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This paper proposes a method to generate an integrated air-rail timetable at a hub airport with direct access to a train station. A passenger-oriented metric is introduced to assess the connection time between trains and flights. In order not to impact severely initial flight and train schedules, only small perturbations on the initial timetable are authorized. An integer linear programming formulation is proposed based on this metric. An approached resolution method is implemented to solve the optimization problem. Solution quality and computational time are compared with an exact resolution method. Computational results on the case study of Paris-Charles de Gaulle airport are presented. Results show that a change of an average 11 minutes in schedules could increase passenger comfort by almost 10%.

Key Words : Air-rail integrated timetable, passenger-oriented metric, multimodality, integer linear programming

1 Introduction

In its Flightpath 2050,[1)] the European Commission sets the objective that "passengers and freight are able to transfer seamlessly between transport modes to reach the final destination smoothly, predictably and on-time". Thus, aviation should no longer be considered as an isolated system but as a component of the overall global transportation system. However, an efficient multimodal network can only be implemented if coordination and communication between modes exist, both at the strategic and the tactical levels. The Meta-CDM project[2)] highlights benefits that could be obtained through a better coordination between air and ground transportation systems. The authors stress that communication between transportation stakeholders is essential to ensure passengers a seamless door-to-door journey. One key indicator to assess the smoothness of passenger trips is transfer times between modes. These times result from the scheduling process of each mode, which is generally made without coordination between transportation stakeholders. Hence, there is room for improving the passenger experience by developing an integrated schedule.
From two initial air and rail timetables, the objective of this work is to generate a new air-rail (AR) schedule that optimizes the transfer time between trains and flights at a given airport from a passenger perspective. The contributions of this paper are the following:

- A new metric is proposed to assess the quality of a timetable from a passenger perspective, characterized by transfer times between flights and trains.
- Based on this metric, an Integer Linear Programming (ILP) model is formulated to maximize passengers comfort through an integrated AR timetable.
- A metaheuristic algorithm is implemented. The algorithm succeeds in finding a solution at 0.1% from the optimal value in less than the third of time required by the exact method.
- The method is tested on the real-case study of Paris-Charles de Gaulle airport (CDG).

This paper is organized as follows. First, Section 2 presents previous work related to AR integration. Section 3 details the passenger metric introduced. Section 4 and Section 5 describe the mathematical formulation of the problem and the resolution method, respectively. Finally, results obtained on the CDG case study are presented in Section 6.

2 Related work

Givoni and Banister[3)] are among the first authors to highlight the potential benefits of a cooperation between airlines and railway operators. They emphasise the fact that High-Speed Rail (HSR) could relieve airport congestion by replacing feeder flights. Later, Clewlow *et al.*[4)] show that the introduction of HSR in France has decreased the air market on Origin-Destination (OD) pairs equipped with HSR. This highlights that rail lines could substitute feeder flights on covered lines. To achieve that goal, the authors underline that coordinating timetables is a key factor. However, they stress that partners can have different objectives and are not always prone to change their network. In the same manner, Xia and Zhang[5] study the benefit of reducing AR connecting times for passengers. They show that passengers value smoothness in their door-to-door trip, hence will prefer shorter connecting times. However, they show that airlines and railways are interested in cooperation only if it does not require hard changes in their respective networks. Chiambaretto *et al.*[6] study several aspects or AR cooperation such as connecting times, luggage service or guarantee in case of delays. Their analysis reveal that depending on whether the trip purpose is business or leisure, passengers will prefer shorter or longer connection times. This shows that a coordination is required to fit better passengers expectation. However, even if potential benefits of cooperation between air and rail have largely been studied, few timetable coordination methods have been proposed. Recently, Ke *et al.*[7] aim at synchronizing trains and flights at a specific airport by adjusting the railway timetable. Their objective is to maximize the number of feasible connections between trains and flights. They also considered maximizing the number of synchronized flights and maximizing passengers' satisfaction by limiting the deviation from the initial schedule. Jiang *et al.*[8] propose a method to minimize passengers transfer times within an intercity HSR network. They enrich their model by adding flight synchronization constraints. This constraint ensures that enough trains serve flights in the new schedule. These studies both focus on adjusting a railway timetable to improve synchronization with flights. However, they mainly focus on maximizing coverage.

Here, compared with Ke *et al.*,[7] we do not assume that passengers discomfort is due to change from the initial schedule, but that passengers have a preferred transfer time. Moreover, in addition to rail schedules, we propose changes to the flight schedule so as to synchronize both ways: from trains to flights connections, and from flights to trains connections. Domestic and international flights are considered distinctly as they involve different transfer times to go through the airport security process. The purpose of the present work is to develop a methodology to generate an integrated timetable between flights and trains at an airport that maximizes transfer comfort for passengers. The objective is to improve existing connections, by maximizing the number of *suitable* connections from a passenger perspective: connections that are close to be the optimal connection, according to passengers. The next section proposes a metric to assess the quality of a connection from a passenger view point.

3 Passenger-oriented metric

The connection time between modes is crucial to enable passengers to shift seamlessly between modes. One needs to define an appropriate passenger-oriented metric to assess the quality of an intermodal timetable. The definition of a reasonable connection time depends on the modes involved. For instance, due to the airport processing time, a 30-minute train-flight connection at a hub airport is likely to induce stranded passengers. Moreover, such a short connection is not robust to delays occurring on the first leg. Theis *et al.*[9] show that passengers are not necessarily looking for short connection times, due to the risk of missed connections. On the contrary, a 5-hour connection is not attractive for passengers, since it prolongs the journey and breaks the smoothness of the trip. Also, as explained by Wardman,[10] waiting time is perceived longer than in-vehicle time. Thus, long connection times are not desired in the final schedule. Hence, an optimal connection time for passengers must be considered. The objective is to construct an integrated schedule between trains and flights that would provide connections that are both attractive and robust for passengers. A connection between two modes can be characterized by the following three parameters:

- a minimum connection time (t_{min}): under this value, the connection between the two legs is considered as unfeasible,
- an optimal connection time (t_{opt}): this value is the ideal trade-off between a tight connection and a too-long waiting time at the station,
- a maximum connection time (t_{max}): above that time, the connection is considered not attractive for passengers, due to the too-long waiting time at the transfer station.

These parameters depend on the connection type considered. Indeed, a train-flight connection requires additional time due to the airport security process, compared with a flight-train connection. We propose quality function for a connection type, k, that is piecewise linear:

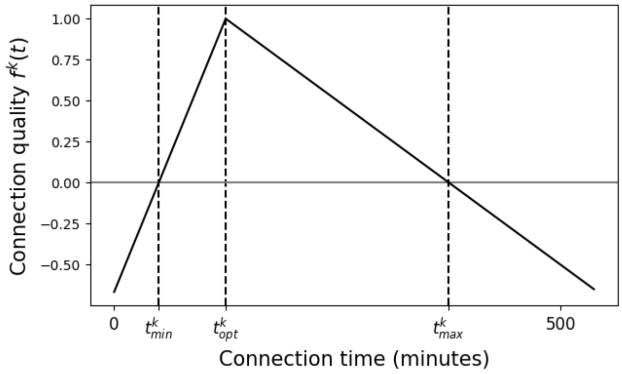

Fig. 1: The connection quality function.

$$f^k(t) = \begin{cases} f_1^k(t) = \frac{t - t^k_{\mathrm{min}}}{t^k_{\mathrm{opt}} - t^k_{\mathrm{min}}} & t \le t^k_{\mathrm{opt}} \\ f_2^k(t) = \frac{t^k_{\mathrm{max}} - t}{t^k_{\mathrm{max}} - t^k_{\mathrm{opt}}} & t \ge t^k_{\mathrm{opt}} \end{cases} \quad (1)$$

where t^k_{min}, t^k_{opt} and t^k_{max} are the time parameters associated to k, the connection type, and t is the connection time. It is displayed on Fig.1 where we assume that passengers prefer long connections to short connections since they are more robust in case of delays. This function can be interpreted as the passenger satisfaction regarding the connection time. If the connection is too short ($t < t^k_{\mathrm{opt}}$), the satisfaction decreases due to the risk of missed connection. Beyond t^k_{opt}, passengers would make their connection but after a waiting time that increases. The illustrated asymmetry is representative of passengers' behavior who are more inclined to select long-time connections than non-robust ones. The objective is to create an AR timetable involving as many suitable connections as possible. The optimization problem is presented in the following section.

4 Problem formulation

This section describes the AR schedule optimization problem, and then proposes a mathematical-optimization formulation of it: the input data, the decision variables and, finally, the objective function and constraints.

4.1. Problem description

Consider a hub airport with a direct access to a HSR station. In the sequel, the term leg refers to either a rail-leg or a flight. The problem consists in creating a synchronized timetable between trains and flights at the given airport. Given two initial and independent air and rail schedules, the objective is to generate a

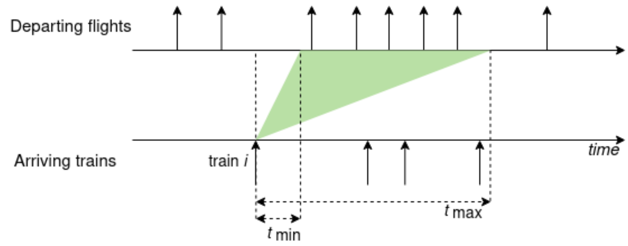

Fig. 2: Set of positive-quality connecting flights (above the triangle) for one arriving train i.

new planning which favors high-quality connections. A connection corresponds to a leg couple (train-flight or flight-train) with connecting passengers. Connections are characterized by an initial connection time which corresponds to the difference between the initial departure time of the second leg and the initial arrival time of the first leg. Figure 2 illustrates the set of flights that can be connected from a train i with a positive value of the quality function. Note that flights can be connected from several trains. The objective of the method is to adjust initial timetables in order to improve connection times according to the passenger-oriented metric defined through the quality function. Since transportation suppliers are looking for regularity in their planning, only small changes in the initial schedules are authorized.
In order to model our problem under the form of a discrete optimization problem (the set of possible time slots at both airports or train stations is not continuous), we discretized time. More precisely, for each leg l the initial arrival/departure time, noted t^0_l, can be deviated to one of the following $2n+1$ possible candidate values: $t^0_l - nh,\ t^0_l - (n-1)h,\ \ldots,\ t^0_l - h,\ t^0_l,\ t^0_l + h,\ \ldots t^0_l + (n-1)h,\ t^0_l + nh$, where h is the discretization step size.

Data, decision variables, constraints and the objective function of the proposed ILP formulation are presented below.

4.2. Data

We use a graph data structure whose vertices correspond to legs (rail-legs or flights) and whose arcs correspond to connections.

- h: discretization time step.
- n: deviation window width.
- $\mathcal{F} = \mathcal{F}_A \cup \mathcal{F}_D$: index set of flights, partitioned in those scheduled to arrive at the airport and those to depart from the airport.
- $\mathcal{R} = \mathcal{R}_A \cup \mathcal{R}_D$: index set of rail legs, partitioned in those scheduled to arrive at the airport and those to depart from the airport.

- $\mathcal{L} = \mathcal{F} \cup \mathcal{R}$: index set of legs partitioned in flight indices and train indices.
- $\mathcal{E}_F$: the set of consecutive flight pairs operated by a same aircraft.
- $\mathcal{E}_R$: the set of consecutive rail-leg pairs operated by a same train.
- $\mathcal{S} = \{s_0, s_1, \ldots, s_N\}$: the set of slots starting times, with N the number of slots.
- $\mathcal{K}$: the set of connection types.
- $\mathcal{A}^k$: set of arcs of connection arcs of type k involving connecting passengers, $k \in \mathcal{K}$.
- w_{ij}^k: number of passengers connecting from leg i to leg j, for arc $(i,j) \in \mathcal{A}^k$, k in $\mathcal{K}$.
- λ_{ij}^f: the minimum turnaround time between flights i and j, $(i,j) \in \mathcal{E}_F$.
- λ_{ij}^r: the initial dwell time at station of the train that operates rail-legs i and j, $(i,j) \in \mathcal{E}_R$.
- t_i^0: the initial departure/arrival time from/at the airport, $i \in \mathcal{L}$.
- $\mathcal{S}_i$: set of possible slots at which leg i can be scheduled to arrive/depart, $i \in \mathcal{L}$.
- $\mathcal{F}_A^s = \{i \in \mathcal{F}_A | t_i^0 - nh \le s \le t_i^0 + nh\}$: set of flights that are allowed be scheduled to arrive at the airport at slot s, $s \in \mathcal{S}$.
- $\mathcal{F}_D^s = \{i \in \mathcal{F}_D | t_i^0 - nh \le s \le t_i^0 + nh\}$: set of flights that are allowed be scheduled to take off at slot s, $s \in \mathcal{S}$.
- $\mathcal{R}_A^s = \{i \in \mathcal{R}_A | t_i^0 - nh \le s \le t_i^0 + nh\}$: set of trains that are allowed be scheduled to arrive at the train station at slot s, $s \in \mathcal{S}$.
- $\mathcal{R}_D^s = \{i \in \mathcal{R}_D | t_i^0 - nh \le s \le t_i^0 + nh\}$: set of trains that are allowed be scheduled to leave from the train station at slot s, $s \in \mathcal{S}$.
- n_Φ: the window length for the airport arrival and departure capacity evaluation.
- $\mathcal{S}_\Phi = S - \{s_{N-(n_\Phi-1)}, s_{N-(n_\Phi-2)}, \ldots, s_N\}$: the set of slots starting times for which airport capacity is evaluated.
- Φ_A: airport arrival capacity (*i.e.,* the maximum number of arrival flights that could be scheduled within the n_Φ time window).
- Φ_D: airport departure capacity.
- $J_{\max}$: number of rail tracks.
- J_0: the number of trains stopped at slot s_0.

4.3. Decision variables

The decision variables are defined by:

- $x_{i,s} = \begin{cases} 1 & \text{if leg } i \text{ is scheduled at } s \\ 0 & \text{otherwise,} \end{cases}$ $s \in \mathcal{S}_i$, $i \in \mathcal{L}$
- t_i: new scheduled time of leg i, $t_i \in \mathcal{S}_i$.
- o_s: the number or trains stopped at the station at slot s

4.4. Objective function and constraints

The objective function to be maximized is the sum of the connection quality for each passenger. This yields the following ILP model:

$$\max_{x,\,t} \quad \sum_{k \in \mathcal{K}} \sum_{(i,j) \in \mathcal{A}^k} w_{ij}^k f^k(t_j - t_i) \tag{2a}$$

s.t.

$$\sum_{s \in \mathcal{S}_i} x_{i,s} = 1 \qquad i \in \mathcal{L} \tag{2b}$$

$$\sum_{s \in \mathcal{S}_i} s x_{i,s} = t_i \qquad i \in \mathcal{L} \tag{2c}$$

$$f^k(t_j - t_i) \le f_1^k(t_j - t_i) \qquad k \in \mathcal{K}, (i,j) \in \mathcal{A}^k \tag{2d}$$

$$f^k(t_j - t_i) \le f_2^k(t_j - t_i) \qquad k \in \mathcal{K}, (i,j) \in \mathcal{A}^k \tag{2e}$$

$$t_j - t_i \ge \lambda_{ij}^f \qquad (i,j) \in \mathcal{E}_F \tag{2f}$$

$$t_j - t_i = \lambda_{ij}^r \qquad (i,j) \in \mathcal{E}_R \tag{2g}$$

$$\sum_{\tau=s}^{s+n_\Phi h} \sum_{i \in \mathcal{F}_A^\tau} x_{i,\tau} \le \Phi_A \qquad s \in \mathcal{S}_\Phi \tag{2h}$$

$$\sum_{\tau=s}^{s+n_\Phi h} \sum_{i \in \mathcal{F}_D^\tau} x_{i,\tau} \le \Phi_D \qquad s \in \mathcal{S}_\Phi \tag{2i}$$

$$o_s = o_{s-h} + \sum_{i \in \mathcal{R}_A^s} x_{i,s} - \sum_{i \in \mathcal{R}_D^s} x_{i,s} \qquad s \in \mathcal{S} \backslash \{s_0\} \tag{2j}$$

$$o_{s_0} = J_0 \tag{2k}$$

$$o_s \le J_{\max} \qquad s \in \mathcal{S} \tag{2l}$$

Constraints (2b) and (2c) ensure that exactly only one time is selected for each leg and that an arrival or departure time is assigned to each leg respectively. Constraints (2d) to (2e) are the standard linearization of the concave piecewise linear function f^k: they assign the appropriate quality to each connection. Constraints (2f) and (2g) guarantee that turnaround constraints and stop times are respected for each pair of consecutive flights and rail-legs respectively. Finally, constraints (2h) and (2i) stipulate respectively that the airport arrival and departure capacities are not exceeded at each time step. Finally, constraints (2j) to (2l) ensure that the number of trains stopped at the station never exceeds the number of tracks.

5 Resolution method

In this section, a brief reminder of the metaheuristic employed. Then, a description of its use in our application is detailed.

5.1. Simulated annealing principle

The principle of the Simulated Annealing[11] (SA) algorithm is the following:

- The algorithm starts with an initial solution X_0.
- At each iteration, a neighbour X' of the current solution is generated
- If X' improves the objective function value, it is accepted as the current best solution. If not, X' is accepted with a certain probability. This probability decreases over time according to the *temperature* parameter, T, and the quality of X'. Accepting worst solutions can help the algorithm to escape from local optimum by exploring the research space.
- The temperature is decreased at each iteration and the algorithm stops when a temperature threshold ϵ is reached.

Detailed descriptions of the neighbour generation process, and of the solution evaluation are given in the following sections.

5.2. Neighbour generation

From a current solution $X = (x, t)$, a solution X' is generated randomly choosing a new time t_i for one leg i. At this step, for flight legs, the minimum turnaround constraints are verified. More precisely, if the new departure or arrival time t_i generates a turnaround conflict with another flight j, a new time t_j is selected so as to respect the constraint. Finally, the choice of the particular leg i to change follows the following principles. One first measures the *optimal score* of each leg i: it is the number of passengers that shift from/to that leg to/from other ones. For instance, for an arriving leg i, the score is equal to $\sum_j w_{ij}$ with j each departing leg with passengers arriving from i. Similarly, for a departing leg i, the score is equal to $\sum_j w_{ji}$ with j each arriving leg with passengers transferring from j to i. Hence, a so-called optimality gap for one leg can be measured by subtracting the sum of the scores with each leg connecting with i. The higher the difference is, the higher is the probability to select leg i.

5.3. Delta evaluation

For each neighbour, only connections affected by a change in one leg arrival or departure time have a different score than in the previous solution. Consequently, a so-called delta evaluation can be applied to avoid recomputing the terms of the objective functions that are not impacted. Only connection scores related to the new decision need to be computed to update the value of the objective function. This reduces substantially the computational time. Finally, constraints (2h), (2i) and (2l) are relaxed and replaced, to take into account capacity constraint violations, by the penalty term:

$$-\mu \left[\sum_{s \in \mathcal{S}_\Phi} \left(\max(0, \sum_{\tau=s}^{s+n_\Phi h} \sum_{i \in \mathcal{F}_A^\tau} x_{i,\tau} - \Phi_A) + \max(0, \sum_{\tau=s}^{s+n_\Phi h} \sum_{i \in \mathcal{F}_D^\tau} x_{i,\tau} - \Phi_D) \right) + \sum_{s \in \mathcal{S}} \max(0, o_s - J_{max}) \right],$$

where μ is a penalty parameter to be set by the user so that airport capacity constraints are respected.

More precisely, the best possible gain in the objective function for each connection is still lower than 1 (the best possible score). In addition, train stop constraints induce that two rail legs are impacted by a change. Similarly, flight turnaround constraints may lead to change the scheduled time of two flights. Consequently, for each neighbour, the best possible gain in the objective function remains lower than $2w$, with w the number of passengers affected. Thus, the value of μ can be set to $2w_{\max}$, where $w_{\max}$ is the maximum number of passengers that can be affected by a change. The next section presents results obtained for CDG airport.

6 Paris-Charles de Gaulle airport case study

This section describes the case study considered. The metaheuristic efficiency is assessed by comparing both computational time and solution quality with exact solver. Finally, results are presented and discussed.

6.1. Case study description

CDG airport is the largest French airport with a direct access to HSR station at Terminal 2. The HSR station is equipped with six tracks. We use historical data on flights operated at CDG, covering flight scheduled departure and arrival times, and train data from the French railway operator SNCF.[12] These air and rail schedules are those of 4^{th} December, 2019. On that day, 1,163 flights and 112 rail-legs were operated at CDG. Four trains were initially stopped at the train station. Moreover, in Europe, no border controls are performed within the Schengen area. This area is an agreement between 26 countries that abolished border controls between them. In the following, a distinction is made between connections with flight operated within the Schengen area, denoted by Schengen flights (SF), and flights operated out of the Schengen area, denoted by non-Schengen flights (NSF). For the latter, additional time for connection should be considered to go through security process. The three connection types considered are:

- Train-Schengen Flight (T-SF) connection: passengers use the train on the first leg to reach the airport, then catch a flight with a destination within the Schengen area,
- Train-non-Schengen Flight (T-NSF) connection: passengers use the train on the first leg to reach the airport then catch a flight with a destination out of the Schengen area,
- Flight-Train connection (F-T): passengers catch a train at the hub airport after their flight.

Danesi[13] propose values for t^k_{min}, t^k_{opt} and t^k_{max} for flight-flight connections depending on the connection type (continental-continental, continental-intercontinental and intercontinental-intercontinental). The same values for t^k_{opt} and t^k_{min} are retained for the train-flight connection types. Indeed, as explained above, T-SF connections can be considered as continental-continental connections, and T-NSF connections as continental-intercontinental ones. Regarding F-T connections, no check-in nor security process are required at the train station. Hence, t^k_{min}, t^k_{opt} and t^k_{max} are smaller. According to CDG website,[14] the train station is accessible from every terminal in less than 30 minutes. This value is retained for t^k_{min} for the F-T connection type. Table 1 summarizes the different values selected for the study. Since the method aims at studying benefits of an integrated timetable with limited changes for transportation operators, n is set to 3. Also, the time discretization step, h, is set to 5, in accordance with usual slots. These values limit the deviation from the initial schedule at 15 minutes around the initial departure/arrival time of each leg and consequently the cost for companies. Finally, since no information on passenger flows were accessible, we made the following assumptions in our tests:

Table 1: Values of t^k_{min}, t^k_{opt} and t^k_{max} for the three connection types considered.

Connection type	t^k_{min}	t^k_{opt}	t^k_{max}
F-T	30	60	180
T-SF	45	90	270
T-NSF	60	120	300

- All connections (i, j) have the same number of transferring passengers w_{ij}.
- Among all feasible connections for a given day, only relevant connections are considered: *i.e.*, only connections between OD pair with no direct flights between them are considered. These direct connections were obtained from Eurocontrol archive data[15] on that date.

These assumptions led to optimize 2,360 T-SF connections, 3,263 T-NSF connections, and 3,786 F-T connections.

6.2. Resolution approach comparison

Tests are performed on a laptop with an AMD Ryzen 5 4500U with Radeon CPU and 16GB RAM. In order to assess the accuracy and the speed of the metaheuristic, our resolution approach has been compared with the solution obtained by the exact solver Gurobi version 9.1.2,[16] with the optimality gap set to 10^{-4}. Regarding our SA implementation, the penalty parameter μ has been set empirically to 530. Moreover, an initial temperature parameter has been determined by a *heat up* phase.[11] That consists in progressively increasing the temperature parameter until 80% of solutions are accepted. This heating phase yields an initial temperature T_0 of 1.4. At each iteration, the temperature decreases by a decay parameter set to 0.99. For each temperature level, 1000 neighbour generations are performed. The stopping threshold, ϵ, is set to $5.10^{-3}T_0$.

The exact method and the metaheuristic find a solution in 849 seconds and 260 seconds, respectively. The solution found with SA is at 0.1% of the optimal value. Although the computation time is acceptable with the exact solver (since the problem is to be solved only at the scheduling step), it is expected to face difficulties when considering a full transportation network for which CDG would be only one node. Moreover, the metric previously introduced depends heavily on an assumption about the passengers' behaviour. However, in practice, the shape of the quality function, f^k, might well not be concave. Non-concave ILP formulation requires one binary variable for each breakpoint. Regarding the dimension of the problem, this leads to thousands of binary variables. Preliminary computational experiments on this sensitivity reveal that this increases substantially the exact-solver computational

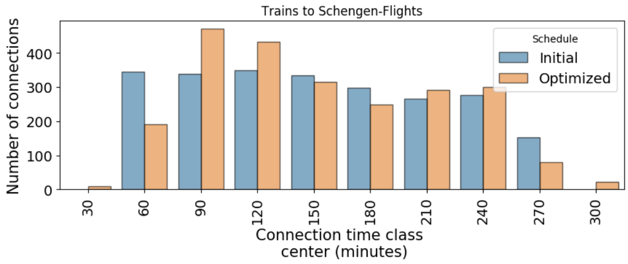

Fig. 3: Volume of connections grouped by connection times before and after optimization for T-SF connections.

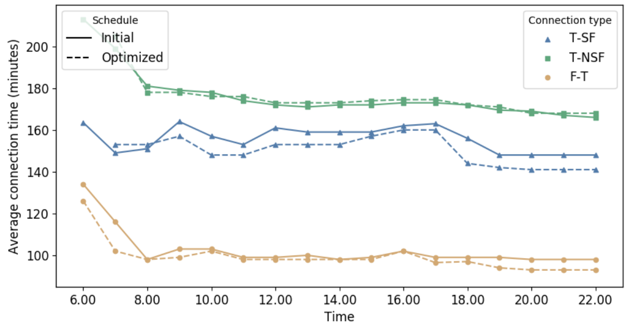

Fig. 4: Average connection time for passengers arriving between one-hour window

time. Indeed, the same quality solution is found in 35 minutes for the exact solver, compared to 254 seconds for the SA. The results presented in the sequel are obtained with SA.

6.3. Connection-time evolution analysis

In this section, the evolution in connection time distribution after optimization is studied. Results obtained on T-SF connections are displayed in Fig. 3. Connections are grouped by classes of connection time. Each class corresponds to a set of connections for which the transfer time is ±15 minutes around the center class time. The class whose the center is t^k_{opt} is referred to the *suitable* connections previously evoked.

Note that the solution satisfies airport capacity constraints. Moreover, the volume of suitable connections has increased by 39%. This means that the algorithm succeeds in providing more comfortable connections for passengers. This observation also holds for T-NSF and F-T connections, whose numbers of suitable connections increase by 40% and 37%, respectively. Also, classes of short connection times ($t < t^k_{\text{opt}}$) are less represented than in the initial schedule. However, one observes that a few connections are suppressed, since the transfer time in the integrated schedule is lower than t^k_{min} or greater than t^k_{max}. This can be explained by the fact that some schedule times may benefit more connections if they drop some other ones. This phenomenon rises up since all connections are assumed in this preliminary test to have the same number of transferring passengers w_{ij}, which is not the case in practice. Nevertheless, when flexibility is authorized, legs will tend to synchronize and there is an improvement in transferring comfort for most of passengers. The absolute average deviation from the initial schedule is 11.3 minutes, with a gain of 9.8% in the objective-function value. This shows that only a small deviation from the initial schedule, which respects transportation operators constraints, may improve passengers' door-to-door journey.

For each one-hour window, the average connection time for each connection type is presented in Fig. 4. For T-SF and F-T connections, on average connection times have been reduced to get closer from the optimal connection times defined. However, one can observe that this is true for T-NSF connections only for passengers arriving between 8AM and 10AM. One remarks from departing flights distribution that non-Schengen flights are mainly scheduled between 10AM and 12AM. Hence, these flights are better synchronized with arriving trains. On the contrary, during the afternoon, trains are better synchronized with Schengen flights. The distribution of both flights and trains arrivals and departures along the day before and after optimization is displayed in Fig. 5.

One observes that the optimization slightly increases the banking scheme operated. However, these waves newly include multimodal connections. For instance, the wave of arriving flights in the morning is brought forward to synchronize with departing trains scheduled around 9AM. Without airport capacity limitations, the algorithm would schedule all arriving flights at the same time, followed by all trains scheduled to stop 60 minutes later. Then all SF and NSF would depart 90 and 120 minutes after the trains, respectively. However, airport capacity constraints avoid this phenomenon. Moreover, information on passengers' preferred departure or arrival times would limit this effect. This additional information will enrich the methodology proposed.

7 Conclusion and future works

An ILP optimization model for AR timetable synchronization and a method to generate an integrated schedule at a given airport have been presented, based on a passenger-oriented metric. The method has been

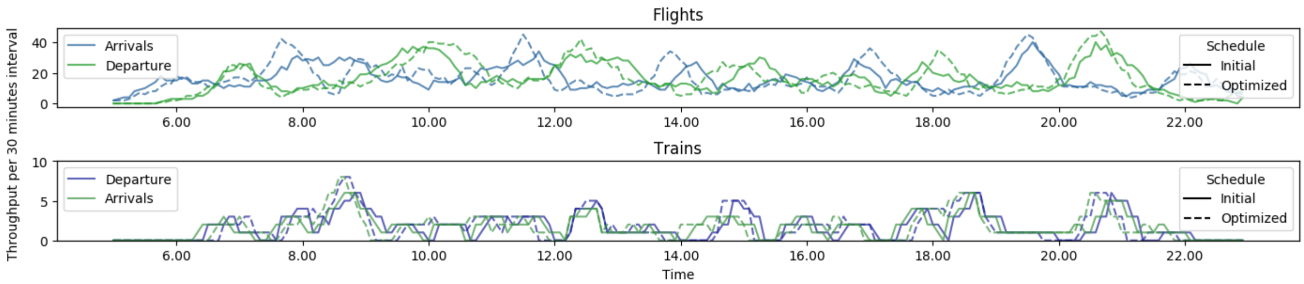

Fig. 5: Flights and trains arrival and departure throughput at CDG before and after optimization.

tested on a case study of CDG airport. Results show that a maximum schedule deviation of only 15 minutes from the initial planning for each leg can increase transfer times quality for passengers by almost 10%. Moreover, the number of suitable connections is increased by more than 38%, on average. Results show that improvements for passengers can be obtained with slight changes in the initial schedule of transportation operators taking into account operational constraints.

Future tracks of research may be envisaged. First, one can consider air-air connections to the model. Moreover, leg frequencies should also be considered. Indeed, if for a given OD pair only one flight from the airport to the destination is scheduled, the connection with the train must be well synchronized. On the contrary, one can assume that when several flights are available, passengers may be reassigned to next flights. Second, other ILP formulations can be tested to reduce computational time of the exact method. Finally, one can extend the scheduling process to a whole network of airports and train stations. Indeed, in this study, the algorithm is performed only at one airport. However, changing an arrival time (respectively departure time) of a flight operated at this airport is likely to change its departure time (respectively arrival time) at the origin (respectively destination) airport. The complexity of the problem is then expected to grow exponentially with the number of airports considered.

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References

1) Flightpath 2050. Europe's vision for aviation. *Report of the high-level group on aviation research.* European Commission, 2011.
2) Laplace, I., Marzuoli, A., and Féron, E.: META-CDM: Multimodal, efficient transportation in airports and collaborative decision making. *Airports in urban networks*, 2014.
3) Givoni, M., and Banister, D.: Airline and railway integration. *Transport policy*, 2006, 13(5), 386-397.
4) Clewlow, R. R., Sussman, J. M., and Balakrishnan, H.: Interaction of high-speed rail and aviation: Exploring air–rail connectivity. *Transportation research record*, 2012, 2266(1), 1-10.
5) Xia, W., and Zhang, A.: Air and high-speed rail transport integration on profits and welfare: Effects of air-rail connecting time. *Journal of air transport management*, 2017, 65, 181-190.
6) Chiambaretto, P., Baudelaire, C., and Lavril, T.: Measuring the willingness-to-pay of air-rail intermodal passengers. *Journal of air transport management*, 2013, 26, 50-54.
7) Ke, Y., Nie, L., Liebchen, C., Yuan, W., and Wu, X.: Improving synchronization in an air and high-speed rail integration service via adjusting a rail timetable: A real-world case study in China. *Journal of advanced transportation*, 13 pages, 2020.
8) Jiang, Y., Chen, S., An, W., Hu, L., Li, Y., and Liu, J.: Demand-driven train timetabling for air and intercity high-speed rail synchronization service. *Transportation letters*, 2022, 1-15.
9) Theis, G., Adler, T., Clarke, J. P., and Ben-Akiva, M.: Risk aversion to short connections in airline itinerary choice. *Transportation research record*, 2006, 1951(1), 28-36.
10) Wardman, M.: A review of British evidence on time and service quality valuations. *Transportation research part E: Logistics and transportation review*, 2001, 37(2-3), 107-128.
11) Delahaye, D., Chaimatanan, S., and Mongeau, M.: Simulated annealing: From basics to applications. *Handbook of metaheuristics.* Springer, 2019, 1-35.
12) SNCF. Horaire des TGV. `https://ressources.data.sncf.com`, 2022.
13) Danesi, A.: Measuring airline hub timetable co-ordination and connectivity: definition of a new index and application to a sample of European hubs. *European transport\ Trasporti europei*, 2006, 54-74.
14) EASYCDG. Train station terminal 2. `https://easycdg.com/transport/train-station-terminal2/`, 2022.
15) Eurocontrol. R&D data archive. `https://www.eurocontrol.int/dashboard/rnd-data-archive`
16) Gurobi Optimization, LLC. Gurobi Optimizer Reference Manual. `https://www.gurobi.com`