Optimizing air-rail travel connections: A data-driven delay management strategy for seamless passenger journeys

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***Abstract*—In the world of modern travel, where multimodal trips are becoming increasingly common, flight or train delays can jeopardise passengers' journeys by threatening connections. To address this issue, we present a delay management strategy on a multimodal network that involves seamless collaboration between air and rail transportation stakeholders. The objective is to minimise the total delay experienced by passengers at their final destination by rescheduling flights and trains at a tactical level. The decision whether to hold a train or a flight for connecting passengers depends on the available re-accommodation options. We propose an integer linear programming formulation of the problem at the network level, considering real-world constraints such as train station and airport capacities, minimum aircraft turnaround time, and flight slot adherence. To demonstrate the potential of this approach, we dive into a data-driven case study covering 496 airports, including three major hubs and 72 train stations across Europe. We simulate an incident on the French rail network that causes significant delays at Paris-CDG station. The results show that delaying 5% of departing flights at Paris-CDG airport by 13 minutes on average could reduce the number of stranded passengers at the airport by 71%. Such a decrease translates into a 40% reduction in the total delay experienced by passengers at their destination. This work highlights the potential benefits of air-rail integration, and the importance of information sharing between stakeholders to improve passenger journey reliability.**

***Keywords*—Multimodal transport network, Air-rail, Delay management, Passenger metrics, Integer linear programming**

I. Introduction

Improving air passengers' door-to-door journey is one of the European Commission's main objectives for 2050 [1]. In addition, in the context of climate change and increasing airport congestion, a new paradigm has emerged in which trains are replacing short-haul flights to relieve airport congestion and reduce passengers' carbon footprint. In such a case, coordination between trains and flights is necessary to maintain a high level of service for passengers. To support the development of air-ground system integration, in 2020, the European Commission launched several research projects under the SESAR research and innovation program, such as MODUS [2], X-D2D [3], IMHOTEP [4], TRANSIT [5], SYN+AIR [6]. In 2023, new projects focusing on multimodality started, such as MAIA [7], MultiModX [8] or SIGN-AIR [9]. When considering multimodal journeys, one of the key challenges is managing delays efficiently. Such events could cause passengers to miss their connections, resulting in significant delays at their final destination. To protect passengers, Regulation 261 [10] imposes airlines to re-accommodate or compensate them in case of delay. However, there is no equivalent of such regulation for multimodal transportation services [11]. Such a service might, in practice, be one key lever to encourage people to use the train as a feeder mode, especially for non-frequent travellers [12].

Here, we envision a scenario where airlines and rail service providers would cooperate and communicate actively. In this scenario, passengers travel using an air-rail integrated ticketing system, submitted to similar compensation laws defined in Regulation 261. This collaborative environment would enable transportation providers to be promptly notified if a train or a flight carrying connecting passengers is delayed. In addition, transport operators would share the costs of re-accommodating stranded passengers, incentivising them to minimise delays. In this context, we present a tactical rescheduling of flights and trains to limit the impact of delays on passengers. More specifically, we propose to solve an extension of the delay management problem originally introduced by Schobel [13] with the aim of minimising the total delay experienced by passengers in an air-rail transportation network. This problem relies on deciding, in a transport network, whether a connecting vehicle (e.g. train, bus, plane, etc.) should wait for connecting passengers who are delayed on their first leg. We propose an extension of the problem to include both airside and ground side constraints. In addition, we use a data-driven approach to evaluate the passenger reallocation time in the case of a missed connection. In the following, we refer to this problem as the Air Rail Delay Management Problem (ARDMP). We address the ARDMP through the Western Europe air-rail network case study, with a model including 496 airports and 72 railway stations. We apply the proposed delay management strategy considering a disruption occurring on the rail network.

This paper is structured as follows. Section II presents a

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state-of-the-art related to the delay management problem on the ground and air sides. Sections III and IV introduce the ARDMP and its mathematical model, respectively. Section V describes the European case study considered, and Section VI presents the results.

II. Literature Review

Previous works have studied the Delay Management (DM) problem on the ground side. Schobel [13] is the first to formulate the problem of deciding whether or not to delay a vehicle in a public transport system to wait for transferring passengers. She proposes a mixed-integer formulation to minimise the total delay of passengers at their final destination. She assumes that passengers' delay is equal to the delay of their train, if they catch it, or to a constant delay otherwise. Gatto *et al.* [14] show that even restricted versions of this problem are NP-complete. Later, Schobel [15] considers track capacity constraints for a railway system. Dollevoet *et al.* [16] propose integrating passenger rerouting into the DM process. The same authors consider station capacity constraints and track re-allocation in [17]. For a review of DM problem handling, the reader can refer to [18].

On the airside, Santos *et al.* [19] are the first to propose a version of the delay management problem applied to the airline. Montlaur and Delgado [20] consider the problem of balancing airport capacity at a hub airport by assigning delays to departing flights at a pre-tactical level and to arriving flights at a tactical level. They test different strategies to minimise either flight or passenger delays, considering connecting passengers and turnaround constraints. Delgado *et al.* [21] propose a delay recovery strategy at a hub airport through gate delays to wait for delayed connecting passengers and a dynamic cost index to recover from such delays. Delgado *et al.* [22] propose an agent-based model for handling air traffic delays through 4D trajectory adjustment to reduce costs and delays for connecting passengers.

Collaboration between air and ground transportation systems received a growing interest these last years. Li *et al.* [23] present an overview of actual collaboration between airlines and train service providers to create an integrated air-rail service for passengers. Laplace *et al.* [24] present the META-CDM project, which aims to involve ground transport stakeholders into the airport Collaborative Decision Making (CDM) to improve passenger door-to-door journeys. In this context, studies on multimodal recovery solutions in case of massive disruptions show promising results in mitigating the impact of such events on passengers (see for instance [25]–[27]). Regarding air-rail coordination mechanisms, Buire *et al.* [28] suggest strategically synchronising air and rail timetables to ensure smooth passenger transfers. However, they do not consider delays and their impact on the passenger journey. Scozzaro *et al.* [29] propose flight rescheduling at the tactical level to mitigate the impact of airport access mode disruptions on passengers. They consider airside constraints such as terminal capacity, maximum runway throughput or minimum passenger connecting time. Their work focuses on a single airport and does not consider reactionary delay. Here, we propose a tactical delay management strategy at the network level, combining the works of [28] and [29]. This study is the first to address the delay management problem in a long-haul multimodal network, combining constraints on the air and ground sides. We extend the original version of the problem developed by Schobel [13]. We take into account real operational constraints, such as airport and railway station capacities, Air Traffic Flow Management (ATFM) slot adherence or even minimum aircraft turnaround time. We also consider the reallocation time for passengers who miss their connections.

III. Air-Rail Delay Management Problem

This section introduces the *total passenger delay* metric and then defines the ARDMP.

A. Total passenger delay

As explained by Cook et al. [30], flight delays do not necessarily capture the actual delays experienced by passengers. The situation is similar for train delays, which can lead to missed connections and potentially late arrivals at the final destination. We therefore introduce the *total passenger delay* as the sum of the delays experienced by passengers when arriving at their final destination. To compute passenger delays, we define the following three groups of passengers:

- *on-time passengers*: passengers who catch their flight/train; their delay is equal to the delay of the flight/train;
- *reallocated passengers*: passengers who miss their connections due to a delay on the first leg, they are consequently reallocated to another flight/train going to the same destination within the same day;
- *stranded passengers*: passengers who miss their connections and without reallocation option (no seat available or no more flight/train going to the same destination within the day).

The delay of *reallocated passengers* is computed as follows. For each flight and train, we consider the direct alternative, enabling the passengers to arrive at their destination with the smallest possible delay. This alternative can be either a train or a flight, and, in this study, we only consider direct alternatives for the sake of simplicity. The delay of *reallocated passengers* corresponds to the difference between the arrival time of the new flight/train at the destination and the initial one. Regarding *stranded passengers*, we assume they will be re-accommodated to the same flight on the next day at the same departure time, thereby experiencing a 24-hour delay. The objective of the ARDMP is therefore to reschedule flights and trains at the tactical level to minimise the total passenger delay.

B. ARDMP description

To address the ARDMP problem, a one-day time window is considered. In the event of disruptions on the ground or air sides leading to train or flight delays, we assume that service providers are notified ahead of time about the affected vehicles and their expected delays for the remainder of the day. For instance, consider a power outage on a railway network between 6 am and 8 am, causing delays for several trains throughout the day due to a domino effect. We assume that the rescheduling of trains and flights can occur once operators anticipate delays caused by the incident, such as when power is restored at 8 am. The key challenge is deciding whether a vehicle should wait for connecting delayed passengers. For example, consider a flight of 100 passengers scheduled to leave at 9 am, with 10 passengers connecting from a previous train. Due to the disruption, these passengers arrive at the boarding gate 10 minutes after the scheduled boarding time. There are two options: depart on time or delay the flight. On the one hand, if there is another flight to the same destination in three hours, departing on time will result in a total passenger delay of $3 \times 60 \times 10 = 1800$ minutes. On the other hand, if the flight waits for the delayed passengers, the total passenger delay will only be $100 \times 10 = 1000$ minutes. In this situation, the aircraft should wait for the connecting passengers. However, if only five passengers were connecting, it would be better to depart on time.

This study considers an air-rail transportation network covering a specific region. The time scope is discretised into h-minute time steps. Air and rail networks can be represented by graphs, where nodes correspond to airports and train stations, and links model flight and train legs that are operated between stations. Each flight or train has expected departure and arrival times. Passengers' itineraries on this multimodal network are known, including possible transfers between modes. Assuming that delays arise on several trains or flights during the day, ARDMP problem consists in assigning tactical delays to other trains and flights so as to minimise the total passenger delay. The following operational constraints are taken into account:

1) the number of trains scheduled to stop at each train station cannot exceed the number of tracks at this station (train-station capacity constraint),
2) the number of airport departure and arrival movements, operated at each time step and at each hour is limited (airport capacity constraint),
3) a minimum turnaround time between two flights operated by the same aircraft is considered,
4) train dwell time at the station remains the same as in the initial schedule,
5) the train and flight travel times remain unchanged (the vehicle maintains its scheduled speed),
6) a Minimum Connection Time (MCT) is ensured for passengers who are not directly affected by the disruption (*i.e.* whose first leg is on time), to let them enough time to transfer between their first and second legs,
7) the departure time of flights subject to an ATFM slot must happen within a [-5,10]-minute interval around the scheduled departure time (ATFM slot adherence),
8) a maximum tactical delay of 30 minutes can be assigned to flights or trains (except for flights under ATFM slot).

IV. ARDMP MODEL

This section describes the optimization model of the ARDMP. Data, decision variables, constraints and the objective function are detailed below.

Sets and Parameters	
N^a/N^r	index set of airports/train stations
L	index set of flights and rail legs scheduled for the day of operation
L^{atfm}	index set of flights subject to the ATFM slot adherence constraint
$\mathcal{S}$	index set of slots
$\mathcal{S}'$	index subset of slots for which airport occupancy is computed
$\mathcal{C}^{\text{P}}$	index set of priority leg pairs for which passenger connections must be maintained.
$\mathcal{C}_l$	index set of legs with passengers connecting to leg l, $l \in L$
P^{air}	index set of flight leg pairs operated consecutively by the same aircraft
P^{rail}	index set of rail leg pairs operated consecutively by the same train
L_n^A	index set of legs scheduled to arrive at station n, $n \in N^a \cup N^r$
L_n^D	index set of legs scheduled to depart from station n, $n \in N^a \cup N^r$
W	index set of slot window duration on which the airport runway capacities are evaluated
h	discretisation time step
Δ	maximum pushback parameter, multiple of h
Δ_{atfm}	maximum pushback parameter for flights subject to the AFTM slot adherence constraint, multiple of h
$o_n^{\max}$	number of tracks at train station n, $n \in N^r$
$y_n^{A,w}$	runway arrival capacity for a window of length w, $w \in W$, (*i.e.,* the maximum number of arrival flights that could be scheduled within the hw minutes window), $n \in N^{air}$
$y_n^{D,w}$	runway departure capacity for a window of length w,, $w \in W$, $n \in N^{air}$.
$\text{MCT}_{l',l}$	minimum connection time to connect from leg l' to leg l, $l \in L, l' \in \mathcal{C}_l$

Input data	
T_l^D	initial scheduled departure time of leg l, $l \in L$
T_l^A	initial scheduled arrival time of leg l, $l \in L$
o_n^0	the initial number of trains at train station n, $n \in N^r$
IVT_l	in-vehicle time of leg l, $l \in L$
TAT_{l_1,l_2}	minimum turnaround time between legs l_1 and l_2, $(l_1,l_2) \in P^{air}$
dw_{l_1,l_2}	stop time between legs l_1 and l_2, $(l_1,l_2) \in P^{rail}$
n_l^D	volume of passengers using l as a direct connection, $l \in L$

$n_{l',l}$	volume of passengers transferring from leg l' to leg l, $l \in L, l' \in C_l$
r_l	reallocation delay for passenger missing their connection with leg l, $l \in L$

Main decision variables	
k_l^D	index of slot at which leg l is scheduled to depart, $l \in L$

Auxiliary decision variables	
k_l^A	index of slot at which leg l is scheduled to arrive $l \in L$
t_l^D	new scheduled departure time of l, $l \in L$
t_l^A	new scheduled arrival time of l, $l \in L$
d_l	delay associated to leg l, $l \in L$
$d_{l',l}$	delay experienced by passenger connecting from leg l to leg l', $l \in L, l' \in \mathcal{C}_l$
$y_{l',l}$	binary, indicates whether the connection from leg l' to leg l is feasible or not, $l \in L$, $l' \in \mathcal{C}_l$
$x_{l,s}^D$	binary, indicates whether leg l is scheduled to depart after s, $s \in S$
$x_{l,s}^A$	binary, indicates whether leg l is scheduled to arrive after s, $s \in S$
$o_{n,s}$	the number or trains stopped at n at slot s, $n \in N^r$

The model, which aims to minimise the total passenger delay, therefore reads:

$$\min \sum_{l \in L} \left(n_l^D d_l + \sum_{l' \in C_l} n_{l',l} d_{l',l} \right), \tag{1}$$

subject to:

$$t_l^D = h(k_l^D - 1) \qquad l \in L \tag{1a}$$
$$t_l^A = t_l^D + IVT_l \qquad l \in L \tag{1b}$$
$$k_l^A = k_l^D + \frac{IVT_l}{h} \qquad l \in L \tag{1c}$$
$$k_l^D \leq s + M x_{l,s}^D \qquad l \in L, s \in S \tag{1d}$$
$$\sum_{s=0}^{N_s} x_{l,s}^D \leq k_l^D \qquad l \in L \tag{1e}$$
$$k_l^A \leq s + M x_{l,s}^A \qquad l \in L, s \in S \tag{1f}$$
$$\sum_{s=0}^{N_s} x_{l,s}^A \leq k_l^A \qquad l \in L \tag{1g}$$
$$t_l^D \leq t_l^{D,0} + \Delta \qquad l \in L \tag{1h}$$
$$t_l^D \leq t_l^{D,0} + \Delta_{\text{atfm}} \qquad l \in L^{\text{atfm}} \tag{1i}$$
$$t_l^D - t_l^{D,0} = d_l \qquad l \in L \tag{1j}$$
$$t_{l_2}^D - t_{l_1}^A \geq TAT_{l_1,l_2} \qquad (l_1, l_2) \in P^{air} \tag{1k}$$
$$t_{l_2}^D - t_{l_1}^A = dw_{l_1,l_2} \qquad (l_1, l_2) \in P^{rail} \tag{1l}$$
$$o_{n,0} = o_n^0 \qquad n \in N^r \tag{1m}$$
$$o_{n,s} = o_{n,s-1} + \sum_{l \in L_n^A} (x_{l,s-1}^A - x_{l,s}^A) + \sum_{l \in L_n^D} (x_{l,s-1}^D - x_{l,s}^D) \qquad n \in N^r, s \in \mathcal{S} \tag{1n}$$
$$o_{n,s} \leq o_n^{\max} \qquad n \in N^r, s \in \mathcal{S} \tag{1o}$$
$$\sum_{\tau=s}^{s+w-1} \sum_{l \in L_n^A} x_{l,\tau}^A - x_{l,\tau+1}^A \leq y_n^{A,w,s} \qquad n \in N^a, w \in W, s \in \mathcal{S}' \tag{1p}$$
$$\sum_{\tau=s}^{s+w-1} \sum_{l \in L_n^D} x_{l,\tau}^D - x_{l,\tau+1}^D \leq y_n^{D,w,s} \qquad n \in N^a, w \in W, s \in \mathcal{S}' \tag{1q}$$
$$t_{l'}^D - t_l^A \geq \text{MCT}_{l',l} \qquad (l, l') \in \mathcal{C}_l^{\text{p}} \tag{1r}$$
$$t_{l'}^D - t_l^A + M y_{l',l} \geq \text{MCT}_{l',l} \qquad l \in L, l' \in \mathcal{C}_l \tag{1s}$$
$$d_{l',l} \geq y_{l',l} r_l \qquad l \in L, l' \in \mathcal{C}_l \tag{1t}$$
$$d_{l',l} \geq d_l \qquad l \in L, l' \in \mathcal{C}_l \tag{1u}$$
$$k_l^D, k_l^A \in S \qquad l \in L \tag{1v}$$
$$t_l^D, t_l^A \in \{0, \ldots, h(|S| - 1)\} \qquad l \in L \tag{1w}$$
$$d_l \in \{0, h, \ldots, \Delta\} \qquad l \in L \tag{1x}$$
$$d_{l',l} \in \{0, h, \ldots, r_l\} \qquad l \in L, l' \in \mathcal{C}_l \tag{1y}$$
$$y_{l',l} \in \{0, 1\} \qquad l \in L, l \in \mathcal{C}_l \tag{1z}$$
$$x_{l,s}^A, x_{l,s}^D \in \{0, 1\} \qquad l \in L, s \in \mathcal{S} \tag{1aa}$$
$$o_{n,s} \in \{0, \ldots, o_{n,s}^{\max}\} \qquad n \in \mathcal{N}^r, s \in \mathcal{S}. \tag{1ab}$$

Constraints (1a) and (1b) link the time slot to the actual auxiliary time variable for the departure and arrival time of leg l, respectively. Constraints (1c) calculate the arrival time slot of leg l based on its departure time slot. Constraints (1d) and (1e) fix the values of the binary variables $x_{l,s}^D$. Similarly, the constraints (1f) and (1g) fix the values of the binary variables $x_{l,s}^A$. Constraints (1h) limit the maximum departure delay for each leg l. Constraints (1i) ensure ATFM slot adherence. The actual delay is calculated by constraints (1j). The turnaround time constraints and the train dwell time constraints are given by (1k) and (1l), respectively. Constraints (1m) to (1o) fix the train station occupancy and ensure that it does not exceed the number of tracks at each train station. The maximum arrival and departure flight movements per time window are limited with constraints (1p) and (1q), respectively. Constraints (1r) ensure that passenger minimum connecting times for priority flights are maintained. Constraints (1s) fix the value of variables $y_{l',l}$ that characterise if passengers connecting between legs l' and l miss their connection. Constraints (1t) and (1u) fix the reallocation delay between flights l' and l to d_l if passengers have their connection, and to the reallocation delay r_l, otherwise. Finally, constraints (1v)-(1ab) define the definition domain of the decision variables.

V. Western Europe case study

This section focuses on the Western European case study. It first outlines the data used and the assumptions made. The modelling approach for passenger transfers is then presented. Finally, it describes in detail the post-processing procedure for reallocating passengers, which is crucial for accurately assessing the total passenger delay.

A. *Network characteristics and data*

TABLE I. Case study characteristics

Case study description	
Case Study	Western European Transport Network
Number of airports	496
Number of train stations	72
Number of flights	10407 (593 from CDG)
Number of trains	646 (66 to CDG station)
Airports with limited capacity	18 largest airports in France, Germany, and Spain
Airport with connecting passengers	CDG, FRA, MAD
Train stations with limited capacity	3 stations, each associated with a hub
Train schedule data source	GTFS data
Flight schedule data source	OAG
Minimum aircraft turnaround time (TAT)	45 min
Disruption scenario characteristics	
Date	4 December 2019
Considered events	French railway company on strike
Disruption duration	From 00:00 to 23:59
Train delay percentage	30% of trains are late at CDG
Train delay duration (min)	$X \sim \mathcal{U}(30, 90)$
Train cancellation	Not considered
Flight/Train travel time	Constant
Priority flights	25% of flights need to comply with their ATFM slots at main airport hubs
ATFM delays	Not considered
Maximum priority flight delay	10 min
Maximum flight delay	30 min

Table I presents the characteristics of the case study considered. This case study focuses on the historical day of December 4, 2019 when the French National Railway Providers (SNCF) went on strike. We gather initial flight schedules [31] from the 18 largest airports in France, Germany, and Spain, including three major hub airports: Frankfurt Airport (FRA), Madrid-Barajas Airport (MAD), and Paris-Charles de Gaulle Airport (CDG). Throughout this day, 10,407 flights were operated, with 593 departures scheduled at CDG, as illustrated in Figure 1. We also consider the train schedules associated with each hub airport and their respective connecting airports, involving 646 train legs [32]–[34]. The train schedules were collected on each operator website. It is important to note that we could not access the actual train delay data or the number of train cancellations. Therefore, we simulate the disruption by randomly delaying 30% of trains arriving at CDG-High Speed Rail train station. The delay times were randomly selected using a uniform distribution ranging from a minimum delay, denoted as $t_{\min}$, to a maximum delay, denoted as $t_{\max}$.

Air Traffic Flow Management (ATFM) delays were not considered here. Therefore, *delayed* flights are only those impacted by the proposed rescheduling algorithm. We assume

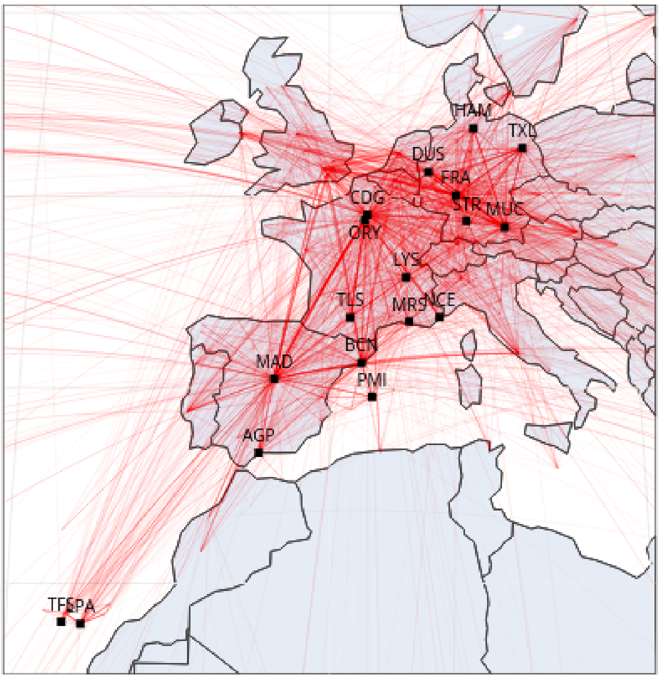

Figure 1. Illustration of flights operated on December 4, 2019, on Western Europe (source: [35]).

that the maximum delay assignable to a flight is 30 minutes and that 25% of flights at each main hub airport were subject to ATFM slot adherence. This percentage is arbitrarily fixed and can be tuned by a final user, depending on airport characteristics. The maximum assignable delay for flights subject to ATFM slot adherence is set to 10 minutes.

Additionally, we allowed train tactical rescheduling to ensure compliance with the maximum train station capacity, which may have been compromised due to the initial train delays and disruptions caused by the strike. Lastly, we assume that all information regarding train delays and connecting passengers is fully known before rescheduling. Therefore, we employ a one-iteration process to reschedule all legs operated from the morning until the end of the day.

B. *Modelling passenger transfers*

In order to model passenger transfers between modes, the same method proposed by [35] is used. In a nutshell, the method consists in modelling intramodal (air-air) and intermodal (train-air) passenger connections at a hub airport, using a Constraint Programming approach [36]. Based on airport modal share and flight passenger volume, the method generates passenger volume that transfers between two scheduled legs. We limit the study by considering only passengers with at most two legs in their total journey. The number of connecting passengers simulated with the proposed methodology is presented in Table II.

C. *Passenger reallocation procedure*

Similarly to the rebooking procedure proposed by [37], we propose the following passenger reallocation procedure.

TABLE II. Number of connecting passengers per airport. A distinction is made between train-air connections and air-air connections.

Airport	Connection type	Number of connecting passengers
CDG	air-air	30638
	train-air	18022
FRA	air-air	41599
	train-air	12101
MAD	air-air	22277
	train-air	8168

In the mathematical model, we assume that passengers will be accommodated on the next flight to the same destination if they miss their scheduled flights. However, each aircraft has a finite capacity, defined by the number of seats it can offer. To overcome this limitation, we present a post-processing method that effectively reallocates stranded passengers to alternative flights, considering each aircraft capacity. Since we do not know the actual number of seats available, we assume an 80% load factor for each aircraft. For example, if an original flight carried 50 passengers, we assume $50 \times \frac{100}{80} - 50 \approx 12$ available seats. We extend this reallocation approach to direct trains as an alternative method, again assuming an 80% load factor for each train.

The reallocation process follows a systematic sequence. We consider the chronological list of passengers who have missed their flights and a corresponding set of feasible direct alternatives for each individual. These alternatives are ranked according to the delay they cause at the passenger final destination. For each passenger, we offer the best available re-routing option (in terms of delay). In the case where the best alternative flight/train is full, we select the second best option, and so on. When no re-accommodation option is available, the passenger is stranded and subject to a 24-hour delay. Note that the reallocation procedure is operated after the rescheduling, i.e. flight and train delays are considered to select the best reallocation options for passengers who miss their flights.

VI. Results

Computations are performed using an AMD Ryzen 5 4500U CPU and 16 GB RAM laptop. The resolution of the optimization problem formulation is made with the MIP solver Gurobi, version 9.1.2 [38]. The computation time is 23 seconds.

A. Passengers gain

Figure 2 displays the distribution of buffer time for passengers transferring from a train to a flight at CDG airport. The transfer buffer time equals the difference between the actual passenger transfer time and the minimum required connection time. We only display buffer times of passengers who would have missed their flight based on the original schedule but can still make it on time if the flight is delayed. We do not show passengers who arrive before the initial departure time or who arrive more than 30 minutes after the initial departure time. The figure shows a significant increase in passenger connections with a 0-minute buffer time after rescheduling. A

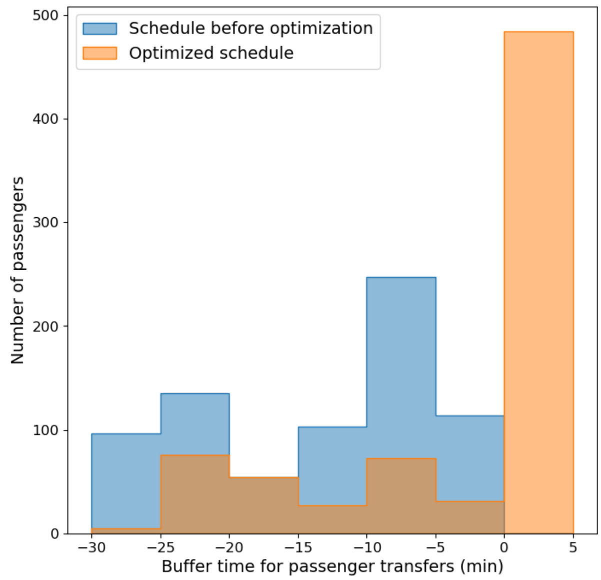

Figure 2. Distribution of passenger transfer buffer times before and after rescheduling. Buffer times are calculated by subtracting the minimum connecting time from the actual passenger transfer time. A negative buffer time indicates that passengers do not have enough time to transfer, caused by a delay on their first leg. This graph only shows passengers who could recover their initial flights thanks to the rescheduling (*i.e.* missing their flights by 30 minutes or less before rescheduling).

0-minute buffer time corresponds to a transfer time equal to the minimum connection time required for passengers to catch their flight. Consequently, the delay management strategy allows 484 of the 1221 passengers who initially missed their flights to arrive on time for boarding. The rescheduling does not induce buffer time strictly larger than 0 minutes for these passengers as this would delay the *on-time passengers* and, therefore, increase the total passenger delay.

Figure 3 depicts the total delay experienced by passengers before and after optimization. The main difference between the initial and the optimized schedule lies in the number of stranded passengers. Indeed, 614 passengers have no reallocation option before optimization and should wait until the next day to reach their final destination. After optimization, the number of stranded passengers is reduced by 71% and the total passenger delay by 55%. Indeed, the algorithm prioritises these passengers if the flight can wait since the cost of a missed connection is large. However, the maximum flight delay authorised to wait for passengers is 30 minutes (or 10 minutes for priority flights that need to respect their departure slots). Hence, some passengers might not have their connections if the required time to make the connection is above that limit. Therefore, several passengers remain stranded even after the rescheduling. Finally, the total delay experienced by direct passengers departing from CDG is 12810 minutes, resulting in an average passenger delay of 0.3 minutes. As a result, the rescheduling has a minimal impact on *on-time passengers*.

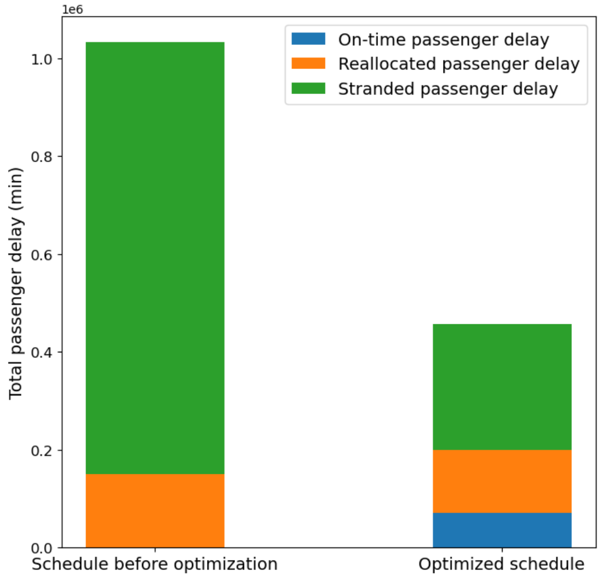

Figure 3. Total passenger delays before and after rescheduling, stacked by passenger types (*on-time passengers*, *reallocated passengers* and *stranded passengers*).

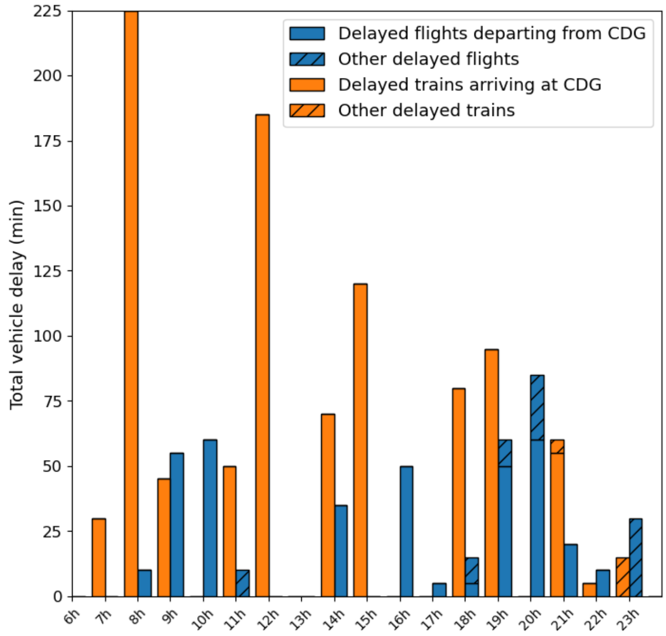

Figure 4. Distribution of total vehicle delays per hour. Flight and train delays are displayed in blue and orange, respectively. The hatched bars represent reactionary delays.

B. *Operator delays*

Regarding operator delays, Figure 4 displays the total vehicle (train or aircraft) delay per hour. Orange plain bars represent the total train delay, including the delay due to the strike and the one assigned during the rescheduling due to train station constraints. One can observe that most of the delayed trains are in the morning. The hatched bars correspond to flights not departing from CDG and trains not arriving at CDG, *i.e.* the reactionary delay on the network. Reactionary delays may occur for several reasons. A tight initial turnaround time could not absorb the delay of an arriving flight. Limited airport and train station capacities could also lead to rescheduling other flights and trains to avoid congestion. Finally, delayed flights or trains with connecting passengers could also create reactionary delays at their arrival station to maintain passenger connections. After rescheduling, seven trains are delayed, including four at stations other than CDG. 35 flights are also delayed, out of which eight are from CDG. Significant flight delays are observed during the morning rush hour (9 am and 10 am) and evening (7 pm and 8 pm). The morning hours see a surge in missed passenger connections due to significant train delays in the previous hour. The second peak of flight delays is either due to reactionary delays from previous flights (displayed by hatch bars) or fewer flight reallocation options. Indeed, passengers who miss their connections at the end of the day are more likely to be stranded without reallocation options until the next day. Hence, rescheduling gives higher priority in waiting for them.

On average, due to the rescheduling, all flights across Europe experience a delay of 0.04 minutes, while the departing flights at CDG experience a delay of 0.84 minutes. The proposed rescheduling plan delays 5% of the departing flights at Paris-CDG airport by 13 minutes on average. To put this into perspective, Table III shows the characteristics of the actual delays experienced by flights during the historical operating day in question. As per the table, departing flights at CDG were

TABLE III. ACTUAL FLIGHT DELAY ON DECEMBER 4TH 2023 (IN MINUTES). (SOURCE: EUROCONTROL)

	CDG	All
Average actual flight delay	11.0	6.1
Maximum actual flight delay	120	1310

operated with an average delay of 11 minutes. Therefore, our proposed rescheduling approach seems reasonable compared to the actual delays the airport has to deal with during a typical operating day.

Figure 5 shows a map of delayed flights and the magnitude of these delays. The colour and the width correspond to the departure time and the delay assigned to the flight, respectively. More specifically, a darker colour indicates that the flight's departure time is later in the day, and the greater the width, the greater the delay. It can be seen that long-haul flights are generally those with the highest assigned delay. The colour of these flights also indicates that they are scheduled in the morning. In fact, these long-haul flights tend to have a daily frequency compared to short-haul flights. The re-routing time for passengers who miss their connections is, therefore, 24 hours. On the other hand, delays on short-haul flights are generally assigned in the evening, when passengers have no more opportunities for re-routing. It can also be observed that a few flights are delayed due to network propagation. These delays occur because the turnaround time initially planned by

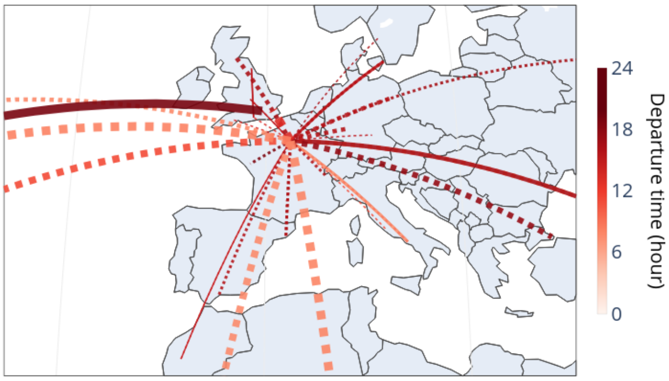

Figure 5. Visualisation of post-rescheduling flight delays. The linewidth and the colour-coding system indicate the delay magnitude and the departure time of the day, respectively. Dotted lines correspond to flights departing from CDG airport, plain lines to other flights.

the airlines between a delayed flight at CDG and the following flight is small. It can be observed that the rescheduling delays an evening flight by 30 minutes departing from the US due to minimum turnaround time constraints and the assumption of constant in-vehicle time. However, in practice, the previous flight operated by the aircraft could have been speeding up to recover from its departing delay, reducing the impact of the proposed delay management strategy. Such action is especially true for long-distance flights and could be included in further work.

Finally, as mentioned above, exogenous ATFM delays were not considered in this study. However, the proposed rescheduling strategy could deal with these delays by rescheduling flights to wait for connecting passengers and reduce station congestion. Taking these exogenous delays into account would have an impact on the rescheduling solution, as ATFM delays of departing flights could already reduce the number of passengers missing their rail/air connections.

VII. Conclusion and Future Works

Europe's investment in different multimodal research projects underlines the need for collaboration between air and ground transport stakeholders, to provide passengers with reliable journeys. Such air-rail integration would not only improve passenger experience but also allow airlines and airports to have accurate information about passenger connections. This could create a win-win situation for the stakeholders involved, by boosting passenger demand while limiting extra expenses for the service providers. In this context, we have presented a delay management strategy tailored to a large integrated air-rail network. We simulated a disruption occurring on the French railway network which led to passengers missing their connections at CDG airport. The results highlight the effectiveness of our mitigation strategy, demonstrating its ability to reduce passenger delays by 55%, while only delaying 5% of departure flights at CDG airport. By considering the entire network, our delay management strategy creates new flight and train schedules that satisfy operational constraints such as station capacities and minimum aircraft turnaround times at other airports throughout the day. This rescheduling approach limits delay spread by identifying which flights may propagate delays.

The research conducted in this study contributes to enhancing the passenger experience when travelling across a multimodal long-distance network. Further research on the operator rescheduling cost and passenger preferences should be conducted to implement the proposed delay management strategy. This extension will ultimately lead to better acceptance among transportation stakeholders and an improved passenger travel experience. Analysing a potential airside disruption would provide valuable insights into how the rescheduling differs, based on constraint differences on the air and railway sides. Another interesting extension would be to consider dynamic cost indexing, as proposed by [21], which relaxes the constant travel time assumption and allows aircraft and trains to speed up to recover from delays. Finally, the rescheduling process should consider ATFM constraints such as en-route capacity and airside delays.

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