Multimodal air-rail simulation model for evaluation of tactical disruptions

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Abstract

Efficient cooperation between transport stakeholders (airlines, rail and airport operators) is essential for improved multimodal journey times and passenger experience during disruptions. There is a need for a platform where solutions for managing these disruptions can be evaluated.

This paper presents the extension of Mercury, a detailed air transport agent-based model, to include rail network modelling capabilities, enabling the evaluation of multimodal itineraries. New agents are introduced to simulate train operations (arrivals, departures), to handle multimodal transfers, to represent airport processes, and to rebook passengers when connections are missed. By modelling transfer times between train stations to airports' gates, solutions, such as expedited airport processes (e.g. security) for delayed passengers, can be evaluated.

Due to the buffers on multimodal itineraries, even in the case of disruptions, many missed connections are caused by just a few minutes. In this context, prioritising delayed passengers in airport processes is expected to reduce missed connections and total experienced delays significantly. Furthermore, an effective multimodal rebooking capability can replace missed flights with trains and vice versa, reducing the number of passengers stranded.

The new simulation platform is a multimodal modelling and evaluation tool that comprehensively describes the impact of multimodal solutions for delay mitigation. The paper also demonstrates how external tools would be integrated into Mercury in future, taking advantage of the existing models such as airport terminal simulation or journey planner for a more detailed simulation.

Keywords

Agent-based model, multimodal air-rail transport, performance assessment, delay management mechanism, passengers

I. INTRODUCTION

Multimodality is considered one of the key elements for creating an efficient and interconnected transport system within Europe that can help to achieve the goals of the Paris Climate Agreement [1]. The cooperation of individual transport modes is crucial for the overall system's performance, especially during disruptions. However, the current research lacks platforms for evaluating multimodal system performance, particularly disruption management solutions.

In this study, we extend the Mercury simulator platform [2], [3], which features a detailed description of the air transportation system at the European level, including passengers, aircraft, and various important actors such as the Network Manager, airports, etc. Mercury has been applied to evaluate a range of air traffic management (ATM) solutions, such as consideration of network-level interactions [4], analysis of emergent behaviour on delay management [5], and the analysis of User Driven Prioritisation Process concepts [6].

In this study, we exploit Mercury's agent-based simulation paradigm to add new agents to achieve multimodal capabilities. The new agents model train operations (arrivals, departures), passengers' journeys between the train stations and the airports during multimodal transfers, and the airport processes. This enables Mercury to simulate multimodal passengers' itineraries.

The modularity of Mercury is used to modify the behaviour of airports to expedite delayed passengers from their arrival to the airport to the departing gate (*Fast Security Check-Point* for passengers processing, as in [7]. Together with the rebooking process in case of missed connections, these mechanisms mitigate the impact of disruptions.

The extended Mercury provides a performance assessment tool that is usable early in the innovation pipeline to better estimate the impact of new changes to the air transportation system, particularly with a combination of other transport modes.

This article presents the extension of Mercury to account for these multimodal itineraries and how the disruption management mechanism can be integrated for its evaluation in the platform as a *module*, directly modifying the behaviour of some agents in the platform, or as an *external system*. A case study in Madrid-Barajas airport is presented. A two-and-half-hour flight ban in Spain is assumed, with passengers' itineraries modified to use rail alternatives in multimodal itineraries when required. Disruptions on the ground mobility are modelled to assess the benefits of the *Fast Security Check-Point* disruption mechanism, focusing on passengers' metrics.

The paper is structured as follows: Section II presents the background on disruption management tools and Mercury; Section III describes the architecture for the extension of Mercury Agent-Based Model (ABM) to enable the modelling of multimodal passengers' itineraries and how new mechanisms can be integrated into the platform for their evaluation; and Section IV presents the case study simulated in this article.

II. BACKGROUND

This article considers the impact of disruptions and how resources can be used to minimise their impact on multimodal passengers' itineraries. Different *mechanisms* are currently used or have been previously researched in this context; Section II-A summarises some of these. As previously stated, the current article extends the capabilities of the Mercury model; Section II-B presents the required background on the air transport mobility model.

A. Previous research on disruption management

The focus of this research is the evaluation of mechanisms for the management of disruptions on the day of operations. Therefore, strategic actions, such as robust scheduling, are out of the scope of this review.

Different mechanisms are currently used and reported in previous studies for managing disruption in the air and rail transport systems with a focus on minimising the impact on passengers. The review below briefly describes some of the main actions that could be performed in the air system and compares them with their rail counterpart. Multimodal disruption mechanisms (that consider multimodal itineraries) are also briefly presented.

This list of air disruption management mechanisms builds upon [8]–[10]. A comprehensive review of rail disruption management approaches can be found in [11]–[14]:

1) *Actively delaying flights*. Flights are delayed to wait for connecting passengers. Similar activities can be performed with trains by rescheduling a vehicle's timetable (or part of it).
2) *Cancelling flights*. During recovery, if the allocated resources to carry out a flight are not feasible, or if the flight can take place but the expected delays (and costs) are too high, the flight can be cancelled. This can also facilitate reallocating resources (fleet) to manage network-wide disruptions. Rail operators also use this mechanism when dealing with significant disruptions in the network.
3) *Rerouting*. An alternative route could be used if a flight is delayed due to airspace congestion. This might, however, impact the arrival time, as longer routes might translate into some arrival delay. In the rail system, rail operators can also consider rerouting a service and finding alternative paths when the infrastructure is congested or unavailable.
4) *Swapping resources*. When aircraft or crew members are not ready for the next flight, other aircraft or crew in the same airport can substitute for the original ones to carry out the flight. The recovered aircraft or crew is then reallocated to other flights. The rail system uses *vehicle reassignment* when faced with similar issues.
5) *Using reserved resources (aircraft and crew)*. Reserved resources are available in airports and do not perform any flight tasks.
6) *Deadheading and ferrying*. This mechanism is a repositioning of resources. Deadheading means the crew is transported to another airport as passengers, whereas ferrying means an aircraft is assigned to an unscheduled flight without passengers. Given the high costs incurred by these operations, they are rarely adopted.
7) *Speed controlling / Trajectory updating*. Various studies have recently addressed speed controlling as a recovery operation that modifies the flight time to reduce the impact of a disruption and its corresponding delay. This can be done jointly with *rerouting*.
8) *Passenger reallocation*. If itineraries are disrupted, passengers can be reallocated to itineraries with the same origin and destination. Rail passengers tend to have more freedom to choose their service; however, in some cases, rail operators can provide similar services.
9) *Enhancing ATM system – airspace*. Congestion in the network can lead to delays. The Air Navigation Service Providers might be able to provide extra capacity to minimise the need for Air Traffic Flow Management (ATFM) regulations and their associated delays.
10) *Enhancing ATM system – airport*. Both land and airside processes can be improved by managing the available resources. For example, with fast turnaround operations, optimisation of gate allocation to ensure connections, or managing check-in and security resources to expedite delayed passengers arriving at the airport. Rail operators can also optimise the rail station resources, for example, by assigning different platforms to trains (replatforming).

Most studies consider the optimisation problem from an airline operating centre (AOC) point of view. They try to recover the disruption by modifying individual flights within the airline fleet (using mechanisms 1-7). Crew assignment and passenger reallocation are included in the optimisation scope of the crew and passenger recovery problems, respectively.

When optimising the air transportation system, research also considers how to manage the ATM resources optimally, for example, modelling ATFM slot swapping and sequencing [15]–[17].

Considering the airport processes on the management of disruption, most studies consider airport constraints such as simultaneous numbers of take-offs and landings or time windows for airports [10]. The airport resources, such as ground operations assignment, are decision variables in [18].

In addition to the previously indicated mechanisms, rail operators also consider additional mechanisms such as *reordering*, where trains are swapped on their use of the infrastructure, *short-turning* and *stop-skipping*, where either some stops are not served to expedite the service or the rail service finishes before reaching their final destination.

There is a small amount of literature on disruption management of multimodal air-rail systems. Most studies focus on integrated passenger reallocation considering multiple modes (e.g. air to rail) in case of disruptions [19]–[22]. Improved information sharing to passengers [23] and collaborative decision making [24] are also employed. The work presented in [25] shows how actively delaying flights can be used to minimise multimodal rail-air passengers' missed connections in the event of rail disruption.

Previous research has also shown how landside airport processes (e.g. security check allocation) can play an important role in managing delayed passengers in a multimodal environment, e.g. when passengers arriving at the airport are delayed on their rail journey [7].

Regarding the solution methodology used for minimising disruption, most studies adopt exact, heuristic or hybrid methods to solve the optimisation problem in a centralised way. In contrast, Multi-Agent Systems (MAS) is an emerging approach in airline disruption management employing distributed optimisation with multiple interacting intelligent agents. Examples of MAS include [26]–[29].

B. Mercury: An Agent-Based Model for air transport mobility

Evaluating the performance of a complex system like air transport is a challenging task. Uncertainty, disruptions, and the interaction of many actors drive the system's performance. Agent-based modelling (ABM) can tackle these types of systems. In these types of platforms, the decisions of each agent (element in the system) can be modelled individually with relatively simple rules.

The open-source Mercury simulator has been developed with these considerations over different research projects to estimate flight-centric and passenger-centric indicators [2], [3]. Mercury incorporates the processes and behaviours of actors in air transport. The model has successfully been applied to a range of problems, such as the evaluation KPIs at the European level [30], assessment of SESAR Solutions [4], or the analysis of ATFM slot management with SESAR mechanisms [6].

The event-driven approach of Mercury, with events associated with flight milestones, such as 'Push-back' or 'Flight arrival' times, enables a fast-time simulation of a day of operations in the whole of the ECAC[1] region in a few minutes.

Mercury models the main activities performed in the system as *roles* with interactions between them. These are then grouped into *agents*; this process was guided by existing entities in the ATM domain, where naming and representation would refer to a coherent actor/entity (such as the Airline Operating Centre (AOC)).

The following agents are represented in Mercury (also depicted in Fig. 2):

- 'Airline Operating Centre' (AOC): They are tasked with the reassignment of passengers to flights if they need to be reallocated due to missed connections and with the airline's fleet management (i.e., dispatching processes), including the selection of flight plans, flight cancellations and flight plan adjustments.
- 'Flight': Represent the flight along its operations: ground and air movement. These agents also capture the actions performed by the crew, such as requesting a departing slot.
- 'DMAN' and 'E-AMAN': Each airport has associated 'DMAN' and 'E-AMAN' agents to manage the departure and arrival queue of slots needed to respect the runway capacities.
- 'Radar': This agent broadcasts the flight position to all other interested agents.
- 'Network Manager': There is a 'Network Manager' agent per simulation with a simplified view of the European airspace and ATFM restrictions.
- 'Ground Airport': These agents process arriving passengers (computing the actual transfer time between flights in the terminals) and the arrival of flights (providing estimated and actual turnaround times). In the implementation used in this article, this agent has been divided into 'Airport Operating Centre' (APOC) with the airside operations (turnaround processes) and 'Airport Terminal', which, besides the connecting times between flights, also models the access and egress processes.

The Mercury's agents react to events triggered by other agents or the environment. An agent might require interaction with others in a message-driven approach.

It is worth noticing that passengers are represented by passengers' groups with the information on their planned itinerary, i.e., flight(s) that are planned by that group. These are processed by the different agents in the system as needed, e.g., the AOC will rebook the passengers into alternative flights if connections are missed.

Mercury can evaluate ATM Solutions by modifying the behaviour of the system's elements. This is achieved either by modifying the functionalities within agents' roles using *modules*, or connecting Mercury with external systems by redirecting the inter-agents messages to an external interface (currently under development).

[1] European Civil Aviation Conference, which encompasses 44 Member States.

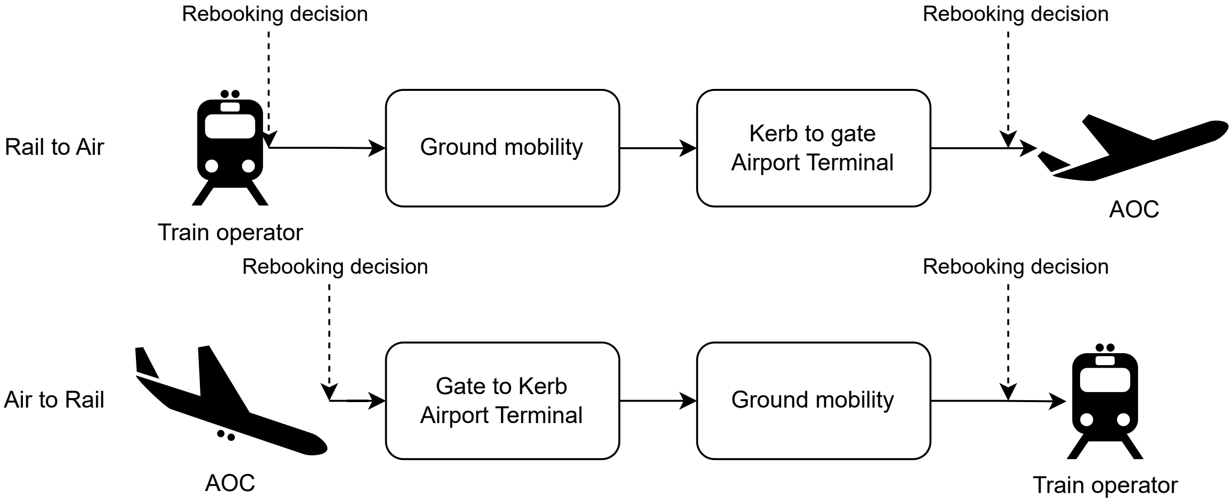

Fig. 1: Multimodal processes.

III. MODELLING APPROACH

A. Multimodal passengers itineraries and processing

This study considers two types of multimodal itineraries: 1) rail to air and 2) air to rail. Monomodal connections from air to air are already part of Mercury. Monomodal connections from rail to rail are out of the scope of this study. It should be noted that other types of connections, such as rail to air to rail, etc., are possible by chaining the before-mentioned types.

Following the approach described in [31], passengers' itineraries are divided into differentiated processes to build the full multimodal journey. For example, a rail-to-air multimodal trip can be model by concatenating the platform-to-platform, platform-to-kerb, kerb-to-gate, and gate-to-gate processes.

Fig. 1 represents the flow of a passenger for the two types of multimodal journeys considered. The rail-to-air flow starts with deboarding the train by the train. Next, the passenger moves from the rail station to the airport terminal by ground mobility. In the airport terminal, the passenger travels from kerb-to-gate while going through baggage drop, airport security, etc. Finally, the passenger is boarded to the aircraft. The air-to-rail flow is similar to rail-to-air flow, with processes in reverse order. Gate-to-kerb in the airport terminal consists of collecting the baggage, immigration, passport control, etc.

There are two rebooking decision locations in each flow. The first rebooking decision is considered after deboarding the train or the flight. The passengers can change their remaining leg in case of an anticipated missed connection before commencing the journey to the next multimodal leg. The second decision point is after arriving at the rail station/airport. The passengers can change their legs, i.e., be rebooked for a different service, if they miss a connection.

B. Mercury evolution for multimodality

Some agents have been modified and others added to Mercury to enable the simulation of the multimodal journeys previously described. Fig. 2 shows the acquaintances (connections) between agent types derived from interactions between their underlying roles. The newly added multimodal agents are highlighted on the right. As can be seen from the graph, the Passenger handler agent has a central position on multimodality, facilitating most of the interactions between other agents. Next, we describe the new agents and multimodal roles incorporated into Mercury.

1) Airline Operating Centre: The AOC considers multimodal passengers to be like any other passengers. For passengers who missed an air connection but are already at the airport, a reallocation process to the next flight is triggered based on itineraries, aircraft space, and fares.

2) Airport terminal: The 'Airport Terminal' agent captures the processes of passengers within the airport. For passengers connecting air-to-air, the agent provides connecting times between gates. For multimodal passengers, the agent provides kerb-to-gate (baggage drop, airport security) and gate-to-kerb processes (baggage collection, immigration) for rail-to-air and air-to-rail passengers, respectively. These processes are modelled as probabilistic distributions.

3) Passenger handler: The 'Passenger Handler' agent represents the decision processes of a passenger. From an architectural point of view, there is only a single passenger handler agent in the simulation that manages passenger groups. Passenger groups are modelled as simple placeholders which contain information on the passenger itineraries and their characteristics. The passenger handler agent moves the passenger groups through different processes facilitated by other agents during the rail-to-air or air-to-rail connection.

As mentioned above, there are two rebooking decision locations: 1) after deboarding the train/aircraft of the first leg and 2) before boarding the train/aircraft of the next leg. In the first case, the passenger handler agent collects the estimated ground

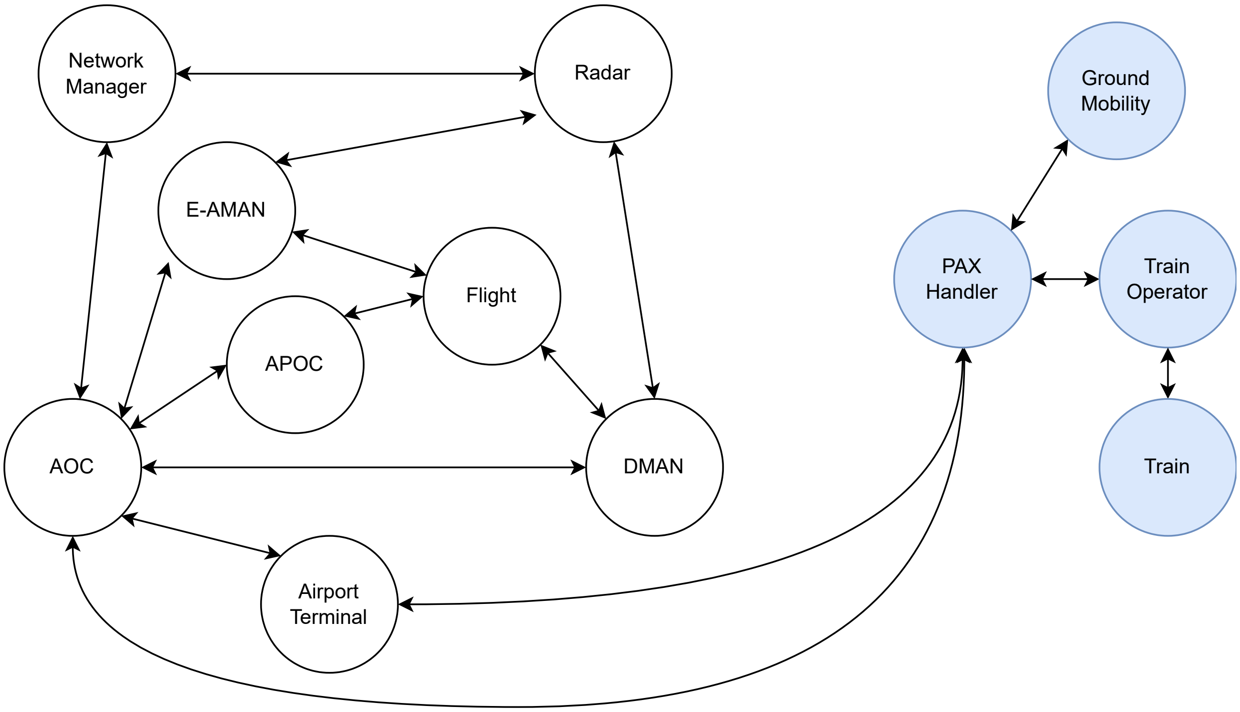

Fig. 2: Acquaintances between agent types, derived from interactions between their underlying roles.

mobility and kerb-to-gate times, together with the estimated departure time of the next leg. The rebooking process is triggered if a passenger is likely to miss the connection (based on estimated times). This way, the passengers can change their itinerary based on the actual situation, considering the estimated delay. The rebooking process involves finding the next available flights/trains for the remaining part of the itinerary. In this study, the rebooking process chooses the first available service with sufficient capacity. In the second case, the same rebooking process is initiated after arriving at the gate/platform and missing the connection.

4) Train: The ‘Train’ agent models the processes related to the operation of train services, mainly arriving and departing from stations. An initial delay which occurs with a given probability is modelled as a probabilistic distribution.

5) Train operator: The ‘Train Operator’ keeps track of the arrivals and departures of trains and any train delays. It manages the boarding and deboarding of passengers and, in case of missed connections, can rebook passengers on the next direct train. In this study, we assume sufficient capacity for trains.

6) Ground mobility: The ‘Ground Mobility’ agent provides the connection times between the rail stations and airports and vice versa. There is only one ‘Ground Mobility’ agent in the simulation. Passengers could take different modes of transport (taxi, bus, metro, etc.); however, in this study, we only assume a single transfer time for simplicity. This time is modelled as probabilistic distributions estimated using Google Maps considering public transport transfer times.

IV. CASE STUDY

A. *Scope of study*

A day of air traffic on 22^{nd} September 2023 has been used as an example for the analysis, with flights arriving/departing to, from and within Spain (2,740 flights in total).

For the rail network data, we used an open GTFS dataset from Renfe (Spanish Public Rail Service Operator) containing information on long and medium-distance rail services for high and conventional speeds. These data are processed to extract all possible direct rail trips between the airports in Spain as in [32]. In the simulation, the train times are modelled according the timetables with some added noise. An initial delay of mean 0 and standard deviation of 5 minutes is applied to all trains. The modelling approach is that the trains are delayed at the source, and this delay is propagated through their service.

A flight ban for short-haul flights is imposed to generate multimodal itineraries. All flights with at least a rail alternative faster than 2h30 have been removed. The fastest services between all origins and destinations are identified to assess if this threshold is breached. For example, between Valencia (LEVC) and Madrid (LEMD), at least a train service takes 1h50. Therefore, all flights between the two cities are removed with the 2h30 ban. This threshold is in line with the proposed ban by the Spanish government [33]. In the proposed version, only flights to *non-connecting* airports will be affected, similar to the equivalent French regulation [34]. In this article, we ban all flights as analysed in [32]. This means that passengers with connecting fights in Spain whose journey required a short-haul flight that is now cancelled will become multimodal passengers. Following the

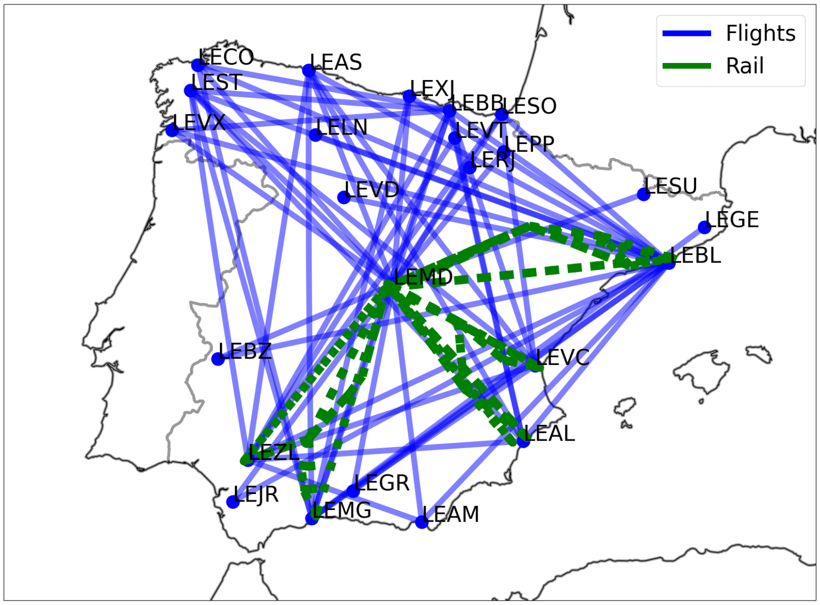

Fig. 3: Flight and rail network within Peninsular Spain with the application of a 2h30 threshold flight ban.

TABLE I: Ground mobility mean times.

Rail station	Airport	Mean (min.)	σ (min.)
Chamartin	LEMD	30	5
Atocha	LEMD	53	5
Principe Pio	LEMD	58	5
Barcelona	LEBL	48	5
Alicante	LEAL	36	5

TABLE II: Kerb-to-gate and Gate-to-kerb mean times.

airport	K2G (min.)	G2K (min.)
LEMD	114	32
LEBL	125	33
other	114	31

analysis performed in [32], 71 flights are cancelled (with a remainder of 2,669 operated flights), and 154 rail services are used to maintain the same connectivity. The strategic impact of this ban is out of the scope of this research. For example, schedules are not optimised but maintained as originally, and some potential itineraries might not be valid anymore if the rail timetable does not match the air connectivity. Fig. 3 shows the air and rail network that remains after the ban within Peninsular Spain.

The possible connections between flights and between modes are based on the connectivity that was originally possible in the air network with the same restrictions as in [32]. When considering multimodal itineraries, connecting times between rail stations and airports and modelling the processes at the airport from their kerb to their gates are required. Mean ground mobility times between modes of transport are obtained by exploring Google Maps as presented in Tab.I. These times are assumed to be symmetric, i.e., the same between the rail station and airport and vice versa.

Finally, the values from Tab. II are used to model the airport terminal processes. The values are taken from Modus [35] and Dataset2050 reports [36].

The above values are used when estimating which connections between rail services and flights are possible, as in [32]. Note that the most *efficient* connection is only kept. For example, if a given flight can connect with onward trains going to a final destination. Several train services might be used; however, the approach keeps only the fastest alternative, which respects the connecting times. On one hand, this avoids going to the train station to wait for a service when an earlier one could be used; on the other hand, this means that the buffers used by passengers are the shortest possible given the schedules and timetables available.

Once flight, trains and their possible connectivity are defined, the services must be populated with passenger itineraries. Aggregated passengers' itineraries data for September 2019 from AviationWeek [37] are used to obtain the demand, including multi-leg journeys. These passenger flows are disaggregated into the flights and train services to accommodate the maximum number of passengers from the September 2019 demand. With this approach, individual passengers' itineraries are generated. Note that the starting point is the air demand and this is tried to be satisfied with the new multimodal network. Changes in demand are not captured in this research. The total number of assigned passenger itineraries is 15190 with 303997 total passengers, out of which 13944 are multimodal. The majority of multimodal passengers (93%) is transferring in Madrid.

Finally, nominal (with ground mobility running close to their timetables) and disrupted conditions (with delays in the ground mobility) are defined. In the disrupted case, all ground mobility is set to be delayed by 30 minutes. This is similar to the assumption done in [25].

B. *Disruption management mechanism*

Following the work done in [7], a *Fast-Track Security* is used as a disruption management mechanism. In this simplified version, multimodal and delayed passengers can use a dedicated fast-track, which reduces their kerb-to-gate processing times at the airport.

The 'Passenger Handler' will request the 'Airport Terminal' for the time required to perform the kerb-to-gate. In the nominal situation, i.e., without the fast-track mechanism, the 'Airport Terminal' will return the value independently of the passenger's situation. When the fast-track mechanism is in place, the 'Passenger Handler' will include information about the status of the passenger in the request message, i.e., if the passenger is delayed. The 'Airport Terminal' will then provide either the nominal kerb-to-gate time or a reduced factor of 60% of the nominal value. This speed-up factor is consistent with the results presented in [7].

This fast-track mechanism can be implemented with two different approaches in Mercury: 1) as a module of the 'Airport Terminal' agent, which replaces the 'Wait for move kerb2gate times request' role; 2) as an external system which receives a message from the simulation. An external system enables the detailed modelling of the airport processes outside Mercury using dedicated tools if desired.

C. *Results*

The case study results are in progress and will be presented at the ATRS2024 conference.

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