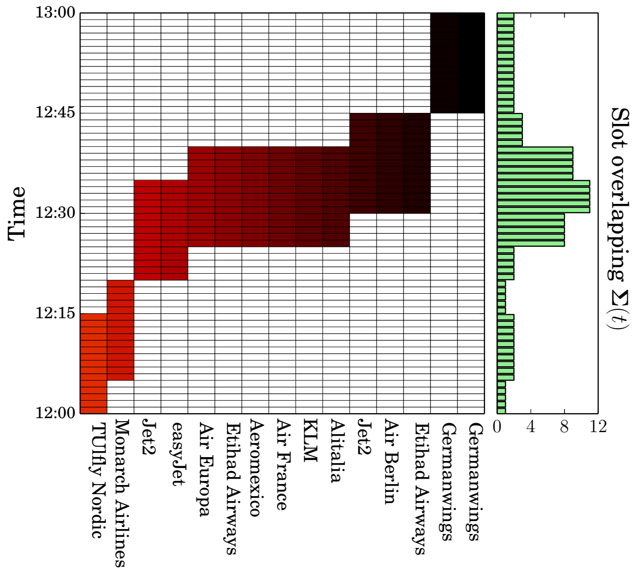

Fig. 1. Example of slot overlapping. Departure slots at PMI airport on the 14th of September 2014, data from FlightRadar24.com.

be assigned if there is available capacity in both origin and destinations airports at the corresponding times. Each possible pair partially or totally overlaps with other slots used by other flights (Figure 1), the chosen pair being the one minimizing $\Sigma(t_b) = \Sigma_{\boldsymbol{O}}(t_b)+\Sigma_{\boldsymbol{D}}(t_b+t_{\text{trav}})$, where t_b is the time at which the departure slot begins, t_{trav} is the duration of the flight being re-scheduled and $\Sigma_{\boldsymbol{O}/\boldsymbol{D}}(t)$ is the number of overlapping slots at origin/destination in the time window $[t, t+15\,\text{min})$; in case multiple pairs have the same $\Sigma(t_b)$, the one with the smaller t_b is selected. If there is no eligible pair, the re-scheduling procedure fails, and slot swapping is tried.

D. Slot Swapping

Through slot swapping, the simulation tries to avoid a flight $\mathbf{F}$ with origin $\boldsymbol{o}$ and destination d being further delayed or cancelled, at the expense of another flight $\mathbf{G}$ belonging to the same airline $\mathbf{A}$, either scheduled to depart from $\boldsymbol{o}$ or to arrive in $\boldsymbol{d}$, and deemed less important than $\mathbf{F}$. As a proxy of the importance of flights, we use the sum of the total daily movements (departures and arrivals) of their origin and destination airports (other information, such as the number of passenger or the average ticket price for each flight, could conceivably be used). The simulation examines the possible arrival/departure slot pairs that could be obtained by requesting a new slot in either $\boldsymbol{o}$ or $\boldsymbol{d}$ and repurposing a matching, already existing slot, currently used by $\mathbf{G}$, in the other airport. The new slots clearly cannot be both newly created, otherwise the re-scheduling would have not failed and there would be no need for swapping. $\mathbf{G}$, which must have smaller importance than $\mathbf{F}$, cannot be already departed at the moment $\mathbf{F}$ is being processed and will be left without slots at the end of the process. Pairs of slots acquired through swapping have temporal restrictions similar to the ones used for flight re-scheduling: the new slot cannot begin after the scheduled departure time of the flight plus a threshold time T_{S}, and the flight cannot be anticipated or shortened in order to get new slots. The pair with the earliest hour of departure is then chosen, and if multiple pairs have the same departure hour, one is chosen randomly with probability inversely proportional to the importance of $\mathbf{G}$. In case neither of the airports have available capacity, $\mathbf{F}$ is cancelled. Note that the model does not allow airlines to obtain new slots for one flight by taking them from two other flights, one departing from $\boldsymbol{o}$ and the other arriving at $\boldsymbol{d}$. Furthermore, as a consequence of our definition of importance, it is not possible for $\mathbf{F}$ to swap slots with another flight with the same origin and destination, since their importance will be the same.

E. External Perturbations

Different kinds of external perturbations clearly must be modelled taking their peculiar features into account: for example, a technical failure or terrorist attack cannot be anticipated, but a strike can. Our first attempt to tackle the problem is to model weather perturbations simply as reductions in capacity in the affected airports, following the same approach taken in [10] (see section V for future plans of simulating other kinds of perturbation). For simplicity, the following assumptions are made:

- perturbations are only allowed to start and end at the beginning of an hour,
- the system cannot react pre-emptively to the perturbation, and
- the system has no knowledge on when the perturbation will end.

When a perturbation event is processed, the affected airports will experiment a reduction in their capacity for the next hours. As long as their reduced capacities are enough to support the movements that should take place in the following hour, operations proceed as usual. If the capacities are not enough, excess flights are postponed to the next hour and labelled as urgent, with the exception of aircraft already flying and scheduled to land during the hour, which are allowed to land even if there is not enough arrival capacity. Note that for simplicity the model does not include aircraft re-routing. The postponed flights are treated differently depending on whether they are supposed to arrive to or depart from the affected airport. Urgent departing flights are given precedence over non-urgent flights and allowed to depart as soon as possible, with the constraints that departure rate cannot exceed the maximum hourly departure rate allowed by the reduced capacity (precedence is given to flights with earlier scheduled departure), and capacity must be available at their destination airports. In the case of arriving flights that have not departed yet at the beginning of the perturbation, the situation is different since the system cannot know if the perturbation will still be affecting their destinations by the time they are scheduled to arrive. Their new arrival times are therefore still assigned by passing everything that does not fit into an hour to the next hour and allowing arrivals of urgent flights according to the maximum hourly arrival rate, but under the assumption that the perturbation will last indefinitely. This process continues until the perturbation is over, i.e. the capacity reduction has ended at the beginning of the hour, and the system has recovered, i.e. there are no urgent flights coming from previous hours. Note that flights that obtain new departure/arrival times due to capacity reductions still propagate delay to their connections and are cancelled if they can only get a new departure time beyond their re-scheduling threshold.

IV. Preliminary Results

Presently, we only have at our disposal five days of data, which were sent to us by CODA. One of these, the 20th of June 2013, is the day with the highest average delay among the days for which we couldnt find any information regarding external problems such as bad weather or strikes. This kind of information can be retrieved from sources such as newspapers websites and the monthly reports published by CODA, although the latter do not provide a day-by-day analysis. Normal operations days can be used to validate the model in the absence of perturbation events. Obviously, our inability to find any news record stating that there were problems suggests but does not guarantee that there were

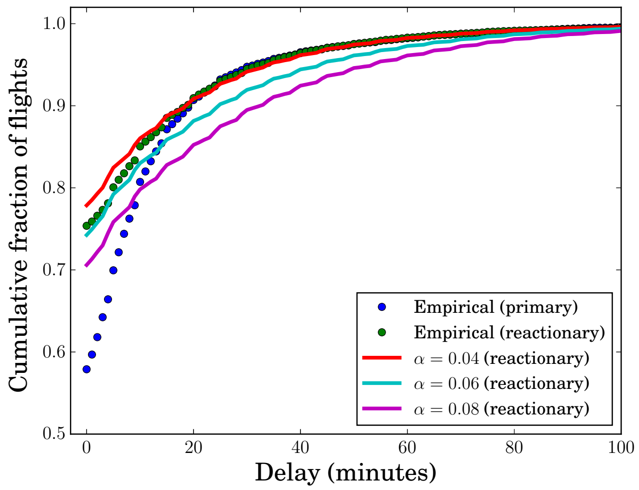

Fig. 2. Cumulative distribution of reactionary delays for the 20th of June 2013.

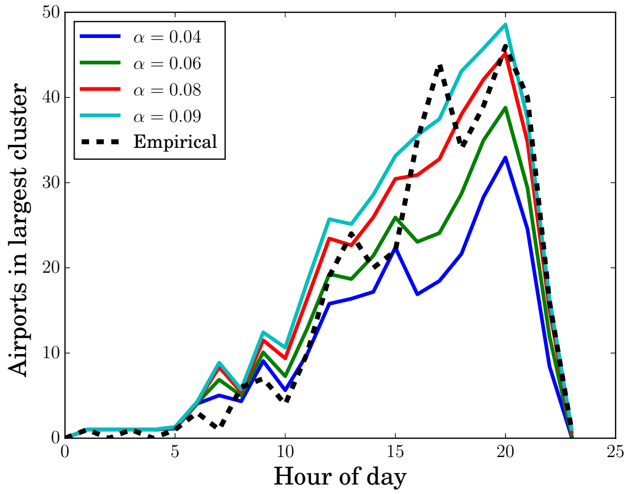

Fig. 3. Temporal evolution of the cluster of congested airports for the 20th of June 2013.

actually no problems; from the results shown in [10], however, we expect finite airport capacities to only be relevant for the propagation of delay when the system is operating with severe capacity reductions. We can then validate our hypothesis a posteriori by looking for qualitative differences between the behaviours of the real system and of the simulated one. We cannot yet run simulations for the system with bad weather conditions, since a single day is not enough to validate the model in the baseline scenario. For the connectivity, since the process of acquiring and analysing passenger connectivity data is not yet complete, here we use a simpler mechanism, where each pair of flights eligible for connection (as defined in section III) is connected with probability α', to be determined by searching for the value resulting in the best agreement between model output and empirical data; this is the same approach used in [10].

The data for the 20th of June 2013 contain 15,721 flights internal to the ECAC area that are used for the simulations. The sum of all the reactionary delays found in the data is 1,490.3 hours, the same order of magnitude of the sum of primary delays (1,828.6 hours). The results shown are obtained by averaging over 1,000 simulation runs and with the parameter values T_C, T_R and T_S equal to three hours. Figure 2 shows the cumulative distribution of reactionary delays found in the empirical data and the one from the simulations using several values of α', among which 0,04 produces the distribution closest to the empirical one. Figure 3 shows the temporal evolution, hour by hour, of the size of the largest cluster of congested airports. Here we define an airport as congested if the average delay of all the flights departing from it in a certain period of time is larger than the average departure delay per delayed flight over all the year 2013 in Europe, which is reported to be 26.7 minutes [23]. Two airports are in the same congested cluster if they are both congested and there is one path in the airport network that goes from one to the other without passing through uncongested airports. As can be seen in the figure, the qualitative features of the clusters evolution, such as the position of the maximum and the asymmetric shape, are correctly reproduced, even if there is room for improvement from the quantitative point of view. Note that the value of α' producing the correct maximum size, 0.08, is not the same best value for the distribution of delays. This is likely due to the use of uniformly random connections, and we believe it will improve once the actual connectivity coefficients based on passenger data will be available.

V. Simulation Scenarios

TREE simulation strategy will drive the model through different scenarios in order to gain proximity to the real network behaviour and establish a baseline scenario to adjust the customizable parameters. Thus, the overall simulation strategy involves three phases:

- *Phase I: Reproduction of Nominal Conditions.* The main goal is to assure the models capability to recreate scenarios under a set of initial conditions or primary delays caused by internal disturbances. It will be used to validate all the hypothesis and assumptions made at the development phase and to fine tuning the simulation parameters.
- *Phase II: Reproduction of extreme cases-scenarios.* The impact due to the occurrence of three different types of external perturbations will be analysed in this phase:
  - *Bad Weather Conditions*: As explained in E, the perturbation is modelled by decreasing the airport capacities in a set of airports.
  - *Strikes*: Three types of scenarios will be tested: *Air traffic controllers' strikes*, implemented reducing the capacity in the affected areas. *Airport staff strikes*, modelled increasing the minimum turnaround time in the affected airports and *Pilots' strikes*, implemented modifying the crew connectivity parameter.

- *Technical Problems*: Two different scenarios are considered, *Technical problems in the air control facility*, reducing the capacity of the affected airports and increasing the flight duration of the over-flights, and *Single aircraft technical problems* (on the runway or in the platform), modelled reducing the capacity of the airport.

- *Phase III: "What-if" case studies*. This phase aims at gaining insight on the system resilience and probing and assessing the effectiveness of alternative airlines strategies to mitigate or suppress delay propagation.

TREE modelling and simulation capabilities will allow airlines to evaluate the daily planning performance and analyse the impact of specific strategies on the propagated delay mitigation. The network and airport manager will assess what the effects of the chosen strategy are at global and local level. The program allows us to compare two schedules for the same daily operations. Essentially, it is run with the same initial conditions for both and the total minutes of delay, the number of delayed flights, the number of affected airports, or any other global performance metric can be directly compared. This fact introduces even the possibility to improve the schedules by changing the aircraft rotations one by one and analyzing the results. Similarly, two crew rotation strategies can be compared or even two slot management strategies in terms of flight prioritization with minimum changes into the model. For instance, instead of following a strategy in which a delayed flight first searches for a new slot and only after for a swapping, another mechanism in which the swapping is favored could be easily implemented.

VI. Conclusion

In summary, we have introduced a model to simulate the propagation of reactionary delays in the ECAC area. The model comprehends aircraft rotation, passenger connectivity and airport congestion as well as crew rotation, and is specifically focused on the European network, including mechanisms for ATFM slot reallocation and swapping. We have already run preliminary simulations, showing a promising agreement with the delay propagation patterns of the CODA flight performance data. The model will be subsequently improved and systematically validated. After first phase, simulations will allow different actors testing different strategies giving highly valuable support in problem solving processes, such as airline disruption management.

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