Air-rail Multimodal Disruption Management

Rail Network supporting Air Disruptions

Michal Weiszer and Luis Delgado
Centre for Air Traffic Management Research
School of Architecture and Cities, University of Westminster
London, United Kingdom
[m.weiszer|l.delgado]@westminster.ac.uk

Lucía Menéndez-Pidal
Nommon Solutions and Technologies
Madrid, Spain
lucia.menendez-pidal@nommon.es

***Abstract*—This paper presents the application of MultiModX's Strategic Multimodal Evaluator for assessing an air-rail multimodal mobility network subject to various disruptions (airport closure, industrial action), considering different degrees of flexibility for reaccommodating passengers in their door-to-door journey. Affected passengers are rebooked into alternative itineraries, taking into account the possibility of using rail services. The article presents case studies for the replanning of air and rail network itineraries for mobility within and to/from Spain when Madrid Barajas Airport (LEMD) is affected by an industrial action, and when it experiences significant cancellations (from 25% of flights cancelled up to a total airport closure). A range of different constraints is considered for finding the new itineraries for the affected passengers and reaccommodating them into the alternative train and flight services. The sensitivity analysis of increasing rail network capacity showed a larger role for the rail network, allowing more passengers to be reaccommodated from air to rail. The experiments demonstrated how one network can support another in case of disruptions.**

***Keywords*—multimodality, disruption, replanning, passengers**

I. Introduction

The multimodal vision of air and rail coordination is gaining traction with a focus on passenger experience and inclusion, and the development of a seamless European mobility system, which meets the goals of the Paris Climate Agreement, is a topic that is gaining traction [1]. In addition to the potential use of the rail network to complement flights, with multimodal itineraries, rail services could be considered as alternatives to support passengers in the event of disruptions in the air network. This additional capacity could be relevant when dealing with significant disruptions or events, such as industrial actions or airport closures. The rail network can complement and, in some cases, replace air operations, thereby opening the door to utilising available rail capacity to manage significant air disruptions [2].

From the passengers' perspective, when disruptions affect their journey, their total door-to-door itinerary should be considered [3]. If their journey is possible, considering their door-to-door travelling time and initial origin and final destination, stranded passengers could be reduced by considering suitable alternatives, such as: using different routes (*e.g.* connecting at alternative airports), starting and ending their journey at different infrastructure nodes (*e.g.* departing and/or arriving at different airports than originally planned), and even switching to a different transport mode for the entirety or part of their trip. The flexibility for passengers to use these alternatives can be analysed to assess their potential benefits.

MultiModX[1], an Exploratory Research Project from the Single European Sky & Air Traffic Management Research (SESAR) programme, provides, among other things, a Strategic and a Tactical Multimodal Evaluator to assess the planned and realised multimodal networks. The Tactical Multimodal Evaluator extends the open-source agent-based model Mercury [4][2], which can simulate and track flights and passengers during a day of operations, to incorporate relevant trains and multimodal journeys. The Strategic Multimodal Evaluator, released also as open-source[3], takes advantage of previous research in graph-based representation of transport networks [5]–[7]. This evaluator enables the assessment of air-rail multimodal networks, calculating mobility performance indicators (PIs) that can be extracted at different levels (*e.g.* region, infrastructure, operator), considering: flight schedules and rail timetables, infrastructure information (connecting times between nodes, region accessibility), policies, and demand. This enables the evaluation of what-if scenarios considering changes in any of these parameters.

The capability to compute possible itineraries for passengers between origin and destination regions of the Strategic Evaluator enables the assessment of disruptions on passenger itineraries. If a disruption is known with sufficient advance notice, suitable alternatives can be calculated for the passengers.

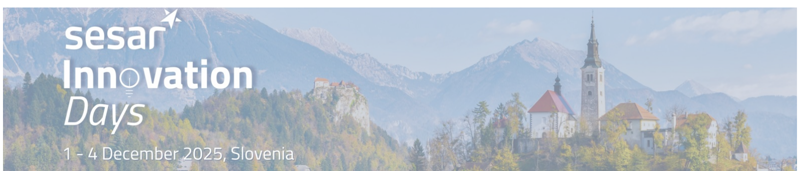
The model identifies the passengers affected by replanned operations (*i.e.*, delayed and cancelled services) and reassigns the demand of passengers stranded due to these changes in the remaining operations. Various PIs are computed to assess the impact of the disruption on passenger experience.

In this paper, we present a case study of the Spanish air and rail mobility network when Madrid Barajas airport (LEMD) is affected by an industrial action, and when it is affected by significant cancellations (from 25% of flights

[1]MultiModX: https://cordis.europa.eu/project/id/101114815 (Accessed September 2025)

[2]Mercury – Tactical Evaluator: https://github.com/UoW-ATM/Mercury (Accessed September 2025)

[3]MultiModX open-source models: https://github.com/UoW-ATM/MultiModX (Accessed September 2025)



cancelled up to a total airport closure). The model identifies new possible itineraries for the affected passengers and reaccommodates them into alternative rail and flight services, taking into account their available capacity. Different flexibilities are considered for finding the new suitable itineraries, from restrictive conditions, when passengers can only be accommodated in very similar itineraries as originally planned (*e.g.* with the same operator), to full flexibility where even departing from their origin before initially planned is allowed. The experiments demonstrate how the rail network can support the air network in the event of such severe disruptions. It is worth noting that a limiting factor in using rail services to accommodate impacted air passengers is the availability of seats on the trains. For that, we also present an analysis of the effect of having additional spare capacity in the rail system.

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 [8], [9], improved information sharing to passengers [10], and multimodal collaborative decision making processes [11]. The work presented in [12] shows how actively delaying flights (waiting for passengers) can be used to minimise multimodal rail-air passengers' missed connections in the event of rail disruption. [13] is an example of a strategic measure, such as air-rail timetable synchronisation to improve multimodality. This means that besides just delaying and cancelling services, a replanned network could try to adapt to maximise the capacity offered.

II. Multimodal air-rail networks modelling

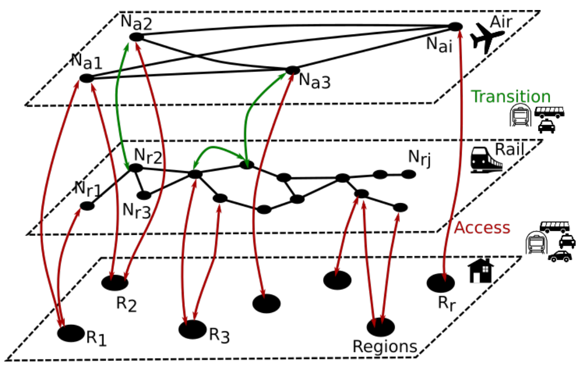


Figure 1. Multilayer modelling approach

As shown in Figure 1, the principle of mobility layers connected with temporal multiplexes is used to model the multimodal networks [14], [15].

In the modelling presented in this article, the starting point is the passenger itineraries with their origin and destination defined at *Region* level (R_r). These itineraries are created considering the preferences of selected archetypes in terms of total travel time, cost, and CO_2 emissions, taking into account possible alternatives between their region of origin and destination, as described in [15].

Each region is connected to one or several infrastructure nodes (airports or rail stations), which can belong to any of the mobility layers. Only two mobility layers are considered in this research (air and rail), but the model allows the definition of as many complementary layers as desired (*e.g.* additional rail or air layers, or modes, such as bus).

$\mathrm{RA}(R_i, N_{lj})$ ($\mathrm{RE}(R_i, N_{lj})$) represent the average access (egress) times (door-to-kerb (kerb-to-door)) from region R_i to (from) the infrastructure node (airport or rail station) j of layer l (N_{lj}). These values enable the estimation of the total door-to-door travel time when comparing alternatives. Not all infrastructure nodes are accessible from each region, and more than one node could be accessible from the same region, even if they are located in different regions.

It is possible to transition between mobility layers using public transportation (*i.e.*, metro, bus, taxi). $\mathrm{TR}(N_{li}, N_{kj})$ represents the required transfer time between two nodes. These could belong to the same mobility layer (for example, to transfers between two train stations within the same city using the metro), or enable multimodal connections between layers. Each node that allows intra-mode transfers has a minimum connecting time defined ($\mathrm{MCT}(N_{li})$), *i.e.*, the minimum time required between flights or between trains.

Some additional processes are considered within the infrastructure nodes: $\mathrm{KS}(N_{li})$ represents the time needed to reach the service (flight/train) from the kerb of the infrastructure (airport/rail station). This includes processes such as check-in or security. $\mathrm{SK}(N_{li})$ represents the time required to reach the kerb from the moment the service arrives at the node, *i.e.*, the flight arrives at the gate or the train to the rail station.

Flights and trains define the connectivity within the air and rail layers, respectively. The model transforms the individual connections provided by these into *services*. A service (S_i) is defined as a temporal link between two nodes in the same mobility layer. For flights, this is a natural association; train trips (from General Transit Feed Specification (GTFS)) are transformed into individual services between the different stops served. For each service, the model defines:

- Departure and arrival times ($\mathrm{SOBT}(S_i)$ and $\mathrm{SIBT}(S_i)$);
- Departure and arrival nodes ($\mathrm{FROM}(S_i)$ and $\mathrm{TO}(S_i)$), *i.e.*, airports (N_{aj}) and rail stations (N_{rk});
- Other parameters: mode type (air, rail) ($\mathrm{M}(S_i)$); operator (or alliance) ($\mathrm{OP}(S_i)$); capacity ($\mathrm{CAP}(S_i)$); cost ($\mathrm{C}(S_i)$); and emissions per passenger ($\mathrm{CO2}(S_i)$), provided or estimated by the model [16].

Intra-layer connectivity between two services (S_i and S_j) is possible if the subsequent service departs from the same node as the previous one ($\mathrm{TO}(S_i) = \mathrm{FROM}(S_j)$), they their operator (or alliance) is the same ($\mathrm{OP}(S_i) = \mathrm{OP}(S_j)$), and the MCT is respected ($\mathrm{SOBT}(S_j) \geq \mathrm{SIBT}(S_i) + \mathrm{MCT}(\mathrm{FROM}(S_j))$.

Finally, multilayer connections between two services (S_i and S_j) are valid as long as a transition exists between the arrival node of the first service and the departure node of the second one, and the connecting times are respected: $\mathrm{TR}(\mathrm{TO}(S_i), \mathrm{FROM}(S_j)) \geq 0$ and $\mathrm{SOBT}(S_j) \geq \mathrm{SIBT}(S_i) + \mathrm{SK}(\mathrm{TO}(S_i)) + \mathrm{TR}(\mathrm{TO}(S_i), \mathrm{FROM}(S_j)) + \mathrm{KS}(\mathrm{FROM}(S_j))$.

III. Replanning of passenger itineraries for disruption management

The computation flow of passenger replanning is carried out in the following steps:

1) Network modification (replanning of operations, *i.e.*, delays and cancellations),
2) Identification of the status of passengers impacted by the replanned operations,
3) Estimation of available capacity on remaining services,
4) Computation of possible alternatives in the replanned network between origin and destination pairs for passengers for which their itineraries are no longer possible in the modified network. This is therefore performed considering the passengers' needs and the services' capacities; and filtering of alternatives based on policies that define the suitability of alternatives, and
5) Reassigning passengers to the possible itineraries.

The computation of possible itineraries and the assignment of passengers to services is based on MultiModX's Strategic Mobility Evaluator [15], which can assess planned air-rail multimodal networks.

A. Network modification considering disruption

Firstly, the planned network's (prior to disruption) supply (flight schedules and rail timetables) is modified considering the impact of the disruption. These changes can be just directly the outcome of the disruption, *e.g.* cancellations and delay of services; or the operators could optimise the remaining services, *e.g.* with additional services due to rerouting.

The outcome of this process is a replanned network where some services remain unaffected with respect to the initial network, others are cancelled or delayed, and potentially new services are added.

B. Identification of passengers' status

The next step is to determine the status of passengers considering the replanned network. Some passengers might not be affected, *i.e.*, their services are not modified, others might be impacted but still have feasible itineraries, *e.g.* delayed operations or connections which are still possible even with the new schedules. Finally, some passengers might be 'stranded', *i.e.*, one (or several) of their services are cancelled or their connections are no longer possible due to delays.

Some indicators can already be computed, such as the percentage of passenger itineraries affected, the expected delay for delayed passengers, and the number of passengers stranded if not rebooked into alternative options.

C. Estimation of available capacity

The spare capacity of each service in the network is calculated considering the passengers who are not stranded. Note that all services used by a passenger itinerary need to be considered, *e.g.* a flight might be cancelled and free up capacity in an onward connecting service.

D. Computation and filtering of possible alternatives

Considering the services that have some capacity available, and respecting the MCTs and network connectivity described in Section II, the n-fastest possible itineraries are calculated with an A* algorithm in the multimodal multiplex network [14]. This is performed by first computing the p-fastest potential paths between each origin and destination, and then looking for itineraries considering service schedules and MCTs over those paths.

TABLE I. Passenger assignment alternatives.

Alternative	Description
PA01	Close to planned (same operator and path)
PA02	Allow different path
PA03	Allow different path and mode swap
PA04	Allow different path, mode swap and different operators
PA05	Allow different path, mode swap, different operators, and to leave origin earlier than initially planned

These alternatives are then filtered out considering different policies: from restrictive conditions when passengers can only be accommodated in very similar itineraries as originally planned, *i.e.*, the same operator (or alliance) and path (*i.e.*, infrastructure nodes) as originally planned, to full flexibility, where even departing before initially planned is available.

As shown in Table I, this article presents five alternatives to evaluate their impact on the passengers' performance. These have been created in increased flexibility: PA01 considers only rebooking of passengers in the same operator and path (airports, rail stations), so, for example, if a flight is no longer possible, a different flight by the same airline (or alliance) must be used. In PA02 we allow for different paths to be considered, *e.g.* flying to a different airport of destination as long as the final region can still be reached from that airport, or connecting at a different airport. In PA03, we allow for mode swap, so part of the itinerary, which was planned by rail or flight, can be performed by the other mode. Note, however, that the operators must still be in the original itinerary, *e.g.* if the passenger has a multimodal ticket with Renfe and Iberia, then it could be rebooked into only Renfe or Iberia services. The rationale is that the liability is kept within the operators of the first itinerary. PA04 finally enables using a different operator from the originally planned; and PA05 considers that, if the disruption is known with enough anticipation, passengers could potentially leave their origin earlier than planned. It is expected that this flexibility will increase the alternatives available to them.

E. Reassigment of passengers

The last step is the assignment of passengers to individual possible itineraries, *i.e.*, to the individual services (flights and trains), while considering their capacity. A lexicographic optimisation is used to reassign the passengers to potentially suitable itineraries. The algorithm allows for adjusting how this optimisation is performed. In the results presented in this article, the optimisation is performed sequentially, first maximising the total number of passengers reaccommodated, *i.e.*, minimising stranded passengers, then minimising the arrival time to their final destination, maximising the itineraries following the same path as planned before the disruption, and finally maximising the number of itineraries starting and ending in the same infrastructure.

IV. Case study: Spain mobility

The results presented in this article focus on Spain's mobility, considering demand flows between the 49 largest cities in Spain (all cities with more than 100,000 inhabitants and all islands with an airport) and flows from international flights to/from Spain. It is assumed that multimodality is a possibility, *i.e.*, it is possible to have itineraries with a combination of air and rail services. A set of disruptions at LEMD is modelled, and passengers are reallocated (when possible) to alternatives available in the air and rail networks.

A. Network infrastructure

For each NUTS-3 region in Spain[4] (provinces, islands, Ceuta and Melilla), an analysis has been conducted to filter out the rail stations, keeping only those that provide connectivity to other NUTS (intra-NUTS mobility is considered part of the access and egress process). The centroid of the population of each NUTS is computed using EUROSTAT census data, and this is used to estimate the access and egress time to the nodes of the networks. The accessibility of nodes from the NUTS is based on the analysis of anonymised mobile phone network data (MND), see Section IV-C.

MCTs for rail stations are provided by International Union of Railways (UIC), and for airports based on historically available datasets [5]. The intra-layer connectivity is based on times observed with mobility applications between infrastructure nodes (*i.e.*, time taken by public transport from rail stations to airports and vice-versa). Finally, processing times (kerb-to-service (KS) and service-to-kerb(SK)) are defined based on previous reports (such as Modus and Dataset2050 projects [7], [17]) and expert judgment.

B. Capacity: Flight schedules and rail timetable

The flight schedules within and to/from Spain (5039 flights) are obtained from Official Aviation Guide (OAG) for the 6th September 2019, which has been selected as a *nominal* busy day of aviation pre-COVID. For each flight, based on its aircraft type, the maximum number of seats is estimated.

Due to the recent increase in rail operations, rail timetables (1418 trains in total), provided by UIC, are from a busy and *nominal* day from 2023 (20th September 2023). In this case, a capacity of 295 seats is considered for all services. This value represents the average for services in Spain, but we acknowledge that it may be too low for certain operations. Future work should more accurately identify capacity per service.

[4]Spanish Nomenclature of Territorial Units for Statistics (NUTS) regions (Accessed September 2025):
https://en.wikipedia.org/wiki/NUTS_statistical_regions_of_Spain

[5]Dataset derived from data originally purchased from Innovata (now Cirium).

C. Demand: Passenger itineraries

The intra-Spain demand is based on the analysis of MND conducted in [18]. A year of mobility within Spain was analysed to estimate the demand between all NUTS-3 regions in Spain for a *nominal* busy 2019 (pre-COVID) for selected passenger archetypes. The regions of origin and destination in Spain are, therefore, defined at this NUTS-3 level. Individual passenger itineraries were generated using MultiModX's Strategic Mobility Evaluator, described in Section II, as detailed in [15], considering the passengers' preferences.

For the international air demand, aggregated air passengers' flows for September 2019 from AviationWeek[6] are used. These flows represent the demand to and from airports, including connecting flows. When the origin or the arrival airport is within Spain, the demand is further disaggregated with a probabilistic model to the NUTS-3 level following an analysis of the catchment areas of Spanish airports from MND, *i.e.*, proportion of passengers to each NUTS-3 is treated as a probability.

The total demand considered (intra-Spain (with rail and flights) and to/from Spain (flights)) is slightly over one million passengers.

D. Disruptions considered

In this paper, the focus is on disruptions that affect Madrid Barajas Airport. LEMD is a major airport for both domestic and international flights (1,228 flights in total) and has a central position in the Spanish transportation network, making it important in terms of connecting peripheral regions.

The disruptions presented consider industrial actions and cancellations at LEMD (up to full closure). These are modelled with flight cancellations and flight delays, *i.e.*, rail services are not modified and no additional flights are considered.

Different disruptions, as summarised in Table II, are evaluated by applying them to the planned network.

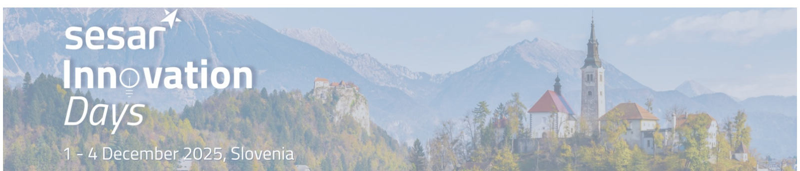
TABLE II. Disruption packages.

Disruption	Cancel. rate	Cancel. flights	Delayed flights
Industrial Action (IA)	7.5%	93	295
Cancellation 25% (C25)	25%	307	0
Cancellation 50% (C50)	50%	614	0
Cancellation 75% (C75)	75%	921	0
Cancellation 100% (C100)	100%	1228	0

C25-C100 represent significant cancellations of flights at LEMD, up to a complete closure of the airport (100% cancellation rate) for the day. A significant number of passengers are expected to be impacted, requiring accommodation within the network. The cancellations are modelled by randomly selecting the flights cancelled (not considering any correlations between cancelled flights) up to the ratio of the disruption.

IA models the impact of an ATFM regulation due to industrial action spanning all day in Madrid airport. Industrial action has been selected as the reason for the regulation due

[6]AviationWeek: https://aviationweek.com/ (Accessed September 2025)



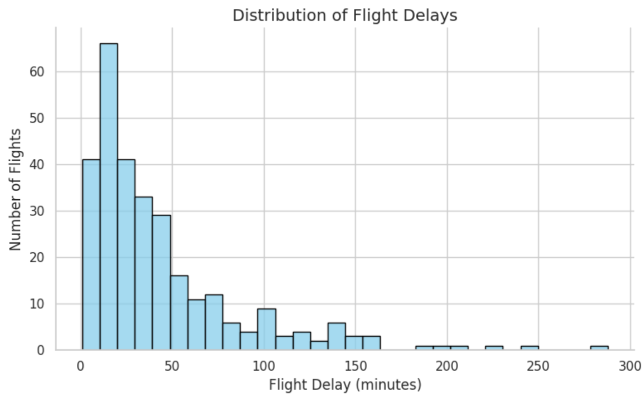


Figure 2. Distribution of delay for delayed flights due to ATFM in Industrial Action (IA)

to the severe impact of these types of regulations on traffic in terms of cancellations and delays [19].

The modelling approach used to replan the network considering the industrial action is as follows:

1) According to the EUROCONTROL's Performance Review Report for June 2023, between June and September 2022, 5.5% of schedules were not operated on average [20]; and strikes increase the ratio of cancellations by up to 37%[7]. Therefore, first, a probability of 7.5% is used for all flights operating in LEMD to be cancelled.
2) Then, for the remaining flights, it is assumed that they would be regulated due to the ATFM regulation. The assignment of delays to flights is based on the analysis and findings from [19]. All regulations due to industrial action from the period AIRACs 1313–1413 and 1702, 1709 were processed, obtaining the probability of being assigned zero minutes of delay and the distribution of the historically observed delay if positive. Therefore, for the remaining flights, a random ATFM delay following these probabilities is drawn. A total of 295 flights are delayed, with a positive delay, as depicted in Figure 2.

V. Results

A. Industrial action at LEMD

A total of 37,198 passengers are affected by the replanning of operations (cancellations and delays) due to the ATFM regulation. As shown in Figure 3, most of them are due to flight delays (26,080 (70.1% of affected passengers)). These are passengers who arrive at their final destination with some delay with respect to their originally planned itinerary. Interestingly, 735 passengers (2.0% of affected ones) are impacted by the ATFM regulation (some of their flights are delayed) but still arrive on time to their destination. This could be connecting passengers whose inbound flight is delayed but still made the connection (either to another on-time flight or rail service).

[7]https://traveltomorrow.com/what-is-the-real-impact-of-the-atc-strikes/ (Accessed September 2025)

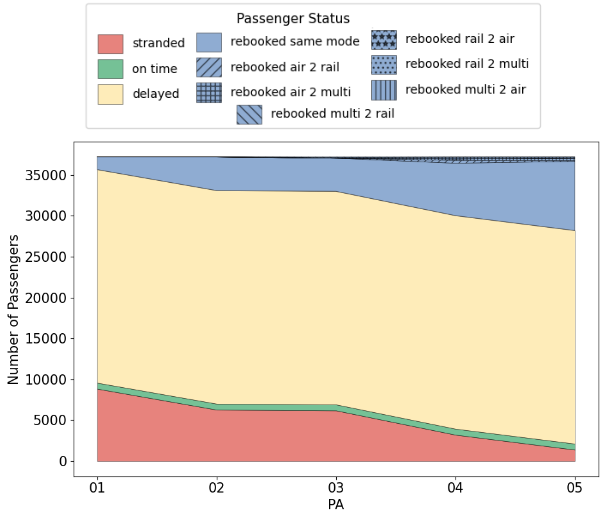


Figure 3. Passengers status for Industrial Action (IA)

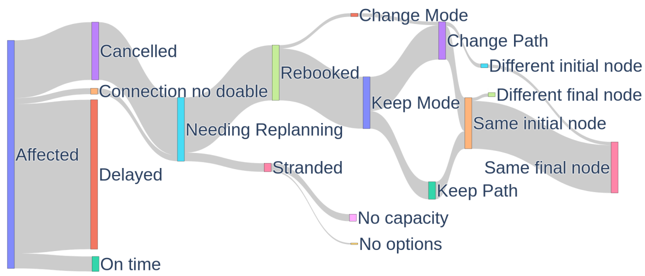
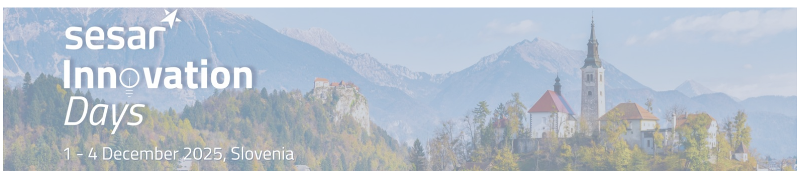


Figure 4. Distribution of itineraries status for Industrial Action (PA05).

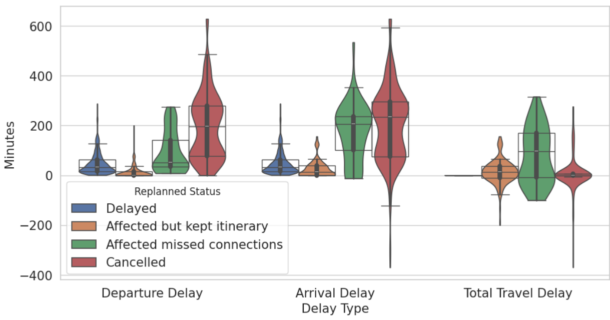
In PA01, when the same operator, mode and path must be maintained, 1545 passengers (4.1% of affected passengers) can be rebooked on alternative flights. Enabling the use of alternative paths (PA02) has a small improvement (11.0% of passengers are reassigned). Enabling the mode swap but maintaining the modes only improves original multimodal passengers who might be replanned as just rail in PA03. Therefore, no benefit is observed. When changes between modes are allowed to all passengers (PA04), 19.3% of affected passengers are replanned and only 8.6% of passengers remain stranded. However, the number of passengers rebooked across modes is still very limited. Finally, if enough anticipation is available and passengers can be reaccommodated into earlier than originally planned services, only 1388 passengers end up stranded (0.2% of the originally planned ones). Most of these are achieved by ensuring that air connections are still possible by selecting earlier flights. It is worth reminding that the cancellation rate used for the flights departing and arriving in Madrid is 7.5% in this disruption.

Figure 4 represents for PA05 the status of the different itineraries affected by the disruption. Once again, as the flexibility to reaccommodate passengers increases, the number of stranded passengers decreases, and passengers are rebooked, mostly by retaining their initial intended mode, even if there

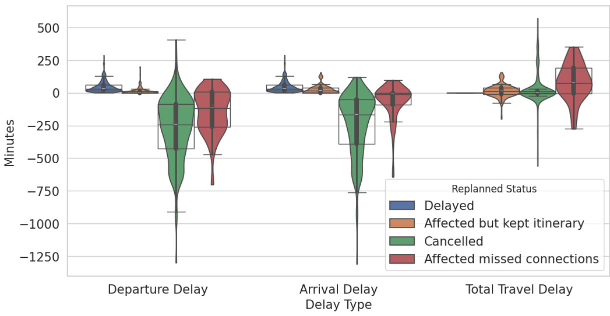


is flexibility to change it (if needed) in PA05. Departing earlier allows passengers to use an earlier service, maintaining their connection without having to change modes. Note that, from the passengers needing to be replanned, very few end up stranded, and most are due to a lack of capacity in the remaining services. The rebooked passengers mostly keep the same mode, even if a significant number change their path.

Next, in Figure 5, we analyse the delays per type of impact on passengers in terms of departure, arrival and travel time delay. As expected in PA02, when passengers must maintain the operator and mode, all passengers who are not stranded depart with some positive delay; those who have some of their services cancelled or who miss a connection need alternative services and therefore suffer a high amount of departing and arrival delays. In contrast, for PA05 the delay is sometimes negative, as departing earlier than planned is allowed; passengers with cancellations and those with missed connections exhibit higher variations with respect to their original plans, despite relatively low travel time delays ($\leq$30 minutes). The delays are -215 minutes and -155 minutes for departure and arrival, respectively, for passengers with cancellations. For passengers with missed connections, the delays are -155 minutes for departure and -35 minutes for arrival, respectively. Passengers with single flights (delayed) maintained their originally planned total travel time (0 minutes), and passengers who could keep their connection increased their travelling time (19 minutes delay), but overall presented low departing and arrival delays ($<$ 21 minutes). These results highlight the distinction between flight- and passenger-centric metrics that can be estimated using the algorithm.



(a) PA02



(b) PA05

Figure 5. Distribution of passenger delay for Industrial Action.

Finally, we analyse the reasons why passengers end up stranded, either because there are no alternative options for them or because there is no spare capacity. In PA01, as the most restrictive replanning, passengers must maintain their operator, mode and path. Therefore, a significant amount of passengers (73.4%) are stranded due to a lack of alternatives. In the PA05 case, as passengers can use different operators, modes and even depart earlier than planned (possibly using a previous service that ensures their connection), the majority of stranded passengers (82.2%) are just because there is no capacity for them, and passengers without an alternative option are much smaller (17.7%).

B. *Cancellations of flights*

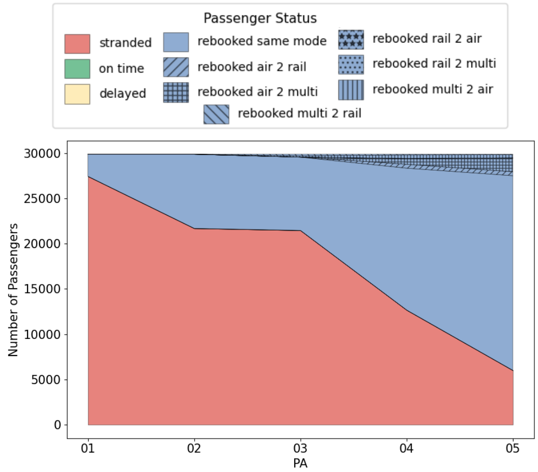
Figure 6 shows the status of the disrupted passengers with increasing cancellation rate from 25% in C25 to 100% in C100. As expected, the number of affected passengers steadily increases from almost 30,000 in C25 to more than 111,000 in C100. As the cancellation rate increases, the network's ability to rebook passengers decreases, particularly for the same mode, while the number of passengers rebooked on different modes increases. In C25 and PA05, 79.9% of affected passengers can be reaccommodated, whereas in C100 and PA05 this number is only 10.3%. As a result, the number of stranded passengers increases. Also note that, in contrast to the Industrial Action case, there are no delayed passengers since all the affected flights have been cancelled.

As in the Industrial Action case, increasing the reacommodation flexibility from PA01 to PA05 significantly decreases the number of stranded passengers as alternatives using early flights are possible to maintain the connectivity. However, the number of passengers rebooked to different modes remains similar at around 7-8% for C25–C100. As shown in Figure 7, this relates to a lack of capacity in the rail system to accommodate them.

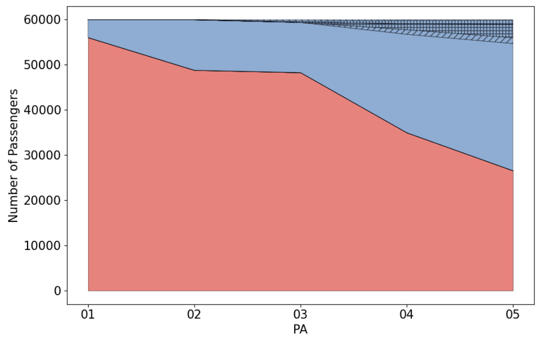
The possibility to change mode represents a larger increment in the total travel time of disrupted passengers, as slower and with more connection alternatives could be used, as shown in Figure 8 for an example from C100 PA05 case. The original itinerary was a train from Cuenca Fernando Zóbel to Madrid Chamartin to connect to a flight from Madrid (LEMD) to Seville (LEZL), which becomes a flight from Valencia (LEVC) to Seville (LEZL). ES423 access time to Cuenca Fernando Zóbel railway station is 77 minutes and to LEVC is 202 minutes. As a result, the total arrival delay with respect to the original itinerary is 90 minutes. Note how in both cases, the airport of arrival is respected, even if the final destination was the adjacent NUTS-3 region of Córdoba.

C. *Increasing capacity of trains*

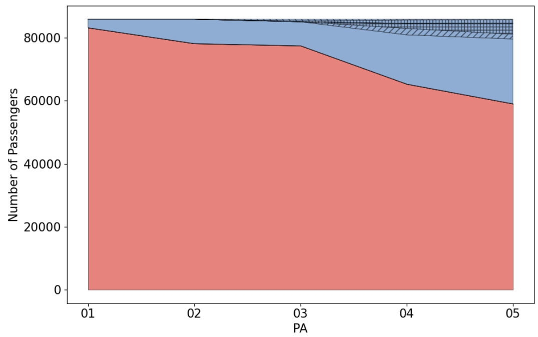
As observed in the previous results, even if transfer to the complementary rail network is enabled, not many passengers benefit from this even in the fully flexible case (PA05); as shown in Figure 4, passengers who end up stranded are so due to lack of capacity in the remaining services. With these considerations, the experiments presented here examine the closure of Madrid Barajas, C100, and full passenger flexibility



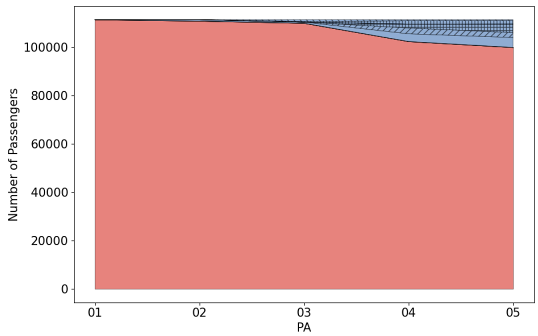
(a) C25



(b) C50



(c) C75



(d) C100

Figure 6. Passengers status for C25–C100.

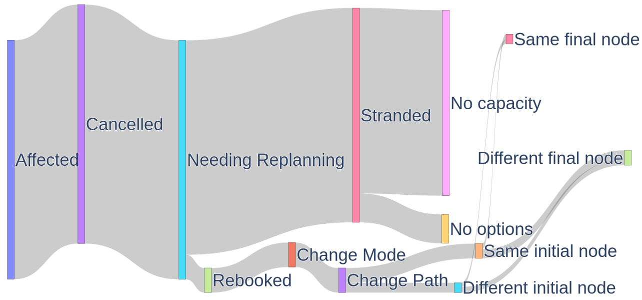


Figure 7. Distribution of itineraries status for C100 (PA05).

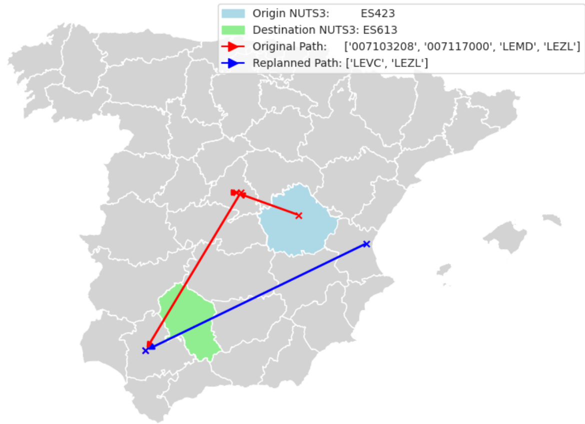


Figure 8. Example itinerary replanned in C100 (PA05).

(PA05) with varying levels of rail capacity increments across the rail network. The sensitivity analysis will enable us to assess whether that additional capacity could benefit passengers in the event of significant air disruptions.

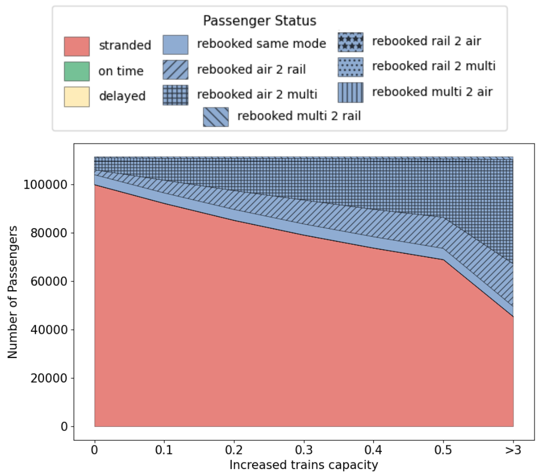


Figure 9. Sensitivity analysis of providing extra train capacity in C100.

As shown in Figure 9, the increased capacity of trains now allows more passengers to be reaccommodated. Figure 9 shows the additional number of passengers who can be rebooked if capacity is increased from 0 to 50% in 10% intervals, and then for a 1000 seat (>300%) increase, which is much larger than what could be produced operationally but would show a the potential benefit of using the rail network to support the air disruption.

As shown, passengers rebooked from air to multimodal increased from 3.5K without extra capacity to 7.8K in 10%, and increases quite linearly up to the 50% increment in rail capacity, reaching 42K for >300% extra capacity. Similarly, the number of passengers rebooked from air to rail increased from 2.0K without extra capacity to 5.2K in 10% extra capacity, and to 17K in >300% extra capacity. The number of stranded passengers due to a lack of capacity decreases from 86K without the extra capacity to 34K with the >300% extra capacity; and only an increment of 10% rail capacity already reduces the number of stranded passengers by 5K. This experiment illustrates how the strategic value of maintaining some extra capacity can be estimated.

The results could be further analysed to identify which particular links (and services) provide the highest benefit in terms of reducing stranded passengers when additional capacity is added. Currently, services which are already full are removed from the network before the computation of possible alternatives to speed up the search. These could be included in the network. Then, as the reasons why passengers end up stranded can be identified, the output would reveal OD pairs for which most passengers end up stranded due to no capacity.

VI. Conclusion and Future Work

This paper presented a model based on MultiModX's Strategic Multimodal Evaluator, which enables the evaluation of a replanned multimodal mobility network subject to different types of disruptions and flexibility to reaccommodate passengers. A case study of the Spanish air and rail network's replanning during an industrial action and a significant cancellation of flights at Madrid Barajas Airport was analysed.

The model is able to find alternative itineraries for affected passengers and compute various performance indicators taking into account door-to-door journey to assess the outcome of the replanned network.

The experiments demonstrated that increased flexibility to reacommodate passengers can efficiently reduce the number of stranded passengers. With PA05, *i.e.*, when passengers can use different operators, modes and even depart earlier than planned (possibly using a previous service that ensures their connection), only 0.2% of passengers end up stranded in case of industrial action at LEMD. For significant flight cancellation at LEMD, 79.9% of affected passengers can be reacommodated with PA05 for the 25% cancellation rate, whereas for a complete airport closure, this number is only of 10.3% even with the maximum flexibility provided by PA05. Although the majority of passengers are reaccommodated to the same mode, the number of passengers rebooked to a different (rail) mode remains similar across all cancellation rates analysed at around 7-8%. This is expected for two reasons: first Madrid Bajaras serves as a connecting hub to international destinations and no alternative is possible when those international flights are cancelled, and second, due to the limited capacity available in the rail system to support the additional demand required for the intra-Spain mobility.

The sensitivity analysis of increasing rail network capacity showed that if capacity is provided, the number of passengers reaccommodated can increase significantly, with a shift from impacted flights to rail services. This experiment illustrated how a strategic value of keeping a reserved extra capacity could be estimated.

Future work could further analyse the results already obtained and improve some modelling assumptions, *e.g.* :

- the replanned services could be optimised for impact on passengers rather than adjusting to the disruption,
- the importance of the access/egress of airports when considering alternative routes could be reviewed, and the model could penalise changes of departing and arrival nodes if they require significant ground access/egress change (in distance and/or time) with respect to the originally planned itinerary, even if feasible.
- when international connections are affected, alternative paths via complementary hubs could be explored,
- the criticality of links identified, where the system would benefit the most from spare capacity, could be analysed,
- more detailed sensitivity analysis of increasing train capacity to identify a value after which performance remains stable,
- regulatory aspects could be analysed, *e.g.* different flexibility for passenger reassignment connected to the passenger archetypes.

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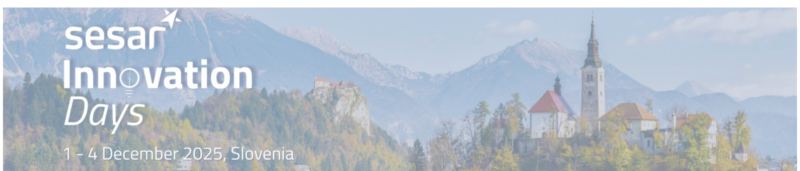

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