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Optimization for complex problems in air and rail transport

Paola Pellegrini

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Optimization for complex problems in air and rail transport

Paola Pellegrini

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Contents

Declaration	vii
Acknowledgments	viii
1 Research context: Air and rail transport problems	1
1.1 Introduction	1
1.2 Description of the infrastructure	2
1.2.1 Air transport system	2
1.2.2 Rail transport system	5
1.3 Infrastructure capacity allocation in air transport	9
1.4 Infrastructure capacity allocation in rail transport	11
1.5 Conclusion	13
2 Research contributions on air transport problems	15
2.1 Introduction	15
2.2 Primary slot allocation	16
2.2.1 Optimal simultaneous slot allocation	16
2.2.2 Metaheuristics for simultaneous slot allocation	18
2.2.3 SOSTA: optimal simultaneous slot allocation precisely modeling regulations and best practices	20
2.3 Secondary slot allocation	24
2.4 Conclusion	27
3 Research contributions on rail transport problems	30
3.1 Introduction	30
3.2 Saturation problem	32
3.3 Energy efficient travel time for timetabling	37
3.4 Timetable rearrangement problem in case of infrastructure maintenance	42
3.5 Real-time railway traffic management problem	45

3.5.1	RECIFE-MILP	46
3.5.2	ACO-TRSP	60
3.5.3	TDRC-MILP	64
3.6	Conclusions	67
4	Conclusions	74
5	Research perspectives	76
A	RECIFE-MILP model	79
B	Research projects and initiatives	85
B.1	European projects and initiatives	85
B.1.1	CATS	85
B.1.2	ON-TIME	86
B.1.3	Capacity4Rail	87
B.1.4	OptiYard	88
B.1.5	X2RAIL-2	89
B.1.6	ENGAGE	90
B.2	National projects	90
B.2.1	SIGIFret	90
B.3	Industrial projects	91
B.3.1	Gronda Sud di Milano	91
B.4	Personal projects	91
B.4.1	Metaheuristic tuning	91
C	Post-doctoral researchers, PhD, master and bachelor students supervision	93
C.1	Post-doctoral researchers	93
C.1.1	Rahimeh Neamatian-Monemi	93
C.1.2	Samuel Deleplanque	93
C.2	PhD students	94
C.2.1	Marcella Samà	94
C.2.2	Diego Arenas	94
C.2.3	Kaba Keita	94
C.2.4	Nicola Coviello	94
C.2.5	Teresa Montrone	95
C.2.6	Franck Kamenga	95
C.3	Advanced training, Master and Bachelor students	95

C.3.1	Gianpiero Francesca	95
C.3.2	Guillaume Douchet	95
C.3.3	Cecilia Negri	95
C.3.4	Martino Marangon	96
C.3.5	Cristina Bernardis	96
C.3.6	Elisa Marcelli	96

Summary

In this manuscript we present some research contributions on the modeling and solution of difficult optimization problems. Specifically, we focus on problems issuing from the fields of air and rail transport.

More in details, we consider problems concerning the effective use of infrastructure capacity in the two transport systems. Indeed, allocating the finite and often scarce capacity to satisfy competing demand is a difficult problem, which is tackled in different ways in the different phases of the capacity utilization planning process. In both systems, the first problem arises in the *strategic phase*, which take place some years before operations. These problems concern decisions on possible extensions or modifications of parts of infrastructure, and often concretize into capacity quantification studies or generic capacity offer definitions. Then, a few months before operations, in the *tactical phase* other problems emerge, more focused on the capacity allocation. In this phase, timetables are created, and they must be compatible with the existing capacity. Hence, important problems consist in identifying suitable ways for defining timetables, as well as appropriate approaches for arbitrating between competing demands when capacity is scarce. After capacity allocation is produced so that smooth operations are possible in nominal conditions, in the *operational phase* possible adjustments are performed to face emerging perturbations. If perturbations are known some time before operations, we talk of problems occurring in the *pre-operational phase*. Otherwise, if they are due to completely unexpected events and they must be dealt with as they happen, we talk of problems of the *real-time phase*. The research contributions described in the following concern problems occurring in these different phases.

In the field of air transport, we focus on problems concerning the *tactical phase*. Specifically, we work on the so-called airport slot allocation problem. This problem consists in fitting the requests of competing airlines to the available capacity: after producing their desired timetables, each airline asks for the permission to use airport facilities for take-off and landing, to be able to perform the planned flights. If demand exceeds capacity, some regulations define the criteria to make the arbitrage. However, no optimization is in place today to select the most convenient way to comply with these regulations. In the research

presented, we propose some ways for modeling and solving optimization problems to do so.

In the field of rail transport, we work on all phases of the capacity utilization planning process. In the [strategic phase](#) we study the maximum fitting of train paths to the infrastructure so as to quantify capacity. In the [tactical phase](#) we propose algorithms to identify relevant train travel times between stations. These travel times are computed to find a good trade-off between the shortening of the times themselves and the minimization of energy consumption. This minimization is becoming more and more relevant as the interest in green transport grows. The so identified travel times are aimed to be used in to wisely define timetables. Then, in the [pre-operational phase](#) we focus on the problem occurring when perturbations due to the need for unpredicted infrastructure maintenance make the planned timetable infeasible. Hence, new train paths must be found to perform the planned services with the unexpectedly scarcer capacity. Finally, in the [real-time phase](#) we consider the problem of dealing with traffic perturbations due to the occurrence of unexpected events concretizing in one or more trains suffering a delay. When this happens, actions must be taken to limit as much as possible delay propagation. To do so, we propose an algorithm to reroute and reschedule trains. Moreover, we work to reduce the search space of the former problem by suitably pre-selecting rerouting possibilities. Finally, we tackle the problem of identifying the best ways to put in place rerouting and rescheduling decisions so as to minimize energy consumption as well as delay propagation. For all these problems, we propose formalized models and optimization algorithms considering a very detailed representation of the infrastructure, which is necessary to fully exploit its capacity as available in reality. In the practice, the problems discussed are solved with very little or no aid from optimization. When some tools are available, they are based on rather approximated representations. With the research proposed in this manuscript we show how relevant size instances can be tackled by defining proper models and algorithms.

The two research streams just sketched profit from the exploitation of links and synergies existing between problems in the two transport systems considered. From our perspective, keeping an eye on the state of the art of one system when working to contribute to the other is important to maintain the open mindfulness necessary to propose relevant ideas.

The rest of the manuscript is organized as follows. In [Chapter 1](#) we introduce the two transport systems, providing the reader with the main concepts and elements necessary to understand the following discussions. In [Chapters 2](#) and [3](#) we propose our contributions in the fields of air and rail transport, respectively. Finally, in [Chapter 4](#) we draw conclusions and in [Chapter 5](#) we underline some research perspectives.

In [Appendix A](#) we propose a focus on one of the models proposed for a [real-time phase](#) problem in rail transport, to give a precise idea of a part of our work. Then, in [Appendix B](#) and [C](#) we mention the research projects and initiatives to which we took part, and the

student and researcher supervisions which allowed carrying out part of the studies described. Finally, at the very end of the manuscript we report the detailed Curriculum Vitae including all activities and publications.

Declaration

I declare this manuscript presents work carried out by myself and to the best of my knowledge it does not contain any materials previously published or written by another person except where due reference is made in the text; and that all substantive contributions by others to the work presented, including jointly authored publications, is clearly acknowledged.

Acknowledgments

I express my acknowledgments to all the co-authors who contributed to the research I carried out in my carrier. Special thanks go to the experienced researchers who devoted their time and effort to teach me how this work should be done. In a sort of chronological and geographical order, I would like to mention: Daniela Favaretto, Elena Moretti, Andrea Ellero and Raffaele Pesenti from University Ca' Foscari (Italy), who made me move my first steps in research and still participate to many of my activities; Lorenzo Castelli from University of Trieste (Italy), who showed me what the air transport system looks like and still collaborates to my works on this topic; Julie Higle from University of Southern California (USA), who taught me that more work is always justified if it improves quality; Mauro Birattari and Thomas Stütze from Iridia-CoDE at ULB (Belgium), who educated me to rewrite a paper a thousand times if it is not clear after the first nine hundred ninety-nine; and, last but not least, Joaquin Rodriguez from IFSTTAR (France), who brought me into the rail transport world and has been coping with me on a daily basis for seven years now.

Chapter 1

Research context: Air and rail transport problems

1.1 Introduction

The research discussed in this manuscript focuses on modeling and solving complex optimization problems in the field of air and rail transport.

Air and rail are two extremely important, and sometimes competing, means of transport. Air transport allows very long distances to be covered in a rather short time. Rail transport allows shorter distances to be covered in a reasonable amount of time at a relatively low economic and environmental cost.

Due to historical and institutional reasons, European air and rail transport systems are managed, to some extent, at a national level, with sometimes significant differences between countries. The consequent fragmentation imposes evident limitations on the development of the systems.

For coping with the need of efficient European transport systems, the European Commission has launched two ambitious programs: the Single European Sky (European Commission, 1999) and the Single European Railway Area (European Commission, 2010). The Single European Sky establishes targets in key areas of safety, network capacity, effectiveness and environmental impact for what concerns the European air transport system. Moreover, it envisages a technological modernization and optimization of the system through the Single European Sky *ATM* Research (SESAR) Programme (SESAR Consortium, 2008), where *ATM* stands for Air Traffic Management. The Single European Railway Area intends to create a unique efficient inter-European freight and passenger market, favoring cross-border competition.

In the optic of this common target, we propose in this chapter an analysis of the main

peculiarities of air and rail transport systems, which summarizes the discussion in Pellegrini and Rodriguez, 2013. In particular, we consider the main elements, processes and formalized optimization problems in the two systems for what concerns the infrastructure capacity management. Indeed, the studies described in the next chapters aim to contribute to the increase of efficiency of infrastructure capacity management through the modeling and solution of some of these optimization problems.

The rest of this chapter is organized as follows. Section 1.2 describes the main elements composing the infrastructure of the two systems. Section 1.3 presents the process implemented for allocating infrastructure capacity in air transport, and Section 1.4 the ones characterizing rail. These processes and problems are grouped according to the phase of the capacity utilization planning process in which they take place: *strategic phase* and *tactical phase*, which typically take place years and months in advance, respectively, or *operational phase*, which goes from few days before operations to the end of operations themselves and is often split into *pre-operational phase* and *real-time phase*. Finally, Section 1.5 concludes the chapter.

1.2 Description of the infrastructure

Although the infrastructure characterizing the air and the rail transport systems are fundamentally different, it is possible to identify some theoretical similarities between them. In particular, here we focus on the elements of the infrastructure which have an impact on the specification and management of the capacity of the systems.

1.2.1 Air transport system

The infrastructure of the air transport system includes *airports* as well as en-route airspace. While this definition is intuitive for *airports*, it may be rather unexpected for en-route airspace. However, as *airports*, en-route airspace has a limited capacity that must be respected for ensuring safety, and the use of which must be properly managed for enhancing the efficiency of the system. The available airspace is the area included between a minimum and a maximum flight level, with the exception of areas around *airports*. These bounds are often different in different countries (Cook, 2007), forcing pilots to adjust their flight plans when crossing borders. En-route airspace is split into *sectors* for allowing a well defined responsibility identification in traffic management. Figure 1.1 shows how the space is organized along a flight route.

Airports consist of several subsystems, such as *runways* (where aircraft land or take-off), *taxiways* (that aircraft use for reaching and leaving *runways*), *apron stands* (where aircraft

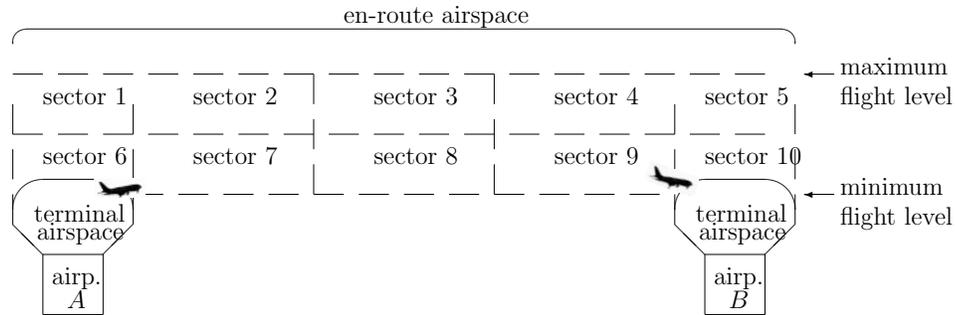


Figure 1.1: Bi-dimensional representation of the organization of airspace along a flight route connecting [airports A](#) and [B](#): terminal airspace concerns the immediate vicinity of [airports](#); en-route airspace covers the space between terminal airspace of different [airports](#) and is split into [sectors](#).

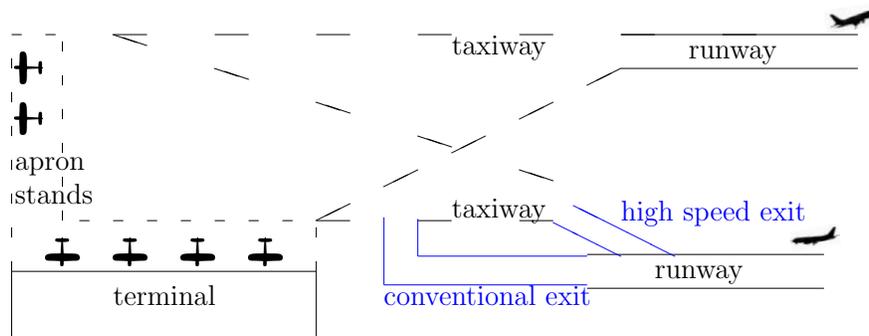


Figure 1.2: Representation of the main [airport](#) elements.

stop), and [terminals](#) (buildings where passengers transfer between ground transport and [airport](#) facilities), each with its own capacity limitations. Figure 1.2 depicts these main [airport](#) elements.

At major [airports](#), the capacity of the set of [runways](#) is the most restricting element in the great majority of cases (Ball et al., 2007). The capacity of a single [runway](#) depends on many factors, the most important of which are:

1. the mix of aircraft classes using the [airport](#). EUROCONTROL typically distinguishes three classes: heavy, medium and light aircraft;
2. the separation requirements imposed by the ATM system. They can be distinguished into wake vortex¹ and airborne separation;

¹While flying, wake turbulence forms behind an aircraft. This turbulence is particularly hazardous behind taking-off or landing aircraft, due to the high angle of attack. For avoiding such hazards, a minimum separation is imposed to aircraft taking-off or landing at an [airport](#).

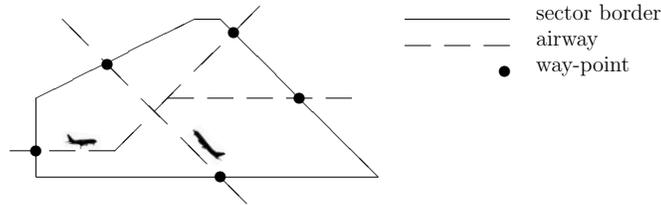


Figure 1.3: Representation of a [sector](#), which includes airways and way-points.

3. the type and location of exits from the [runway](#). They can be either conventional (with a maximum speed allowed of up to about 15 km/h) or high speed (with a maximum speed allowed of about 100 km/h);
4. the mix of movements on the [runway](#) (arrivals only, departures only, or mixed) and the sequencing of the movements;
5. the weather conditions, in terms of visibility, cloud ceiling, and precipitation;
6. the technological state and overall performance of the [ATM](#) system.

Given the large number of variables involved in the capacity specification, the precise [airport](#) capacity is hardly ever specified. In the literature, several mathematical models have been developed over the years for specifying the capacity of a single [runway](#) under different sets of conditions (Barnhart et al., 2003).

Capacity restrictions within the airspace are often associated with [sectors](#). The capacity of a [sector](#) is specified as the maximum number of aircraft that can safely enter a [sector](#) in a given time horizon. Typically, controllers introduce a structure in a [sector](#) for being able to properly deal with several aircraft simultaneously. For example, aircraft may be routed along specific paths (*airways*) and only a few *way-points* may be used for entering and exiting a [sector](#). Figure 1.3 shows these main [sector](#) elements. The specification of the capacity of a [sector](#) depends on the workload that can be borne by controllers without relaxing safety requirements. Hence, no mathematical models can be produced for this specification. The literature in this field is mostly related to the analysis of the factors which affect the complexity of the controller’s task, and on their impact on the controller’s workload (Hinston et al., 2002; Manning et al., 2002).

In the [strategic phase](#) and [tactical phase](#), capacity is handled by [airport](#) managers. Mainly in the latter, they base capacity allocation on the so-called theoretical capacity: a fixed quantity of *slot* is considered available for each [airport](#) when operating in normal conditions. A *slot* is the permission given to an *airline* to use the full range of [airport](#) infrastructure necessary to operate on a specific date and time for landing or taking-off (European Commission,

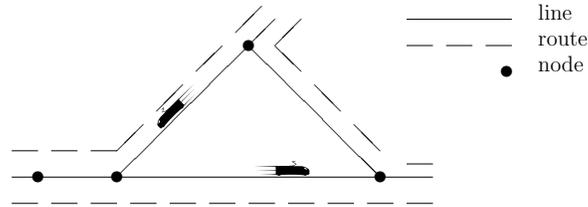


Figure 1.4: Bi-dimensional representation of a railway network at a [macroscopic](#) level.

1993) at a congested [airport](#). Typically, the step used for time discretization in the definition of [slots](#) is of some minutes (of the order of ten minutes Kösters (2007)). Many elements, such as the specific aircraft used, have an impact on actual capacity. However, theoretical capacity is computed based on standard hypothesis. For example, the theoretical capacity of Munich [airport](#) (Germany) is 89 aircraft per hour (Kösters, 2007).

Ordinary maintenance at [airports](#) is normally performed off hours, without impacting operations. Hence, no planned capacity limitations normally exist due to maintenance. When extraordinary maintenance is required, for example when [runways](#) need to be rebuilt, an [airport](#) may be closed for a few months.

When multiple [runways](#) exist at an [airport](#), they can be either parallel (or near-parallel), or crossing. Parallel and near-parallel [runways](#) can be used concurrently, respecting minimum separation constraints. The number of [runways](#) concurrently in use at an [airport](#) operating in normal conditions is a constant value. This number is used for computing theoretical capacity.

In the [strategic phase](#) and [tactical phase](#), airspace capacity is not considered at all. In the [operational phase](#), aircraft movements are managed by *Air Navigation Service Provider (ANSP)*s, both for what concerns [airports](#) and en-route [sectors](#).

1.2.2 Rail transport system

The infrastructure in the rail transport system is represented by the railway network. It is first of all made of tracks on which trains may run and it is often considered split into [control areas](#), where a dispatcher is in charge of regulating traffic. At a [macroscopic](#) level, the network includes nodes and links between nodes. Links between nodes are called lines. Nodes correspond to [junctions](#) in which trains can cross and change their order. According to this definition, a [station](#) is a particular [junction](#) in which passengers may get on and off trains. Figure 1.4 shows a bi-dimensional representation of a railway network seen at a [macroscopic](#) level.

At a [microscopic](#) level, train movements on the infrastructure are regulated through an [interlocking](#) system. The traditional system is based on the [signaling system](#), which is com-

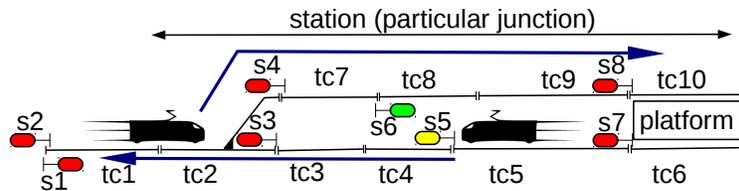


Figure 1.5: Bi-dimensional representation of the main elements included in the railway network at a [microscopic](#) level.

posed of a set of light signals splitting tracks into portion called *block sections*. Several variants exist for the [signaling system](#), typically depending on the country (Hotchkiss, 1995). In general terms, a [signaling system](#) has n possible aspects. In the most common configuration, n is equal to three: green aspect, that allows the driver to proceed at the scheduled speed; red aspect, that imposes, according to the local regulation, either the stop or the travel at visibility speed, i.e., a speed such that the driver is able to completely stop the train if he sees another train or any other obstacle in front of him; yellow aspect, that indicates to the driver that he can proceed but he shall be able to stop the train within the next [block section](#). When n is greater than three, other restrictive aspects (e.g., flashing yellow) exist: the first restrictive aspect indicates that the driver must be able to stop the train within $n - 2$ [block sections](#). Some restrictive aspects impose to have the train running not faster than a limited specific speed at the end of the [block section](#) opened by the signal. The length of the [block sections](#) depends on the [signaling system](#): in a three aspect system, a [block section](#) must be long enough for any train allowed to run on it to be able to stop by the next signal, if entering at the planned speed. In a four aspect system, for example, since two [block sections](#) are available for braking once the first restrictive signal is seen, [block sections](#) can be shorter.

The [block sections](#) may contain sequences of smaller track portions, known as *track-circuits*, on which the presence of a train is detected through an electrical detection system (De Vilder, 1995). Multiple [block sections](#) may share some [track-circuits](#). To allow a train movement entering a [block section](#), the [interlocking](#) system must detect that all its [track-circuits](#) are clear and all other route setting conditions (movement authority) are verified. If the clear condition is not verified, a red light is signaled at the beginning of the [block section](#) itself. Figure 1.5 depicts a schematic representation of the infrastructure of a simple [junction](#), considering the particular case of a [station](#). Here, [track-circuits](#) are indicated as tc and signals are indicated as s, both indexed with a progressive number. A signal allows train movement on a [block section](#) in a precise direction: for example, signal s1 allows movements in the [block section](#) including tc1, tc2 and tc7, in this order, and signal s5 in the one including tc4 and tc3, in this order. Platform tracks, or more simply platforms, allow passengers to

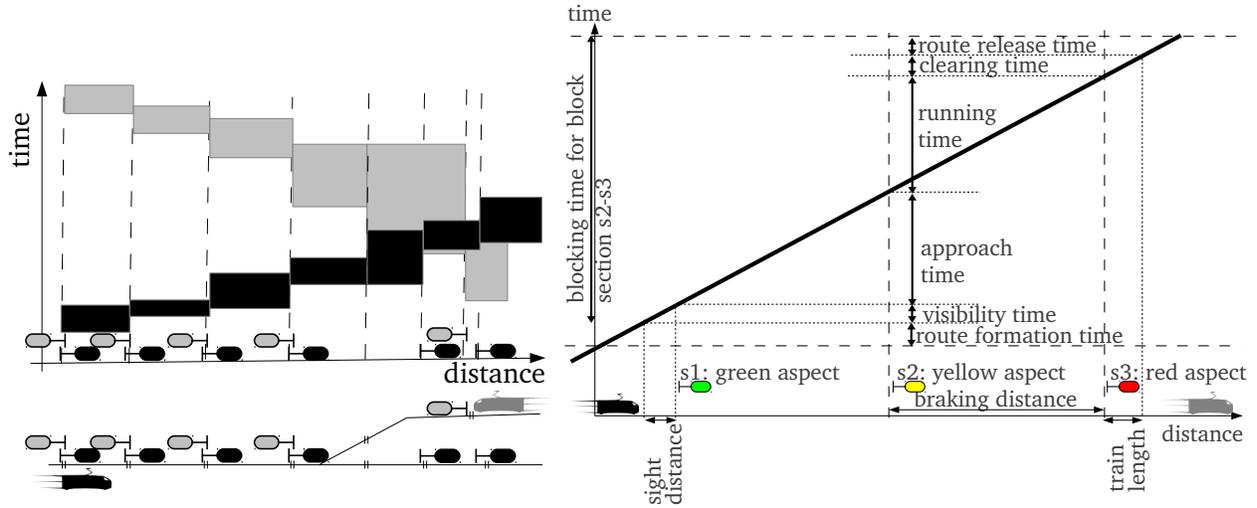


Figure 1.6: Representation of train path. Left plot: *blocking-time stairways* for two trains going in opposite directions. Right plot: components of the *blocking-time* of a *block section*.

get on and off the trains.

A typical representation at the *microscopic* level of a train path is the so called *blocking-time stairway* (Pachl, 2002) on a time/distance plot, as shown in the left plot of Figure 1.6. Here, space is represented on the horizontal axis in terms of distance from a given point. While moving either from or toward the reference point, the train traverses subsequent *track-circuits*. Each *track-circuit* is utilized by a train for a duration equal to the *blocking-time*. It results from the sum of: the time for forming the *block section* of interest by possibly setting its movable parts, the time for the driver to see the signal and react, the approach time for reaching the signal, the time for traveling between the current and the following signal, the clearing time for exiting the *track-circuit*, and the release time to unlock the block system (Figure 1.6, right plot). In the following, we group the first two intervals under the name of *formation time*, which is followed by the *reservation time* and the *occupation time*, and finally by the *release time*. The *blocking-time* for which the track-circuit is not available for any other train is represented on the vertical axis. In the *blocking-time stairway*, a rectangle represents the *blocking-time* for each *track-circuit* used by the train. The *blocking-time stairway* of a train path depends on the *interlocking* system. Two systems are most commonly considered: the *route-lock route-release* and the *route-lock sectional-release* (Theeg et al., 2009). The moment in which the utilization of a *track-circuit* starts is the same in the two systems, while the release occurs at different times. In the *route-lock route-release*, all *track-circuits* of a *block section* are released simultaneously after the train has exited the last one of them. In the *route-lock sectional-release*, instead, each *track-circuit* is released after

the train has exited it, even if the train itself has not left the [block section](#) yet.

In Europe, the signaling systems are progressively being substituted by the [European Rail Traffic Management System \(ERTMS\)](#) (European Commission, 2012), in which the traffic control system is mounted in trains driving cabins, and communications are based on a GSM radio mobile system (GSM-R). However, its deployment at the European level is far from being accomplished.

The capacity of a piece of infrastructure is defined as the maximum number of trains that can be operated on it in a given time horizon (UIC, 2012). As for [airports](#) in the air transport system, capacity of portions of the railway network depends on the characteristics of the movements considered, notably on their number, on their direction, on the average speed maintained, on the stability warranted in terms of *time supplements*, and on the heterogeneity of the trains used. In this context, [time supplements](#) represent margins added to the expected train traveling time during the timetable design. These supplements are inserted to increase the robustness of the timetable. Although the identification of factors relevant for capacity is quite agreed on, formal principles for measuring capacity in the rail transport system are not unanimously accepted.

In the practice, in each country the national *Infrastructure Manager (IM)* handles capacity in all phases of the planning process. In addition to allocate the train-paths to requesting *Railway Undertaking (RU)*, the IM must ensure that maintenance is possible along the network. In fact, the railway infrastructure needs a rather frequent maintenance for being safely and effectively usable. Typically, the IMs schedule all maintenance works in some predefined time periods, for example at night. Another possibility for scheduling maintenance works emerges in case a line includes separate track sections normally used for trains traveling in opposite directions. In this case, it may be possible to schedule maintenance on one track section and use the other one in both directions. The capacity of the only open track section is in this case much lower than the original capacity, as exemplified in [Figure 1.7](#) through [blocking-time stairways](#). The left picture represents the fully operational situation: nine trains are scheduled on the two parallel tracks and superimposition of [blocking-time stairways](#) is not important, since they concern different [block sections](#). The right picture represents the case of closure of a track section for maintenance: only five trains can be scheduled, since we must have one train leaving the shared track section before a train going in the opposite direction can enter it.

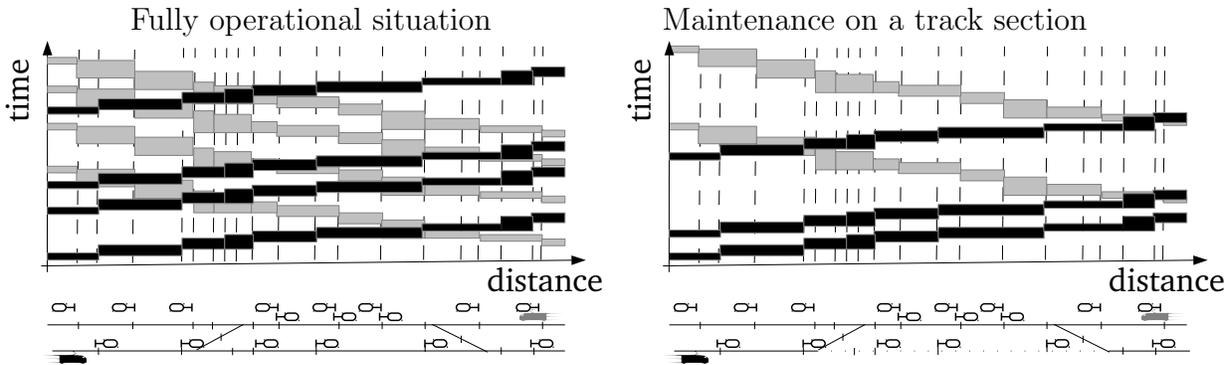


Figure 1.7: Representation of the blocking-time stairways for two trains going in opposite directions on two parallel track sections.

1.3 Infrastructure capacity allocation in air transport

The activities devoted to infrastructure capacity allocation in the *strategic phase* of the planning process concern the build or substantial modification of parts of the infrastructure. Since the quantification of infrastructure capacity is based on purely theoretical computations, no particular processes or optimization problems have been formalized for this phase.

In the *tactical phase*, instead, an important process is carried out to allocate scarce *airport* capacity to competing *airlines*. Indeed, *airlines* define their ideal timetable based on commercial evaluations and on constraints imposed by the available fleet and crew. However, sometimes they must be modified to respect the *airport* theoretical capacities, i.e., the declared limit on the maximum number of *slots* that can be used at each *airport* per unit of time.

In Europe, a quite elaborated administrative *slot allocation process* is currently implemented. It follows the rules and principles described in the *International Air Transport Association (IATA) Worldwide Slot Guidelines* (IATA, 2015) and Regulation 95/1993 of the European Commission (1993) and its subsequent amendments. It is based on the identification of different categories of *airports* based on their congestion level. A *coordinated* airport (Level 3) is an airport “where capacity providers have not developed sufficient infrastructure, or where governments have imposed conditions that make it impossible to meet demand. A *coordinator* is appointed to allocate slots to airspace users and other aircraft operators using or planning to use the airport as a means of managing the declared capacity.” In addition to these airports, flight schedules are controlled at *facilitated* airports (Level 2), which are those “where there is potential for congestion during some periods of the day, week, or season which can be resolved by schedule adjustments mutually agreed between the airspace users

and facilitators. A *facilitator* is appointed to facilitate the planned operations of airlines using or planning to use the airport” (IATA, 2015)². In Europe, there is one *coordinator* per country, meaning that a unique national authority manages the slot allocation and the schedule facilitation at each *coordinated* and *facilitated* airport of this country, respectively. The allocation and schedule facilitation is always performed on an airport by airport basis, though. In Europe there are as many as 107 airports designated as *coordinated* and another 79 as *facilitated*, representing 60% and 61% of these airports in the world, respectively.

Based on these airport categories, the *slot allocation process* in Europe consists of two main steps: *primary slot allocation*, and *secondary slot allocation*, also referred to as slot exchanges and transfers. The primary slot allocation takes place about five months before the start of the season. The secondary slot allocation is a continuous process in which *airlines* can exchange *slots*, always with the agreement of *coordinators*.

Although the *slot allocation process* is well established in Europe, its inefficiency has been the object of many studies. This is a context in which optimization may bring a remarkable contribution: several problems have been formalized for coping with either the primary or the secondary allocation, and several algorithms have been proposed for solving them. The research reported in Chapter 2 describes some contributions in this context.

After the timetable definition and the tactical capacity allocation, the main activity concerning the exploitation of capacity in the *operational phase* is traffic management. Here, *ANSP* operators are in charge of ensuring safety in air operations. Particularly for what concerns en-route *sectors*, they deal with a theoretically very high capacity infrastructure, since a very high number of aircraft could potentially fly in a *sector* at the same time, if we considered only physical constraints. However, *ANSPs* are responsible of guaranteeing safety: for being able to give this guarantee, the capacity is artificially restricted to what a person can control, i.e., according to human factors and ergonomic criteria.

During the *pre-operational phase*, the only system level activity to be performed is the definition of the flight plan of an aircraft. It includes basic information such as departure and arrival locations, estimated duration, alternative airports in case of bad weather, type of flight (whether following instrument flight rules or visual flight rules), information on the pilot, number of people on board and information on the aircraft. Airlines choose the flight plan based on several criteria, including winds and other weather conditions, fuel usage, en-route turbulence predictions, safety constraints, etc. The flight plan is submitted to the Central Flow Management Unit (CFMU) of *EUROCONTROL* between five days and one hour before the flight departure. The system checks the flight plans against the airspace

²Formally, *slots* concern only *coordinated* airports, while *schedule facilitations* concern *facilitated* ones. For ease of readability, in the rest of the manuscript we will refer to both as *slots*, with a slight abuse of notation.

structure, e.g., in terms of sequence of way-points to be met. Once the flight plan is accepted, it is distributed to the **ANSP** controllers that will be concerned with the flight.

Once flight plans are approved, **ATM** takes place through different types of control actions, as ground holding (delaying the departure of a flight to avoid overloading a system element, be it either an en-route **sector** or an **airport**), airborne speed control, airborne holding, route adjustments and arrival sequencing³. Today, no particular optimization approach is in use to support decisions on these actions. However, in the literature, several formulations and algorithms have been proposed to this aim. In the practice, control actions are decided in advance with respect to actual operations. In particular, when a perturbing situation, such as bad weather condition, is expected, possible **ATM** control actions are evaluated for selecting the specific ones to implement. This is typically done with a few-hour advance. What is actually performed in the **real-time phase** is the activity to ensure the safety separation is always preserved. Although in the academic literature separation preservation rules based on aircraft speed variations have been investigated, in the practice, the performed actions consist in either climbing or descending maneuvers. Among those ensuring safety, the selected action is the one minimizing the disruption with respect to the original flight plan. However, no system level efficiency assessments are made.

1.4 Infrastructure capacity allocation in rail transport

In the rail transport system, the **strategic phase** sees two main types of actions. On the one hand, line planning on the existing infrastructure is performed: lines, in terms of origin, destination and intermediate stops, have to be defined and associated with individual frequencies. Several optimization approaches have been proposed in the literature for performing line planning, but their use in the practice is extremely limited. On the other hand, infrastructure modification plans are made. In the practice, different procedures are implemented to select the appropriate infrastructure modifications, sometimes including the use of traffic simulators for assessing various alternatives. Optimization has been proposed as a mean to assess capacity, and hence as a possible decision support tool to be used in this phase. In particular, in Chapter 3 (Section 3.2) we sketch our contribution on the solution of the saturation problem. It consists in the assessment of the maximum number of train movements that might be added to the timetable without violating any safety or operational constraint on a given infrastructure.

In the **tactical phase**, the main activity concerning capacity utilization, similarly to the

³The sequencing of flights can be very important as the maximum arrival rates into **airports** depend on the sequence and mix of aircraft types.

air transport system, is the allocation of scarce capacity to **RUs** requesting train paths. Even if with some possible intervention by transport authorities, in the rail transport system **RUs** construct their own timetable and then request the necessary capacity to **IMs**. According to the European regulation, requests for the use of capacity may be refused by **IMs** only if there are viable alternatives. These alternatives must allow the **RU** to operate the freight or passenger service concerned on the same or alternative itineraries under economically acceptable conditions. When a request is refused, the **IM** must justify the refusal decision and indicate the alternatives. Hence, when the infrastructure manager encounters conflicts between different requests, it shall attempt to meet all requests as far as possible. If no viable alternative is available and it is not possible to accommodate all requests, the excluded **RUs** may complain to the regulatory body established by the Member State. The regulatory body examines the cases and takes actions, where pertinent, to ensure that an appropriate part of the capacity is granted to the complaining **RUs**. Moreover, the regulatory body of each Member State may intervene in the process to guarantee that capacity is allocated to priority services, for public-service requirements or for promoting the development of rail freight. The concerned Member State may grant the **IM** some compensation for the consequent loss in revenue. In some countries, the **IM** relies on simulation tools for verifying the feasibility of different of train path allocations. The academic world has not intensely focused on possible market mechanisms for effectively allocating scarce capacity to competing operators, mostly due to the historical absence of competition in the rail transport system. Instead, a lot of research works focus on the definition of timetable. Among them, we shortly describe our contribution to this problem in Chapter 3 (Section 3.3).

In the **operational phase** traffic management takes place. Differently from the air transport system, in the rail one, the safety of train movements is ensured by the **interlocking** system in the large majority of possible situations, and dispatchers are in charge of smoothing the operations in case of unplanned capacity limitations or unexpected events. In fact, in absence of unexpected events, the train drivers follow the timetable planned, which details the suitable trains' *route* and speed.

Indeed, the **IM** may become aware of unplanned capacity limitations in the **pre-operational phase**. When this happens, the timetable must be re-arranged to cope with them in the most effective way. An example of unplanned limitation is the unexpected need for maintenance of a portion of infrastructure. In the practice, simulation may be used, but most of the times no decision-support tools are available for this re-arrangement. However, more and more studies are being proposed for optimizing the choices in this phase of the planning process, and our contribution in this field is mentioned in Chapter 3 (Section 3.4).

Then, in the **real-time phase** unexpected events may cause either disruptions or perturbations. In disruptions, a part of the network becomes unavailable, imposing major modifi-

cations to the timetable. Actions in this case include train cancellation and short-turning, together with train re-timing at different locations. Decision-support tools are in use in some countries, and a large amount of literature exist on how to re-allocate capacity through optimization. In perturbations, some *primary delay*, due to causes which are external to traffic evolution, occurs. In some cases this may bring trains traveling on the planned *route* at the planned speed to claim the same portion of infrastructure concurrently, i.e., to the occurrence of *conflicts*. The typical consequence of *conflicts* is delay propagation, due to the emergence of *secondary delays*. The role of the dispatcher consists in limiting as much as possible this delay propagation, being relieved of all safety responsibilities.

Dispatchers typically base their decisions on the indication of software tools that differ from country to country. However, dispatchers are often forced to take last minute decisions autonomously. The main decisions which the dispatcher makes for re-allocating capacity are: changing the run order at critical locations and rerouting trains. For changing the run order, dispatchers can either temporarily stop some trains through the signaling system, or suggest suitable speed adjustment actions to the drivers. A remarkable body of literature exists in the use of optimization for aiding dispatchers to make these different types of traffic management decisions. In Chapter 3 (Section 3.5) we discuss our contribution to this part of the literature, which constitute the richest part of the research presented in this manuscript.

1.5 Conclusion

Both the air and the rail transport systems are characterized by the presence of different stakeholders with competing objectives, which either manage or exploit the scarce infrastructure capacity. The existing processes for coordinating the activity of these stakeholders are the results of a rather long history of separate national developments. Recently, the European Commission has envisaged a common future for these systems. This common future consists in abandoning the current fragmentation of the systems for moving toward actual international air and rail transport systems, involving all Member States. This unification and homogenization is foreseen to have a major positive impact on the development of the European economy.

In this chapter, we proposed an analysis of the main processes implemented in the two systems concerning capacity exploitation. What clearly emerges in this analysis is the lack of deployment of optimization tools in these processes. Indeed, due to historical evolution and technological development, the processes implemented for managing the two systems still present some important differences. However, some similarities emerge. They may allow the exploitation of synergies between the uses of optimization in the two systems, or at least

some important knowledge sharing and transfer.

In the optic of this knowledge sharing and transfer, the research summarized in this manuscript tackled problems emerging in different phases of the capacity utilization planning process of the two systems.

Scientific production

Journals

P. Pellegrini and J. Rodriguez. Single European Sky and Single European Railway Area: A system level analysis of air and rail transportation. *Transportation Research Part A: Policy and Practice*, 57:64–86, 2013.

Technical reports

P. Pellegrini. Air traffic management: current practice and main research directions. Technical report, IFSTTAR, Université Lille Nord de France, Lille, France, 2012.

Chapter 2

Research contributions on air transport problems

2.1 Introduction

The contributions proposed in this manuscript on air transport problems concern the allocation of infrastructure capacity in the [tactical phase](#).

As mentioned in Section 1.3, in this phase only airport capacity is considered. This capacity is managed through the [slot allocation process](#), organized into primary and secondary slot allocation.

The [primary slot allocation](#) begins about five months before the start of the season (the winter season starts on the last Sunday of October, the summer season on the last Sunday of March), when [airlines](#) submit formal requests for slots (and schedule facilitation) to airport [coordinators](#).

At [facilitated](#) airports, when mismatches between capacity and demand exist, an [airline](#) might be asked to move the scheduled time of an operation, for the minimum necessary amount of time, on a voluntary basis. At [coordinated](#) airports, the [coordinators](#) endeavor to satisfy the requests, under the existing capacity constraints, respecting historical precedence, the so-called *grandfather rights*. An [airline](#) obtains the [grandfather right](#) on a [slot](#), if it operated the corresponding [slot](#) at least 80% of the times in the preceding equivalent season. In such a case we refer to this [airline](#) as an *incumbent*. Once all [grandfather rights](#) are granted, half of the remaining slots are allocated to *new entrant* [airlines](#), and the rest in a not precisely defined non-discriminatory manner. A *new entrant* is defined as: “an [airline](#) requesting a series of [slots](#)¹ at an airport on any day where, if the airline’s request were

¹Slots are allocated in *series*, which is a sequence of at “least five slots, requested for the same time on the same day-of-the-week, distributed regularly in the same season.” (IATA, 2015).

accepted it would hold fewer than five slots at the airport on that day” (IATA, 2015). IATA slot conference takes place at the end of the [primary slot allocation](#) phase, to facilitate negotiations of slot exchanges between airlines. The aim of the conference is to diminish as much as possible, through negotiations, the difference between the requested and assigned [slots](#), which is referred to as *schedule displacement*. This displacement generates the so called *displacement cost*. However, the [slots](#) an [airline](#) receives are the outcome of several local allocations and, as such, they may be impracticable with respect to, say, the fleet rotation constraints, or undesirable in terms of departing/arriving times for business purposes.

To improve the received [slots](#) considering all the airline-specific constraints, during the [secondary slot allocation](#) process [airlines](#) exchange their slots. These exchanges are bilateral but always submitted to the [coordinators](#) approval. No strict regulation exists for managing this phase of the process, but in few U.S. airports where an actual market mechanism is in place.

In general, the scarcity of airport capacity is a fundamental issue in all major European [airports](#). Most of the times, each of these congested airports also acts as a hub for a legacy [airline](#), such as London Heathrow for British Airways or Paris Charles de Gaulle for Air France. The possible removal of [grandfather rights](#) has been object of long discussions. Indeed, it is likely to have a significant impact on legacy [airlines](#) that actually operate in these hub [airports](#) and offer to their customers a hub-and-spoke network. A milder effect is expected on low-cost or charter [airlines](#) that mainly provide point-to-point services and operate on secondary less congested [airports](#).

Another element that intuitively decreases the effectiveness of the current process is the independent consideration of airports in the [primary slot allocation](#).

The rest of this chapter is organized as follows. In Section 2.2, we describe three contributions on the [primary slot allocation](#) process. In Section 2.3, we present a work on the [secondary slot allocation](#) one. Finally, in Section 2.4 we summarize some conclusions of this chapter.

2.2 Primary slot allocation

The contributions we present on the [primary slot allocation](#) process concern the proposal of models and algorithms for tackling the whole European problem at once.

2.2.1 Optimal simultaneous slot allocation

The first contribution is thoroughly detailed in Castelli et al. (2012). In this work, we propose an integer programming (IP) model for the [primary slot allocation](#) process. The

model simultaneously allocates **slots** in a network **airports** and considers the structure of the airspace and the **airlines'** requests in terms of origin-destination pairs. Specifically, we take into account all the **sectors** which shall be traversed by an aircraft along a route. We rely on a simplified representation of the network, e.g., we assume that the time required to cross every **sector** is fixed (no speed control) and that the **sectors** themselves are uncapacitated. Among all the possible routes which connect an origin-destination pair, the model chooses one which is suitable in terms of duration, i.e., of separation between departure and arrival **slots**. Moreover, our model allows each **airline** to indicate the maximum **schedule displacement** it can bear for each flight. To this aim, some sharing of information is needed. For coping with the reluctance of **airlines** to making their costs and requirements transparent to competitors, in accordance with the literature, our mechanism is regulated by an independent moderator that is in charge of managing sensitive data, such as the foreseen costs of a flight. The independent moderator has thus the role of collecting the requests of each **airline**, to verify that a feasible solution exists, and to ensure the optimal slot allocation is implemented. If a feasible solution does not exist, he must report the failure to the **airlines** and ask for new requests.

By solving the model through a commercial solver, we perform an experimental analysis on realistic instances that aim to simulate air traffic demand over a portion of the European sky in a 5-hour time horizon. In this analysis, we quantitatively assess the economic impact of **grandfather rights** by comparing **airlines'** costs when these rights are either enforced or not. We show that the total **displacement costs** of the individual **airlines** is higher when **grandfather rights** are present.

After this analysis, we introduce some compensation mechanisms in the model for testing the possibility of fairly sharing the **displacement cost** among **airlines**. In order to be effectively implemented the mechanism has to meet two properties: budget balance and individual rationality. A mechanism is budget balanced if the overall amount paid and received by the **airlines** participating in it sums up to 0. In such a way the independent moderator neither subsidizes the market nor gains from it. Then, a mechanism is individual rational if it does not cause a decrement of the utility of any **airline** without compensating it by an appropriate side payment. In other words, each **airline** must have no disadvantage in participating in the mechanism. The amount payed as compensation plus the **displacement cost** must be at most equal to the maximum cost the **airline** is ready to bear. The **airline** itself declares this value when it announces the cost associated with the maximum acceptable displacement with respect to the requested **slots**. Indeed, several combinations of payments meet these two properties. We add to the model a set of constraints ensuring that each airline bears no more than a share of the total **displacement cost** and we test different strategies for fixing this share. One choice is to penalize **airlines** proportionally to their contribution to the infeasibility of the

ideal solution. In particular, we consider the set of combinations **airport**-time in which **slot** demand is greater than capacity. The share of the cost an **airline** must bear is proportional to the number of **slots** it requests in these combinations. So, if an **airline** requests only **slots** in periods with no excess demand and it must bear a displacement for allowing a feasible schedule, the consequent **displacement cost** must be completely compensated. If, instead, an **airline** requires to land at a main **airport** in the peak time then even if it is allowed to do so, it must be ready to refund competitors that do not have the same opportunity. Two other possibilities consist in considering an equal distribution of costs to **slots** or to **airlines**. In the first case, each **airline** bears a share of the total **displacement cost** that is equal to the ratio between the number of **slots** it requests and the total number of requests. In the second case, the total cost is just equally shared among **airlines**.

The results of our experimental analysis show that compensations, in any of the strategies tested may help in redistributing among **airlines** the surplus deriving from the elimination of **grandfather rights**. In this way, it is possible to implement a mechanism in which social utility increases, without inevitably damaging the **airlines** that loose their **grandfather rights**.

2.2.2 Metaheuristics for simultaneous slot allocation

In a subsequent work, detailed in Pellegrini et al. (2012a), we extend the model presented in Section 2.2.1. Specifically, we formulate a simultaneous coherent **primary slot allocation** in a network of **airports** which also respects the capacities of all en-route **sectors** expected to be traversed by aircraft along their route. The first target of the model is to find an allocation that will not prove infeasible on the day of operations, in absence of unexpected disruption of the system such as bad weather conditions limiting **sector** capacities. Then, among all feasible allocations, the model considers two hierarchically ordered objectives: first it maximizes the number of flights to which slots are allocated (*accommodated flights*); second it minimizes the **displacement cost**. Indeed, the introduction of sector capacity constraints makes the exact solution of the IP model impossible for instances of realistic size. Thus, we propose two metaheuristic algorithms, based on Iterated Local Search (ILS) and on Variable Neighborhood Search (VNS), and we compare the performances of the exact and metaheuristics approaches. Furthermore, we compare the obtained **slot** allocations with respect to a simultaneous random **slot** allocation and to a slot allocation where **airports** are considered independently.

Both metaheuristic algorithms proposed are randomised first-improvement local search procedures, and they reiterate recursively as far as they find an improved solution. They consist in, first, randomly de-accommodating or displacing some flights starting from an initial solution. Second, they try to re-accommodate or re-allocate the free **slots** and possibly the

other [unaccommodated flights](#) of the initial solution. The performance of these local search procedures depend on two parameters: the number of unsuccessful trials to be completed before considering the current solution a local minimum, and the number of flights to be either de-accommodated or randomly shifted at the beginning of each trial.

ILS starts from a first randomly generated feasible solution and it explores the solution space by iteratively calling the local search procedure: if there are still [unaccommodated flights](#), ILS randomly de-accommodates some; otherwise, it displaces some randomly selected ones. After a number of consecutive local search calls without improvement, ILS perturbs some randomly selected flights in the best solution found so far, to identify a new solution and start a new local search. The nature of the perturbation on these flights depends on whether there are still [unaccommodated flights](#) or not: if so, the flights are deaccommodated, otherwise, the departures of the flights are randomly shifted. If ILS finds no improving solution for a given amount of consecutive sequences of perturbation and local search, it restarts from a new random solution.

Also VNS starts from a randomly generated feasible solution and explores iteratively the solution neighborhood using one of the local search procedure according to the same rationale used by ILS. It escapes from the basin of attraction of local optima by increasing the size of the neighborhood after a number of local search calls without improvement. This size is increased at each neighborhood change. As ILS, if VNS finds no improving solution for a given amount of consecutive sequences of neighborhood size changes and local searches, the algorithm restarts from a new randomly generated solution.

For assessing the performance of the exact solution of the model and of the two metaheuristic algorithms, we consider a benchmark that tries to mimic the current [primary slot allocation](#) process. It is a two-step procedure: first, it allocates [slots](#) to [airlines](#) at each [airport](#) independently; second, it computes how many flights each [airline](#) can actually accommodate based on the obtained [slots](#). We test the algorithms on three sets of randomly generated instances of different size, including up to 30 [airports](#). Both ILS and VNS outperform the current process on all sets of instances, whereas the exact solution of the model does so only on the smallest ones. The metaheuristic algorithms are able to tackle instances including 30000 flights, that is, about the number of flights that are performed in Europe in one high season day. Simulating realistic size European instances, we consider large instances as the most relevant for practical purposes. Hence, being the best performing on these instances, ILS is the most promising algorithm for real world applications.

2.2.3 SOSTA: optimal simultaneous slot allocation precisely modeling regulations and best practices

In the two above presented studies we show that optimizing the [primary slot allocation](#) process considering a network of [airports](#) may strongly increase the efficiency of the system and that it is technically possible to tackle relevant size instances. Next, we focus on doing so while modeling in higher detail the current practices and regulations. To do so, in Pellegrini et al. (2017c) we propose SOSTA, an IP model for the Simultaneous Optimisation of airport Slot Allocation. The model takes into account different types of [airport](#) capacity constraints and minimizes in lexicographic order the number of [unaccommodated flights](#) and the total [displacement costs](#). Specifically, to model capacity constraints as they are actually set in reality, we distinguish between the “[slot](#)” (the right) and “*interval*” (when this right is exercised), since there is no one-to-one relationship between them: a time [interval](#) is associated with each [slot](#), but more than one [slot](#) can be allocated to the same time [interval](#). Hence, a [slot](#) is the right to use the airport facilities for take-off or landing within a time [interval](#). An [interval](#) is characterised by a start time and a length. Lengths may vary across [airports](#), but all [intervals](#) at the same [airport](#) have the same length. Most frequent values for lengths are 5, 10, 15 and 20 minutes. The start time of an interval can occur only at the minute 0, 5, 10, . . . , 55 of an hour. Depending on the [airport](#), [intervals](#) can be overlapping or sequential. Then, we call *subinterval* the time period equal to the difference of two consecutive [intervals](#)’ start times. It may be shorter than the [interval](#) length. When an [airline](#) requests a [slot](#), the start time of the associated [interval](#) is specified. Similarly, the [coordinator](#) allocates a [slot](#) by identifying the start time of a specific [interval](#). Since for each [interval](#) there is always a [subinterval](#) that shares the same start time, we may associate to every [slot](#) the [subinterval](#) that starts at the same time of that [slot](#)’s [interval](#).

Capacity constraints at [airports](#) are defined for time periods which are typically one hour or one [interval](#) long. Moreover, an [airport](#) has a capacity distribution profile in terms of arrival, departure, and total movements, and hence in terms of arrival, departure and total [slots](#) per time period. Capacity in terms of number of total movements means that any movement is taken into account, without distinction between a departure and an arrival movement. Such value is not necessarily equal to the sum of departure and arrival [slots](#) in the same time period. Based on the current practice, we distinguish between hourly and [interval](#) capacity constraints. In the former, the bound on the number of [slots](#) is given for periods of one hour, and it may be applied either on a rolling basis (type I hourly capacity constraints) or sequentially (type II hourly capacity constraints). In the former case, the beginning of each hourly period is equal to the beginning of the previous one plus five minutes, whereas in the latter case it is equal to the end of the previous one. Depending on the airport, both

types of hourly capacity constraints may be imposed. In the *interval* capacity constraints, the bound on the number of *slots* is given for *intervals*. If *intervals* are sequential, the sum of movements allocated to the unique *subinterval* composing the *interval* has to be lower than or equal to the *interval* capacity. In the case of overlapping *interval* the sum of movements over all *subintervals* of an *interval* has to be lower than or equal to the *interval* capacity. Moreover, a movement consumes one unit of capacity of all the *intervals* that contain the corresponding *subinterval*.

Therefore at one *airport*, up to seven types of capacity constraints may coexist: *interval* constraints in terms of total number of *slots*, and type I and type II hourly capacity constraints, in terms of number of departure and arrival *slots*, and in terms of total number of *slots*. Figure 2.1 shows an example of these constraints, with overlapping *intervals*. For the sake of clarity, Figure 2.1 does not distinguish between type I and type II constraints in terms of number of departure and arrival *slots*, but treats such capacities only in terms of total number of allocated ones. We consider an *airport* with the *interval* and *intervals* length equal to 20 and 5 minutes, respectively. Capacity is set to 7 *slots* per *interval*, and 20 (type I) and 18 (type II) *slots* per hour. In all the other works presented in this chapter, as in the great majority of the papers appeared in the literature, capacity is modeled only for sequential *intervals*.

Several *airports* in our databases have simultaneously active *interval* and type II constraints. The rationale is to smooth the demand while considering operational, environmental and other limitations. For instance, relying on the example depicted in Figure 2.1, if only type II constraints existed, it would be possible to concentrate all allowed 18 movements in a very short time period, e.g., from 7:00 to 7:20, and leave empty the remaining part of the hour (from 7:20 to 8:00). However, this situation could be operationally unmanageable by the *airport*, which imposes capacity constraints on shorter periods (*interval* constraints). Hence, the 18 movements must be spread over the hour. Vice versa, *interval* constraints without type II constraints may lead to an unsustainable traffic level over the longer period. Type I constraints impose an additional limitation that is not captured by the joint combination of type II and *interval* constraints. For instance, the allocation: 4 *slots* from 7:00 to 7:20, 7 *slots* from 7:20 to 7:40, 7 *slots* from 7:40 to 8:00, 7 *slots* from 8:00 to 8:20, 7 *slots* from 8:20 to 8:40 and 4 *slots* from 8:40 to 9:00 satisfies all type II and *interval* constraints, but not type I constraints starting at 7:20, 7:25, 7:30, 7:35, and 7:40. Type II constraints in some cases reflect artificially imposed limits to the *airport* capacity (like curfew restrictions during the night). Type I constraints instead reflect the operational capabilities of the airport over a period that lasts one hour. When both type I and type II constraints are present (as in London Heathrow, for instance), the capacity values of the latter are always strictly less than those of the former. Differently, type II constraints would become redundant.

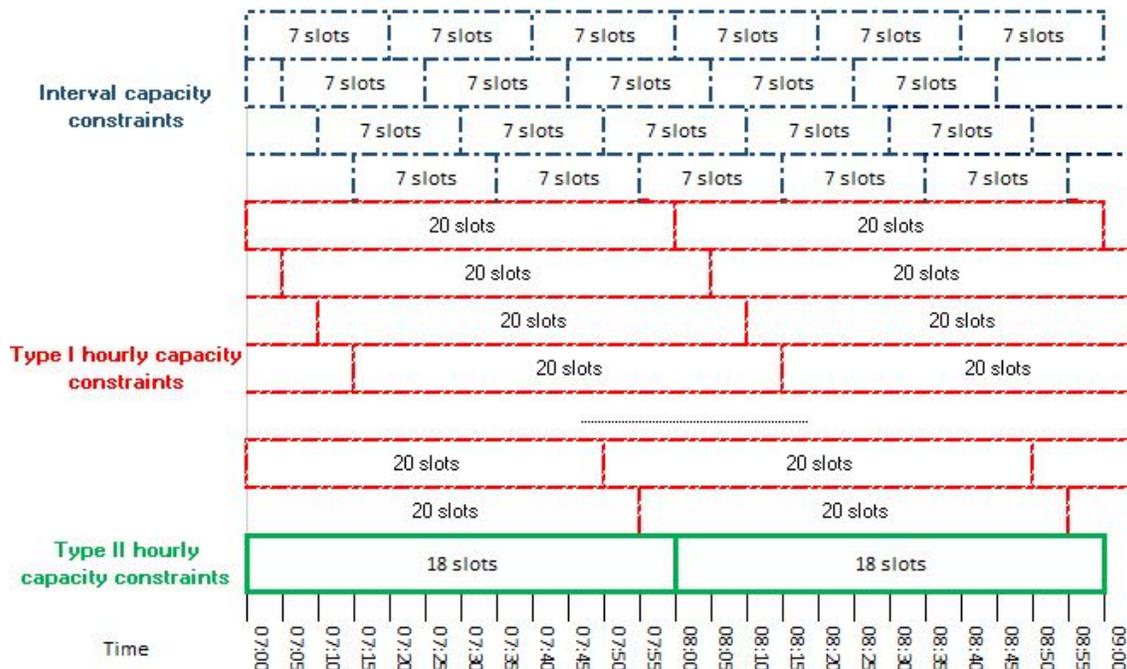


Figure 2.1: Example of [airport](#) capacity constraints: 20-minute [intervals](#) with capacity of 7 slots imposed based on overlapping [intervals](#) ([subintervals](#) of length 5 minutes); type I hourly capacity constraints of 20 slots per hour; type II hourly capacity constraints of 18 slots per hour.

A further novel contribution of the network perspective implemented in SOSTA lies in explicitly linking departure and arrival [slots](#) (when both are requested) of each flight and considering aircraft rotations through the introduction of turnaround time constraints. Instead, to strength the link with the current regulations, SOSTA does not consider [en-route sectors](#) in the network.

The experimental analysis which we run to validate and test SOSTA is in a sense a contribution in itself: we use real data to show that SOSTA can handle all European [airport slots](#) during a busy day, achieving the optimality of the final allocation in reasonable time. The use of real data is extremely rare in the literature, due to confidentiality issues and to the difficulty of collecting significant amounts of them. We apply SOSTA on the busiest day of 2013 and we show that it is a valid model that enforces the rules characterizing the current system: we run it on a set of requests for which the final real allocation is known, and SOSTA returns this same final allocation with only a few exceptions. Specifically, the [slot](#) allocation proposed by SOSTA matches the actual one for all but six requests (32659 matches out of 32665 requests). In all the cases, the displacement proposed differs from the actual one for 10 minutes at the most. The slightly different combination allows reducing

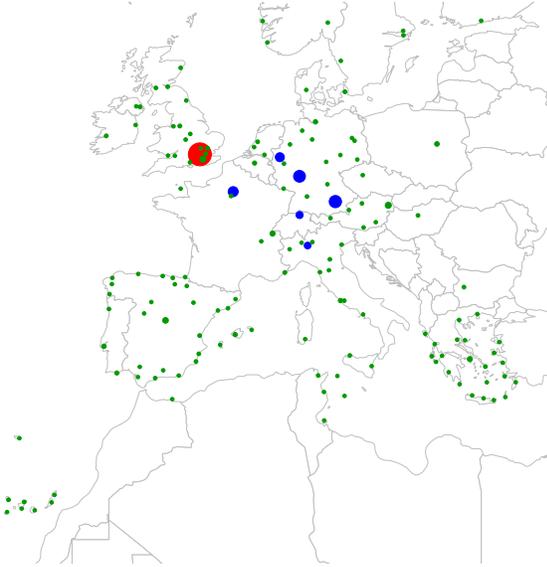


Figure 2.2: Missed allocations induced by 20% reduction of airport capacities using SOSTA

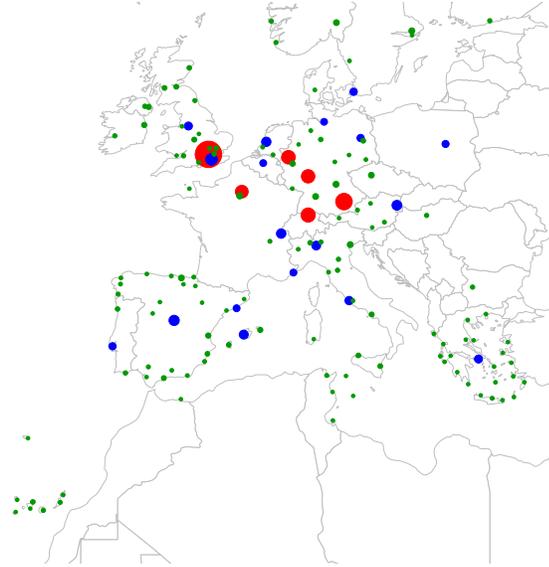


Figure 2.3: Missed allocations induced by 20% reduction of airport capacities in the current scenario

the total displacement of 5 minutes. Next, we quantify the potential improvement brought by SOSTA’s simultaneous [slot](#) allocation at all [airports](#). To do so, we compare the results of SOSTA with the ones of the current allocation process in cases in which the ratio between [slot](#) requests and [slot](#) availability is greater than the current one. This situation is simulated through the reduction of the [airports](#) capacities (all [airports](#), uniformly), to avoid adding fictitious [slot](#) requests. Moreover, we assess the sensitivity of SOSTA when the maximum [schedule displacement](#) or the maximum additional flight time varies. Then we analyze the effects of moving from linear to quadratic [displacement cost](#) functions and of loosening [grandfather rights](#). Finally, we propose two variants of SOSTA to take into account fairness considerations. Through all these experiments, we show that the use of SOSTA may improve the current [primary slot allocation](#) process. Indeed, being able to optimize the [slot](#) allocation at all [coordinated](#) and [facilitated airports](#) in Europe simultaneously, SOSTA can significantly decrease the efforts needed in the current system.

As an example of the results obtained, Figure 2.2 displays the number of [unaccommodated flights](#) over all Europe using SOSTA in the case-study with 20% reduction of [airport](#) capacities. The solution proposed by SOSTA identifies 860 [unaccommodated flights](#), which touch 60 European [airports](#). A colour and a size scale defines the number of [unaccommodated flights](#) at each [airport](#): the larger the bullet, the higher the number of [unaccommodated flights](#) at the corresponding [airport](#). Red bullets represent values of more than 100, blue bullets between 30 and 100, and green bullets between 10 and 30. Many of the minor [airports](#)

experience very few or no **unaccommodated flights**, with the exception of those induced by an **unaccommodated flight** at a major **airport**. Differently, Heathrow and few other major **airports** have little or no spare capacity. In particular, the area around London is particularly congested: some **unaccommodated flights** touch each of its five main **airports** (Heathrow, Gatwick, Stansted, City, and Luton). The benefits of the simultaneous **slot** allocation over the current one, at European level, can be clearly seen when comparing Figure 2.2 with Figure 2.3. Figure 2.3 shows the allocations under the current scenario, using the same colour and size scales.

2.3 Secondary slot allocation

During the **secondary slot allocation**, **airlines** may try to exchange some of the **slots** obtained at the end of the **primary slot allocation** to preserve the feasibility of the planned routes. In addition, **airlines** may also decide to acquire further **slots** to introduce new flights.

In the study described in Pellegrini et al. (2012b), we design a **secondary slot allocation** mechanism as a combinatorial exchange and we formulate it as an IP model. As in the **primary slot allocation** optimization discussed in Section 2.2, the proposed mechanism assumes that each **airline** can manage multiple flights, may have **grandfather rights** at airports, and would like to have an ideal pair of departure and arrival **slots** for each of its flights. When this ideal pair of **slots** is not available, the **airline** has to shift the flight schedule forward or backward, incurring a **displacement cost** due to commercial and operational reasons. Each **airline** indicates the maximum displacement it can afford for each flight. In this study, as in the one presented in Section 2.2.2, we consider the whole route of the aircraft, allocating **slots** also in the capacitated en-route **sectors**.

Our mechanism, while minimizing the total **displacement cost** and satisfying all the **airlines'** requests, is consistent with the following three characteristics: **airlines** trade in a single market rather than through bilateral trades; **airlines** are allowed to condition their trade on a **slot** upon their trade on other **slots**; **airlines** are forbidden to sell their **slots** to specific competitors. These characteristics are the main ones envisaged in the literature, by the several existing qualitative studies on possible evolutions of the **secondary slot allocation** process. In addition, some of these studies envisage the implementation of a mechanism that prevents **airlines** from creating a dominant position through the acquisition of **slots**, e.g., by defining a threshold on the proportion of purchasable **slots**. In our mechanism we do not impose such a restriction, that could be, nonetheless, easily implemented.

Finally, we want our mechanism to ensure budget balance and individual rationality. As explained in Section 2.2.1, a mechanism is budget balanced when the overall amount

paid and received by [airlines](#) participating in the exchanges sums to 0. A mechanism, is individual rational when no [airline](#) is disadvantaged by participating, i.e., the amount paid plus the [displacement cost](#) is always at most equal to the maximum cost the [airline](#) is ready to bear. A further desirable property of a market mechanism is incentive compatibility: no participant in the market has an advantage from cheating. In our context, it corresponds to no [airline](#) having an advantage from declaring a [displacement cost](#) different from the true cost. Nonetheless, a market mechanism cannot be budget balance, individual rational and incentive compatible (Myerson and Satterthwaite, 1983). Here, we privilege the first two aspects. Indeed, if budget balance is not guaranteed, the legislator will be required to decide what the gain coming from the market shall be used for, and who shall pay in case the market needed to be subsidized. On the other hand, if individual rationality is not guaranteed, it will be very difficult, if not even impossible, to ensure [airlines](#)' acceptance of the mechanism. We finally note that linking the individual rationality to the maximum affordable [displacement cost](#) of an [airline](#) may provide some incentive not to cheat (see Pellegrini et al. (2012b) for details).

For coping with the reluctance of [airlines](#) of making their costs and requirements transparent to competitors, as in Section 2.2.1, the [secondary slot allocation](#) can be regulated by an independent moderator who is in charge of managing both sensitive data and collecting the unused [slots](#).

As above mentioned, the mechanism we propose is a combinatorial exchange. A combinatorial exchange is a market mechanism where bundles of items are traded. In this study we limit our attention to market mechanisms with surplus maximization, i.e., where the overall utility is maximized. A combinatorial exchange has three main characteristics:

1. the price of an item is a function of the seller's willingness to gain and the buyer's willingness to pay;
2. multiple sellers and multiple buyers participate in the trade;
3. a single bid can express the willingness to buy (sell) a bundle of items.

The exchange may be managed by a moderator, who collects all bids and finds the optimal solution.

In our mechanism, either [airport](#) or en-route [sector slots](#) are the items to exchange, whereas the sets of [slots](#) composing a route connecting origin and destination [airports](#) are the bundles. The [airlines](#) and the moderator are both buyers and sellers. In particular, the moderator may only sell [slots](#) unallocated during the [primary slot allocation](#) and acquires, for free, the [slots](#) that remain unallocated at the end of secondary one (no free disposal property). For each of its flights, an [airline](#) may express one bid on each possible flight route.

However, at most one of these bids must be executed, i.e., an exclusive-or (XOR) constraint holds between bids referring to the same flight.

The formulations proposed in the literature for combinatorial exchanges do not allow for a timely solution of instances large enough for our goal. Our model overcomes this limitation by considering the total payment made or received by an [airline](#) instead of fixing the price of single [slots](#).

In the practice, our mechanism may be executed periodically, a few times in the interval between [primary slot allocation](#) and start of the season. At each execution following the first one, the initial endowment of an [airline](#) is the set of slots received in previous one.

We propose an experimental analysis which compares the total [airlines'](#) cost of the [secondary slot allocation](#) obtained through either the designed mechanism or a bilateral trade mechanism. The latter mimics the current practice and can be implemented using the same model used for the combinatorial exchange, but allowing exchanges only between pairs of [airlines](#). Pairs of [airlines](#) are iteratively and randomly selected until all new flights are accommodated, or no feasible exchanges are found for a number of random selections. We repeat this procedure 30 times and we compute the average cost after having discarded the runs in which a feasible solution is not found. The same primary slot allocation is used as starting point for both mechanisms. It is obtained through the model described in Section 2.2.1, to which we add constraints for taking into account [sector](#) capacities.

We test our mechanism in three sets of scenarios. First, we vary the number of flight requests. In this set, for mimicking the current situation, [grandfather rights](#) are ensured and [sector](#) capacities are neglected. Second, we introduce various levels of [sector](#) capacities. In this set, the analysis is performed for each level of new flight requests as defined in the first set of scenarios. Third, we vary the [grandfather rights](#). In this set, we consider scenarios characterized by [grandfather rights](#), multi-season rights or no rights at all. Following the literature, multi-season rights would be valid for about three to six years and would imply the re-allocation of about one third to one sixth of the [slots](#) in each season. Hence, for simulating them, we consider a smaller quantity of [slots](#) reserved than when [grandfather rights](#) are enforced. The analysis is performed for each level of new flight requests and [sector](#) capacities as defined in the two first sets of scenarios. In all scenarios, we consider a periodic [secondary slot allocation](#) mechanism with four successive occurrences.

We run the experimental analysis on randomly generated instances in which we simulate five hour demand for a portion of Europe. The area represented in the instances is comparable to the region including, for example, Italy, Switzerland and Austria, or France and Belgium, or Germany, The Netherlands and Denmark.

The results of this analysis show that the use of the proposed mechanism allows a remarkable improvement with respect to the implementation of bilateral trades. The improvement

increases as a function of the number of flights which [airlines](#) wish to add during the [secondary slot allocation](#). Not surprisingly, the total cost increases with the tightening of [sector](#) capacity constraints. However, this increase is lower when our mechanism is implemented than with bilateral trades. Instead, no statistically significant difference appears when applying grandfather, multi-season, or no rights at all. We explain this result considering two factors. On the one hand, guaranteeing additional rights corresponds mathematically to setting additional constraints, and should then result in a more expensive optimal solution value. On the other hand, grandfather (and multi-season) rights may act as an anticipation of forthcoming requests. Optimizing the [slot](#) allocation knowing also future requests (for flights which [airlines](#) will wish to add in subsequent applications of the exchange mechanism) may imply a more convenient final objective function value.

2.4 Conclusion

In this chapter we summarized some contributions aiming to the solution of difficult problems emerging in the field of air transport. Namely, we focused on one of the most important process taking place in the [tactical phase](#), i.e., the [slot allocation process](#).

A main result which we achieved in this research is showing that the problem at European scale is actually tractable through optimization. Namely, we optimized large instances both in the primary and in the secondary slot allocations, considering even real European data in the former.

Another novelty we brought is the quantitative assessment of the impact of the presence of [grandfather rights](#) on the efficiency of the system. Specifically, we observed that, indeed, the overall efficiency would be higher in their absence. However, we also observed that we cannot state that these rights have an impact on [airlines](#)' costs, be them endowed with [grandfather rights](#) or not.

Finally, we tested the introduction of the consideration of capacity constraints along the whole flight routes, rather than considering only [airport](#) capacities. Considering the whole network already in the [tactical phase](#) may bring the modeling of air and rail transport a step closer: in the latter, the literature tries, with various levels of precision, to take into account of the whole infrastructure crossed by trains when planning them. In our experiments, we showed that considering [sector](#) capacities is important also in air traffic: optimal solutions returned when [sector](#) capacities are neglected may be unfeasible when capacities are accounted for. In the practice, the congestion induced by the presence of [sector](#) capacities is paid in terms of costly delays. The possibility of reducing such delays by considering capacity constraints during the [slot allocation process](#) may allow for an important

cost saving for the air industry.

Scientific production

Journals

P. Pellegrini, T. Bolić, L. Castelli, and R. Pesenti. SOSTA: an effective model for the Simultaneous Optimisation of airport Slot Allocation. *Transportation Research Part E: Logistics and Transportation Review*, 99:34–53, 2017.

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Chapter 3

Research contributions on rail transport problems

3.1 Introduction

The contributions proposed in this manuscript on rail transport problems concern the allocation of infrastructure capacity in all the phases of the capacity utilization planning processes.

As mentioned in Section 1.4, several optimization problems have been formalized for each phase. Among them, we focus, first of all, on the saturation problem in the [strategic phase](#). This problem consists in quantifying the capacity of an infrastructure by inserting in an existing (possibly empty) timetable as many trains as possible from a predefined set of desired ones. Measuring the capacity of a railway infrastructure is a task that has been challenging the academic and industrial community for a long time. It is commonly agreed that the theoretical capacity is the theoretical maximum number of trains that can utilize the infrastructure over time, and is an ideal level that only occurs when critical sections of rail are saturated (i.e., it is not possible to add any further train path). However, this definition does not really identifies the conditions under which the maximum number of trains should be planned. Indeed, different specifications of these conditions have been considered in the literature and in the practice (see, e.g., UIC (2012)), bringing to different capacity measurement strategies. Nonetheless, no common practice has emerged as satisfactory yet.

Then, in the [tactical phase](#), we consider a sub-problem of the efficient timetable generation from an energy consumption perspective. Specifically, we deal with the problem of defining suitable travels times between stations, to be then used for timetabling. Optimal timetable generation and its sub-problems have made the object of a really significant number of studies. Nonetheless, most of them are still far from being solved. In particular, only in a couple of countries some optimization is actually implemented when producing the annual timetable:

it remains a mostly experience-based manual activity in most of the cases. One of the main problems related to the application of optimization is linked to the size of the instances which, linked with the complexity of the problem, does not allow the currently existing techniques to be fully effective. Moreover, issues due to the lack or unsuitability of necessary data prevent the application of optimization in many situations.

Third, we study the timetable rearrangement in case of unpredicted needs for infrastructure maintenance. This problem emerges in the *pre-operational phase*. Indeed, maintenance activities are necessary to maintain the functionality of the railway infrastructure. Commonly, the maintenance activities are planned first. Then, the timetable is elaborated respecting the unavailability periods caused by the former. However, sometimes unplanned maintenance activities have to be introduced at short notice, and the timetable must be rearranged to respect the new unavailabilities. In addition, specific trains may be necessary to perform maintenance activities, and they are typically not scheduled in the timetable. In this case, the timetable may need to be further rearranged to integrate the maintenance trains. In the practice, the required timetable rearrangements are usually made either by hand, based on the experience of the dispatchers, or by resorting to some basic optimization tools. The typical result is a rearranged timetable made of train batteries, i.e., groups of trains which follow one-another circulating in the same direction.

Finally, we tackle the *real-time Railway Traffic Management Problem (rtRTMP)* which emerges in the *real-time phase*. This is the problem of rerouting and rescheduling trains during operations when traffic perturbations occur, with the aim of minimizing delay propagation. In our work, on the one hand we tackle the *rtRTMP* through optimization. On the other hand, we consider two of its sub-problems, namely the *real-time Train Routing Selection Problem (rtTRSP)* and the *real-time Energy Consumption Minimization Problem (rtECMP)*. The former consists in selecting an appropriate subset of alternative *routes* for each train to reduce the size of an *rtRTMP* instance while preserving in the feasible region high quality solutions. The latter aims at identifying suitable train driving profiles to respect some previously made routing and scheduling decisions minimizing a combination of delay and energy consumption. In the practice, the *rtRTMP* is tackled by dispatchers, who typically do not dispose of any optimization-based decision support tool. Hence, implicitly they first solve the *rtTRSP* to be able to deal with tractable instances of the main problem. Indeed, they seldom consider sets of alternative train *routes* including more than few possibilities, hence not being able to fully exploit infrastructure capacity. Once routing and scheduling decisions are made, it is up to train drivers to select their driving regime respecting the *signaling system* which impose these decisions.

All the models and algorithms proposed in this chapter belong to the RECIFE platform. RECIFE is a decision support platform under development at IFSTTAR (France) since the

early 2000's. The acronym stays for REcherche sur la Capacité des Infrastructures FERroviaires, i.e., research on the capacity of railway infrastructures (Rodriguez et al., 2007). This platform includes several optimization and human-machine interaction tools aimed at aiding decisions in railway planning and management. All the components of the RECIFE platform share an important characteristic, which distinguishes them from most of the literature. This characteristic is the capability of effectively dealing with relevant size instances of the different problems mentioned while considering the infrastructure modeled at the **microscopic** level. Such representation is crucial to properly capture and manage the actual capacity, but of course implies a larger amount of data than what would be necessary considering the alternative **macroscopic** representation.

The rest of the chapter is organized as follows. Section 3.2 reports our contributions on the saturation problem. Section 3.3 deals with the energy efficient travel time computation for timetabling, while Section 3.4 with timetable rearrangement to cope with infrastructure maintenance. Finally, Section 3.5 presents the works on the **rtRTMP** and its sub-problems.

3.2 Saturation problem

The study of the saturation problem is first motivated by the participation to the SIGIFret project (Sections B.2.1 and C.1.1). To deal with this problem, we propose RECIFE-SAT (Pellegrini et al., 2017b). It is a *Mixed-Integer Linear Programming (MILP)* based algorithm which models the infrastructure at the **microscopic** level and implements the **route-lock sectional-release interlocking** system, taking into account all the relevant operational constraints existing in the practice. Thanks to this **microscopic** representation, it ensures the feasibility of the saturated timetable: in nominal conditions, all trains can be run without the emergence of **conflicts**, that is, without encountering restrictive signals. Moreover, this is ensured while fully exploiting capacity, since the minimum headway times between pairs of consecutive trains depend on the specific **blocking-time stairways** representing the trains themselves. For doing so, a precise representation of the **interlocking** system (signal positions, number of aspects, etc.), the track (slope, curve, speed limit, etc.) and the rolling stock (acceleration capabilities, mass, length, etc.) is crucial.

In addition to the novel model proposed for the saturation problem, a main contribution of this study is the original representation of the infrastructure introduced. It is based on the concept of *section* including one or more **track-circuits** and preserving all the characteristics of the **microscopic** representation while bringing far less computational burden to the decision process. Specifically, we define a section as a sequence of consecutive **track-circuits** along a **route**. If two **routes** share a set of **track-circuits**, their split into sections must be such that,

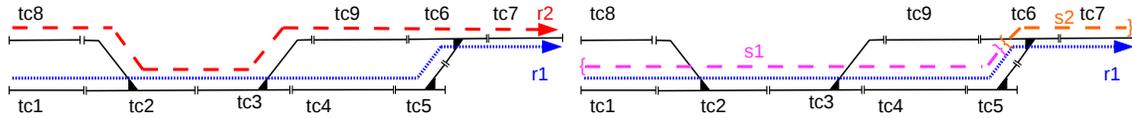


Figure 3.1: Example of the split of route r_1 into sections. Left: representation of the routes crossing the infrastructure. Right: representation of the corresponding split of r_1

if two trains use them, no change in the trains' order is possible within a section. Figure 3.1 shows an example of the split of a route into sections. In this example, two routes cross the infrastructure, r_1 and r_2 (Figure 3.1 - Left). For ease of visibility we pretend here that the interlocking system requires the utilization of only one track-circuit at a time. So we do not represent signals and long sequences of track-circuits. Let r_1 be the route to be split. Its first track-circuit is tc_1 and it is not shared with r_2 , so it can be included in the first section s_1 without setting any constraint. The next track-circuits tc_2 and tc_3 are shared with route r_2 . Indeed if a train passes first on the former it will pass first also on the latter, so no change in the trains' order is possible: they can be included in the same section as tc_1 . Then, tc_4 and tc_5 belong only to r_1 and they can be added to the same section. Finally, tc_6 is shared by the two routes and it is indeed possible that one of the two trains passes first on the first sequence of shared track-circuits (tc_2 and tc_3) and last here. Hence, tc_6 cannot be in the same section as tc_2 and tc_3 , and we must create a new one s_2 . Since no order change is possible between tc_6 and tc_7 , we include the latter in s_2 , too. Sections which share one or more track-circuits are called *incompatible*, and their access need to be coherent to ensure the absence of conflicts. This original infrastructure representation allows tackling much larger instances than what had been previously done in the literature.

Given the so-defined sections, we design the MILP model at the basis of RECIFE-SAT. It is aimed to include in an existing timetable as many saturation trains as possible, to compute the capacity of the infrastructure. Given a saturation time horizon starting at time \underline{H} and ending at \overline{H} , the trains in the timetable which are considered are all those which are present in the infrastructure at some time between \underline{H} and \overline{H} , disregard of their entrance time. Moreover, we include also the trains which enter after \overline{H} , but before the latest possible exit from the infrastructure of a saturation train which may enter at time \overline{H} . Thus, the trains of the timetable which are included depend on the longest saturation train considered. RECIFE-SAT works with sets of saturation trains which may be scheduled, split in terms of train types: all trains in a set are of the same type, i.e., if scheduled, they use the same rolling stock, travel along the same route and perform the same service in terms of intermediate stops. If scheduled, only their entrance time in the infrastructure and their time

of arrival at and departure from intermediate stations differ. In RECIFE-SAT, saturation trains use one out of two available *routes*: either the one traversing the infrastructure and associated to them in the instance definition or a dummy one. If they use the latter, it means that they are actually not scheduled. The binary variables of the model indicate whether a train uses or not a *route*, and the precedence relation between two trains using incompatible sections. The continuous variables represent the entrance time of the saturation trains in the infrastructure. The value of all these variables is chosen to minimize the number of saturation trains using the dummy *route*. Moreover, they must satisfy a number of constraints to ensure the feasibility of operations. Two sets of these constraints are disjunctive big-M constraints to link entrance time and precedence variables. Finally, we include in the model two sets of inequalities to speed up the solution process by eliminating symmetries.

In the RECIFE-SAT algorithm, the MILP model is solved through a commercial solver (CPLEX) and we set a time limit after which the best feasible solution found is returned. Remark that, since the decisions are whether to add or not saturation trains to the existing timetable, and if so, which ones and when, a first feasible solution always corresponds to the existing timetable itself.

To cope with instances representing very long saturation horizons, in the algorithm the horizon to be dealt with is split in time windows tackled sequentially: when the first window is saturated, the algorithm passes to the second one considering the saturation trains already included as non-modifiable, and so on. In the version presented in Pellegrini et al. (2017b), RECIFE-SAT performs a bi-objective optimization: on the one hand, it maximizes the number of saturation trains scheduled; on the other hand, the number of freight ones. This bi-objective optimization is performed by implementing an iterative ϵ -constraint method. We first determine the optimum (or the best solution we can find within a given computational time) with respect to each objective when considered alone. Then, we maximize for the total number of saturation trains imposing the schedule of a given number of freight ones: this number is varied iteratively to build an approximation of the Pareto front.

To assess the applicability of RECIFE-SAT, we consider a portion of the Paris-Le Havre line in France. This is a line characterized by dense mixed traffic: freight, high speed and conventional passenger trains share the infrastructure along the day. The 100 km line portion considered goes from Mantes-Station to Malaunay le Houllme, including sixteen stations and a junction, in addition to the access zones to two important yards. It is shown in Figure 3.2. For this network, we consider the timetable of November 22, 2012. It includes 647 trains, using in total 216 *routes* which result in 215 sections obtained by following the procedure reported above. The longest *route* lasts slightly more than two hours. In this timetable, we saturate two time horizons: the two peak time (7 to 9 am) and the four peak plus off-peak time (7 to 11 am) hours in the morning. The first horizon includes 270 trains in the

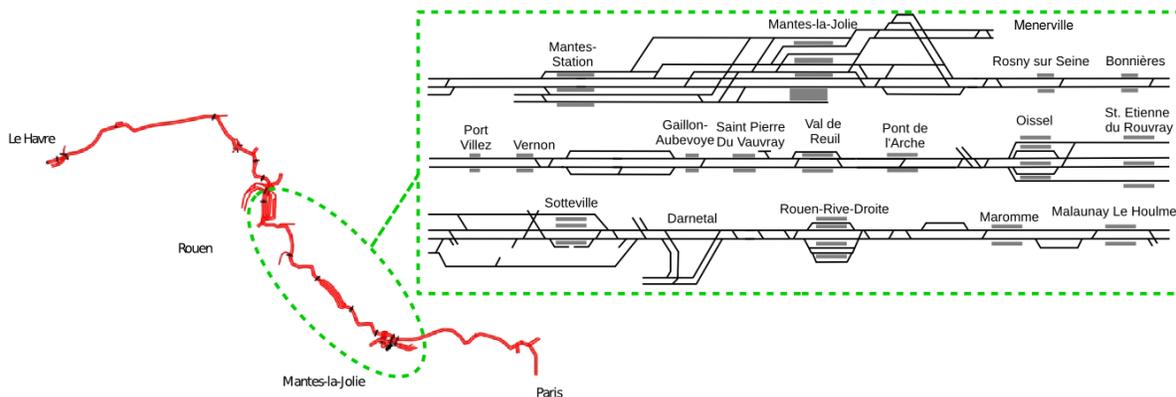


Figure 3.2: Schematic representation of the infrastructure considered for saturation in the SIGIFret project(track representation not in scale).

timetable, while the second one 348. The saturation trains which can be scheduled mimic the ones present in the timetable. The resulting peak time instance includes 8 411 and 852 237 continuous and binary variables, respectively, and 1 720 224 constraints. The peak plus off-peak instance includes 15581 and 3 288 055 continuous and binary variables, respectively, and 6 605 630 constraints.

The total number of saturation trains scheduled in the peak time instance goes from 157 to 162, while the number of freight saturation trains is between 48 and 53. The corresponding figures for the peak plus off-peak time instance are 319 to 332 for the total and 104 to 117 for the freight trains. Two examples of saturated timetables are shown in Figure 3.3 through space-time diagrams. Here, time is on the horizontal axis and space on the vertical one, with the indication of the main stations crossed.

In general, we observe that the results are slightly different from one solution of the approximation of the Pareto front to the other, but the trains are typically scheduled as close as possible. Indeed, the shortest-journey saturation trains are preferred: they contribute to the objective function with a smaller capacity consumption than the longer-journey ones. However, also long-journey saturation trains crossing the whole infrastructure are scheduled. Although having a very large number of short-journey trains may not be desirable, in this phase of the study we decide not to modify the experimental setup, in agreement with SNCF Réseau. In fact, if these saturation trains are considered, it means that the corresponding services are present in the daily timetable, at least three times for passenger trains, and then that they have an economic interest and cannot be discarded.

In a subsequent work, mostly carried out by the PhD student Nicola Coviello (Section C.2.4) and detailed in Coviello et al. (2017), we study the impact of the length of

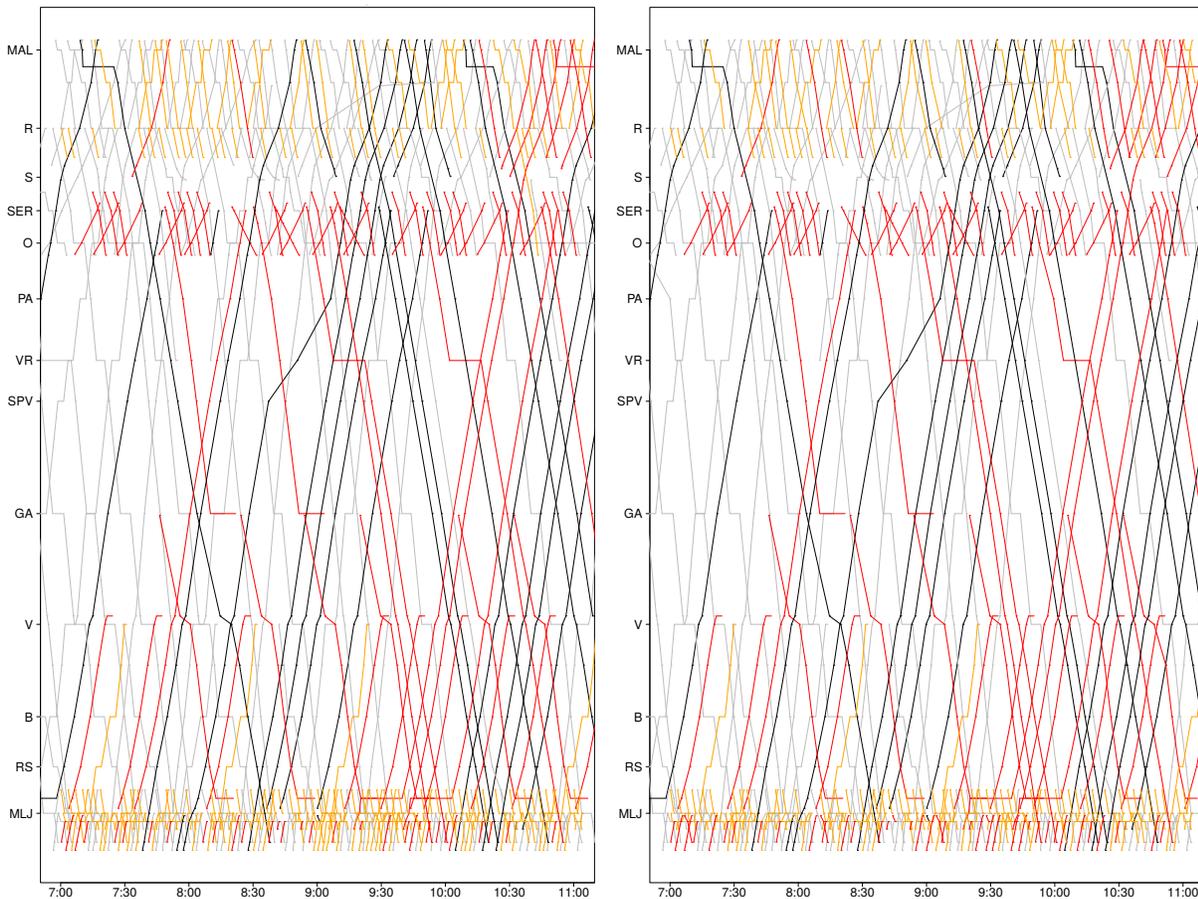


Figure 3.3: Space-time diagram of a saturated timetable. Peak plus off-peak time instance. Extreme solutions of the approximated Pareto front: 332 saturation trains, of which 104 freight (left), and 319 saturation trains, of which 117 freight (right). The grey and black lines represent passenger and freight trains in the timetable. Orange and red ones passenger and freight saturation trains scheduled.

the saturation train journeys on the process. In particular, we consider a portion of the previously tackled infrastructure, between Rosny-sur-Seine and Saint-Étienne-du-Rouvray, and two two-hour saturation horizons. We saturate the timetable with saturation trains chosen as in Pellegrini et al. (2017b) or with a subset of them including only the ones whose journey is longer than 35 km. We optimize according to the single objective of maximizing the total number of saturation trains scheduled. The result of this study show that, while the number of these trains indeed decreases when only long saturation trains can be scheduled, the total amount of km traveled by saturation trains remains rather constant.

In the same work, we also focus on the stability of the saturated timetable. Specifically, stability is defined as the capability of a timetable to limit the spread of traffic perturba-

tions, or even to reduce it through run time margins and buffer times. When a timetable is saturated, its stability is likely lowered by two factors:

- The higher number of train with respect to the original timetable, which likely increases the occurrence of **primary delays**;
- The higher density of train, which may facilitate the spread of traffic perturbations. This causes the occurrence of **secondary delays** due to the interaction of trains.

When producing a saturated timetable, a trade-off should therefore be sought to include a high number of trains on one side while ensuring a minimum level of timetable stability on the other. A compromise can thus be found by introducing constraints on the number, characteristics and arrangement of the scheduled saturation trains in order to keep the stability of a saturated timetable within a desired range. Such a task can be carried out, for instance, by imposing that saturation trains are separated by a given buffer time.

This study aims to investigate the influence of buffer times on the number of saturation trains in the solution of the saturation problem and on the stability of the resulting timetable. Hence, we saturate a real timetable imposing increasing values of buffer times. The so obtained saturated timetables are then simulated with the OpenTrack microscopic railway simulator in the presence of traffic perturbations, then the delays are analyzed to evaluate the stability. The latter is finally studied with respect to the corresponding buffer time and number of saturation trains. The results show, first of all, the evident role played by buffer time in increasing the timetable stability. As intuitive, this is paid through a reduction of the number of scheduled saturation trains. Moreover, the number of saturation trains (and of km traveled by saturation trains) is higher in the off-peak hours time window than in the peak hours one. This is not surprising since the original timetable of the latter time window is denser than the one of the former. However, the saturation time window appears to have a negligible influence on the stability of the saturated timetables. As above mentioned, the choice of the saturation train types affects significantly the number of the saturating paths but not the amount of km they travel. This choice affects also the timetable stability. In fact, it comes out that the best trade-off between amount of km traveled by saturation trains and timetable stability is achieved using longer saturation trains.

3.3 Energy efficient travel time for timetabling

The main work on the definition of energy efficient travel times for timetabling is detailed in Chevrier et al., 2013. In this work, we propose an algorithm to compute the trains' travel times between stations, concurrently minimizing energy consumption and travel time itself.

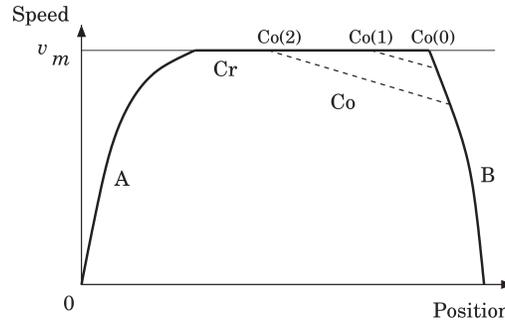


Figure 3.4: Typical speed profile over one section with maximal speed v_m in four steps (assuming no slope): acceleration (A), cruising (Cr), coasting (Co) and Braking (B).

This computation is done by building the speed profile to determine the suitable order of driving regimes that the train driver must follow. Indeed, choosing a travel time longer than the minimum possible one, corresponds to allocating a [time supplement](#) to the train.

Our algorithm provides a set of tradeoff solutions for the decision-makers in a single run. This will allow them to choose a travel time adapted to their needs in the timetabling process. Given that evolutionary algorithms have been shown to be well-suited to multi-objective optimization, our algorithm is based on a state-of-the-art multi-objective evolutionary algorithm, named IBEA.

According to the theory of optimal control, there are four optimal regimes defined by application of the Pontryagin's maximum principle: acceleration at full power; cruising at constant speed; coasting (inertia motion while the engine is stopped); maximum braking (according to the service braking, softer than emergency braking). The problem we deal with consists in designing the most suited speed profile over a given track. This track is composed of a sequence of sections, in which the speed has to be tuned. Here, a section is defined by a length and a constant maximal speed. Consecutive sections always have different maximal speed. In principle, a one-section journey can be divided in four steps as depicted in Figure 3.4 (we assume there is neither slope nor curve in this example). First, the train accelerates (A) to reach the maximal speed as quickly as possible. Then, a cruising phase (Cr) follows during which the acceleration is null and the traction effort equals the resistance to the train advance. Third, exploiting the fact that the wheel/rail adhesion is weak, it is common to let the train coast over long distances, e.g., points Co(1) and Co(2) indicate two positions from which coasting can be started. Coasting from point Co(1) may slightly increase the travel time with respect to the case in which coasting is excluded, while reducing energy consumption. By coasting from point Co(2), energy consumption may be further decreased with a consequent increase of travel time. Point Co(0) indicates the last

position from which the train can brake with its normal service braking (B) for being able to stop at the end of the section, if traveling at maximum speed.

In our algorithm, to build a speed profile between two stations, we decompose the train route into a set of sections depending on the maximum speed variations, and we construct the speed profile in each section sequentially. This construction is based on the use of two target-speeds per section, which are our decision variables. Specifically, each section is split in two parts: a first part in which the acceleration at full power (the most energy-consuming driving regime) can be used and a second part for using energy-friendly (cruising) or energy-free (coasting, braking) driving regimes. During the first part, the train has to reach the first target-speed by braking or accelerating, depending on its entrance speed. The latter is null if the train is departing from a station, and it is equal to the final speed of the previous section otherwise. Then, during the second part, the train tries to reach the second target-speed, initially by coasting. Additional regimes may be used to reach this speed (braking) and complete the rest of the section (cruising). Even if some of these driving regimes may not be used in all sections, typically, their use follows the order: coasting, cruising, braking. Building the profile as described allows the identification of the length of the two parts in which the section is split and of the time necessary for traversing them. During the solution construction, we impose some constraints on the decision variables for each section: the first target-speed must be higher than or equal to the second one, and lower than or equal to the maximum speed; the second target-speed must be higher than zero.

The genetic algorithm we propose consists in starting from an initial population of solutions and having it evolving over time through crossover and mutation, to generate better and better offspring. The main idea is to introduce a total order between solutions by means of a binary quality indicator. Here, quality represents the well-spread aspect of the solutions in a front: each solution somehow contributes to the spread of the front. The fitness assignment scheme is based on a pairwise comparison of solutions from the current population. To each solution, we assign a fitness value which measures its contribution to the population and hence the loss in quality if it is removed.

We define a solution via the set of target-speeds of the train: it is a vector including a number of components equal to twice the number of sections of the train route. For initializing the population of solutions, we start from the one which minimizes travel time alone, in which the train travels as fast as possible on each section. Then, we slightly decrease the first target-speed of each section to obtain solutions which imply longer travel times and lower energy consumption. We do so a number of times equal to the desired population size. We then apply crossover and mutation to push evolution. Crossover is the mechanism allowing solutions to recombine with each other in order to produce new solutions. As the solution space is continuous, we use a well established operator adapted to the continuous

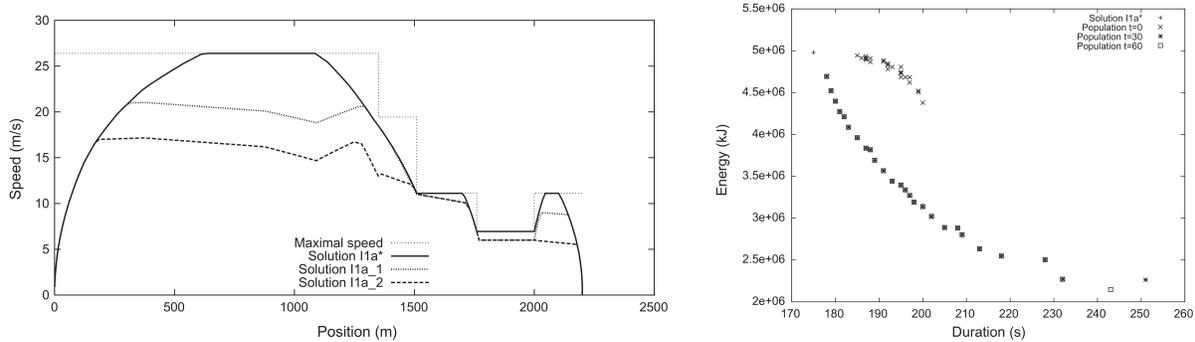


Figure 3.5: Example of results of our algorithm for travel time definition in the first line considered. Speed profiles corresponding to three solutions of the front (left). Complete front returned at different computational times (right).

search: the Simulated Binary Crossover. Mutation consists in providing diversity for the population by modifying a solution randomly chosen. Again, we use an operator adapted to the continuous search, i.e., polynomial mutation. If, during a solution construction, a speed profile meeting the target-speeds cannot be built, the solution is declared infeasible and it is discarded.

We assess the capability of our algorithm to supply a satisfactory front of tradeoff solutions on two lines. The first one comes from the literature. It is 2.2 km long and includes five sections. We derive the second one from our contacts with SNCF Réseau. It is the Saint-Étienne-Rive de Giers line, 20.2 km long with five sections. Along this line, the gradient is mostly negative and thus the outward journey is in descent for the most part of the line. As an example of our results, Figure 3.5 presents on the left plot three speed profiles obtained for the the first line. The one referring to solution I1b* is the profile minimizing travel time alone. The one referring to solution I1b_1 corresponds to a 10% increase of travel time and a 49% decrease of energy consumption. The one referring to I1b_2 brings the variations to 15% and 54%, respectively. The right plot of the figure shows the front evolution throughout the run, considering the initial population ($t=0$), the front after 30 seconds of computation ($t=30$) and the one after 60 seconds ($t=60$), which is the computational time we set as a stopping criterion.

In general, we think that our results support the relevance of a multi-objective algorithm of travel time and energy consumption optimization. Indeed, in a short computational time, our algorithm has been capable of producing a set of distinct solutions, on a front quite nicely spread in the objectives space. Moreover, the results show how major variations in energy consumption can be attained with rather small increases of travel time. This supports

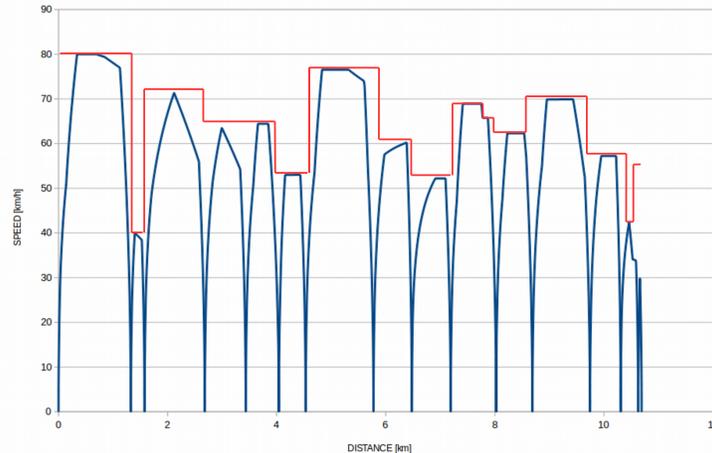


Figure 3.6: Representation of the speed profile of a train optimized through our MOGA-II algorithm to compute travel times minimizing energy consumption. The horizontal axes reports distance, the vertical one speed. The red line indicates the maximum speed allowed along the line.

the importance of solving the problem tackled here to supply the timetabling process with suitable inputs.

In a more recent study (Montrone et al., 2016), which was mainly carried out by Teresa Montrone (Section C.2.5), we consider a slight variation of the same problem. Specifically, we consider complete itineraries, instead of only portions between pairs of stops. We set the total train travel time and the minimum dwell time at stations as inputs and we optimize the speed profiles, and hence the travel times, between pairs of stations to minimize energy consumption. We base our solution algorithm on another evolutionary algorithm, named MOGA-II. As in the previous work, we split the train route in track segments with constant maximum speed. For each of them, the algorithm determines a target-speed to be reached. Based on this, the driving regime combination followed by the train is given by acceleration until the target-speed, cruising, coasting and deceleration until stop. The algorithm finds the lengths of cruising between the stations that guarantee the respect of the overall train travel time. Then it calculates the length for the other driving regimes analytically. We test this algorithm on the infrastructure of a urban line with 16 stations. The considered train stops in each station and the minimum dwell time is always 60 seconds. The slope changes along the line and it reaches quite steep angles. Figure 3.6 shows the best speed profile obtained in 100 iterations, in blue, against the maximum speed allowed on the line, in red. The parts appearing almost vertical of the blue line represent accelerations and brakes. Instead, when a less steep line is visible, coasting is performed. Thanks to the locally steep gradient, even

coasting also allows the increase of the speed at times. Indeed, it is visible here that the train is not always traveling as fast as possible, and the locations for the coasting regime are specifically chosen. This brings an energy saving of 19% with an increase of travel time of less than 2%. This increase is acceptable thanks to the [time supplements](#) which are included in the overall travel time. This result is coherent with those of [Chevrier et al. \(2013\)](#): slight increases of travel time may bring to remarkable reductions of energy consumption. In this work the relevance of considering a whole itinerary emerges, as different characteristics of the infrastructure in different locations may make driving regimes convenient or not in different locations.

3.4 Timetable rearrangement problem in case of infrastructure maintenance

The work on timetable rearrangement to cope with infrastructure maintenance emerging at short-notice appears in the PhD thesis of Diego Arenas (Section [C.2.2](#)). A first version of it appears in a paper which was voted as the best paper of the 7th International Conference on Railway Operations Modelling and Analysis ([Arenas et al., 2017](#)). An extended description of the work is presented in [Arenas et al. \(2018\)](#).

As mentioned in Section [1.4](#), the maintenance needs of the infrastructure are commonly defined before the conception of train timetables. Then, the timetables are conceived taking into account the temporal unavailability of track segments caused by maintenance activities. However, unexpected maintenance needs sometimes emerge in the [pre-operational phase](#) and additional maintenance activities need to be scheduled into existing timetables. Moreover, some of these activities impose a temporary speed limitation on the tracks adjacent to the maintained one for safety reasons. Obviously, by applying a temporary speed limitation on a track segment, the time needed for a train to circulate over this segment is increased. This may require adjustments to the schedule of the train. Furthermore, the circulation of maintenance trains necessary to perform these activities shall also be taken into account. These trains are specifically equipped for the task to accomplish and are not included in the timetable. Their inclusion will likely require additional alterations to other trains' circulations. We denominate the trains that are scheduled in the original timetable as operational trains. They include several types of trains, e.g., passenger, freight, shunting, empty rides, etc.

There are mainly two types of adjustments that can be made to the trains in a timetable: rescheduling and rerouting. We do not consider train cancellations although it may be an alternative, since in the [pre-operational phase](#) this is not always an option. Indeed, train

cancellations may require negotiations with the railway undertaking, which are out of the scope of this work. rerouting decisions of the same nature can be applied to operational and maintenance trains. However, the nature of scheduling decisions is different for the two types of trains. On the one hand, for operational trains, the departure time cannot be advanced, only delayed. The reason for this is that in the [pre-operational phase](#), the timetable is normally already known by the users. For instance, the advance of a departure may lead passengers to miss their train. Another particularity of these trains is that a delay may be only introduced while they are dwelling at some station. This means that an operational train can only stop at its predefined intermediate stopping stations. This behavior is known as green wave policy. There are several reasons to do so: better passengers comfort, lower power consumption, compliance with security and safety issues, etc. Ideally, the modifications to the schedule of operational trains are made while trying to preserve the planned times of the original timetable. On the other hand, since maintenance trains are not bind to a timetable, they can be scheduled as it is best convenient. However, they have to be present at the maintenance locations when it starts, and leave when it finishes. Provided that this holds, maintenance trains can be scheduled to stop at any signal along the track, to be overtaken by operational ones.

The goal of the timetable rearrangement is the minimization of the scheduled time deviations with respect to the initial timetable.

The objective of our study is, first, to propose a formulation that allows the insertion of unplanned maintenance activities into an existing timetable while guaranteeing its feasibility. More specifically, we present RECIFE-MAINT: a [MILP](#) formulation to perform rearrangements on planned train circulations while minimizing the scheduled time deviations with respect to the existing timetable. Thanks to the [microscopic](#) representation of the infrastructure and rolling stock, a number of specific circulation constraints can be defined in RECIFE-MAINT, thus ensuring the feasibility of the resulting timetable while optimizing the railway capacity utilization. Additionally, RECIFE-MAINT takes into account specific aspects related to maintenance activities that are often disregarded in the literature, such as temporary speed limitations and planning of maintenance trains.

Second, we present four algorithms based on the solution of RECIFE-MAINT for a limited computational time. The best solution found within this time is returned. If the optimum is proven before the time limit, the process stops and returns it. The first algorithm (RECIFE-MAINT Full) consists in solving RECIFE-MAINT by using a MILP solver (CPLEX). The second one (RECIFE-MAINT Battery) requires solving a constrained version of RECIFE-MAINT by using a MILP solver. This constrained formulation does not allow rerouting, to emulate the train batteries approach: train batteries are scheduled in both directions over a single track segment in an alternated fashion maintaining as much as possible the

default [routes](#) planned in the timetable. This algorithm serves as a benchmark to compare the performance of the other ones, since it somehow emulates the current practice in which the batteries approach is used based on a [macroscopic](#) infrastructure representation. The third algorithm (RECIFE-MAINT Battery-Full) is a two-phase one where RECIFE-MAINT Battery is first used to obtain a feasible solution. After a first-phase time limit elapses, the best solution obtained is used to initialize RECIFE-MAINT Full. If no feasible solution is found, the execution of the first-phase is extended until this happens or the whole available time limit expires. However, if before the first-phase time limit elapses the optimality of a solution is proven, the first phase ends and the remaining time is devoted to the second-phase. Finally, the fourth algorithm (RECIFE-MAINT Greedy-Full) is a two-phase algorithm, too. Here, the first phase uses a heuristic that allows rerouting to generate an initial solution for RECIFE-MAINT Full. The heuristic in the first phase is based on a greedy approach that plans trains one at the time. Once a train is planned, its [route](#) and schedule can not be changed. More precisely, the heuristic can be divided into three main nested activities: timetable construction, train planning and scheduling:

- *Timetable construction*: A timetable is built by including trains, one by one, through *Train planning* following a predefined train order. Once a train is processed, its plan ([route](#) and schedule) cannot be modified. Once all trains are planned in the timetable, the objective function value corresponding to the resulting timetable is calculated.
- *Train planning*: The schedule attainable with each [route](#) of the train is computed through *Scheduling*, the corresponding objective function contribution value is calculated and the best one is chosen. In this way, the [route](#) with the lowest value can be assigned to the train along with its respective schedule.
- *Scheduling*: Given a route, the schedule is generated in a sequential way, i.e., the utilization of each [track-circuit](#) in the [route](#) is scheduled progressively, from the first to the last one. When a [conflict](#) arises we add an extra time to the closest previous [track-circuit](#) where the train is allowed to experience delay, then, the scheduling is resumed starting from said [track-circuit](#). The scheduling process is finished once the utilization of the last [track-circuit](#) of the [route](#) is set.

Note that the train order may have a high impact on the objective function value of the generated timetable. Indeed, some trains, when planned early in the process, can cause heavy delays to the trains planned later. To mitigate the effect of the train order, we include in the heuristic a mechanism to explore several possibilities. A timetable is generated based on several train orders, and the one with the lowest objective function value is chosen as the solution to initialize RECIFE-MAINT Full.

We use these algorithms in the experimental phase to solve instances based on the French case study tackled in the second set of experiments described in Section 3.2: the 70-km line between Rosny-sur-Seine and Saint-Étienne-du-Rouvray. For creating the instances, we define a set of ten unplanned maintenance activities to be performed (one per instance) by mimicking some actually performed on this line in 2012. When an activity is performed, all the adjacent tracks are subject to a temporary speed limitation of 40 km/h, the maximum speed allowed in this line being 160 km/h. The results show that both two-phase algorithms obtain at least a feasible solution for all instances within the time limit fixed. Instead, RECIFE-MAINT Full fails to do so for 13% of the instances. In general, the number of optimal solutions proven by these three algorithms is similar, although a slightly better performance is detectable for the two-phase ones. By closely analyzing the results of RECIFE-MAINT Full, we observe that this algorithm is systematically outperformed by the two others, except for the instances where all three algorithms find the optimal solution, either proving the optimality or not. In any case, all of them are statistically significantly better than RECIFE-MAINT Battery. We can also state that, for all instances, the solution improvements made by RECIFE-MAINT Greedy-Full are significantly higher than the ones made by RECIFE-MAINT Battery-Full.

Hence, we conclude that the proposed two-phase algorithms are indeed applicable, since they always provide solutions to the real case study. Furthermore, they are well performing, since they outperform the optimized version of the approach used in the current practice. By analyzing some characteristics of the instances together with the percentage optimality gap of the solutions produced by RECIFE-MAINT Greedy-Full, our best performing algorithm, we obtain some insights on the characteristics of the instances which may be more difficult to solve than others. The percentage optimality gap indicates the percentage difference between the best feasible solution found by the algorithm within a run and the best bound identified. The higher the gap, the further the solution may be from the optimum. We consider the gap as an indicator of the difficulty of an instance for the algorithm: if it is equal to 0 (the optimality is proven), we consider the instance easier than if a positive gap is returned. The higher the gap, the more difficult the instance. The characteristic of the instances which appears to better explain the difficulty is the product of the number of trains whose originally planned *route* passes on the track object of maintenance, times the number of those whose originally planned *route* passes through a temporary speed limitation.

3.5 Real-time railway traffic management problem

The studies on the *real-time Traffic Management Problem* probably constitute the most relevant contribution presented in this manuscript. Indeed, in the last year one of the algorithms

proposed has started being recognized as representative of the state of the art.

The work presented in this section is organized according to the specific problem tackled. Namely, in Section 3.5.1 we focus on the general *rtRTMP*, for which we present the RECIFE-MILP algorithm. In Section 3.5.2 we describe ACO-TRSP: our Ant Colony Optimization (ACO) algorithm for the *real-time Train Routing Selection Problem (rtTRSP)*. Finally, in Section 3.5.3 we focus on TDRC-MILP which tackles the *real-time Energy Consumption Minimization Problem (rtRTMP)*.

3.5.1 RECIFE-MILP

Our algorithm for tackling the *rtRTMP* is named RECIFE-MILP. It is a heuristic based on the truncated solution of a MILP model. The proposal of this model appears in Pellegrini et al. (2014) and is subsequently refined in Pellegrini et al. (2015).

The problem formulated through this model is a routing and scheduling one, and it becomes relevant when an unexpected event perturbs traffic. Specifically, when one or more trains suffer a *primary delay*, *conflicts* may emerge implying the propagation of *secondary delays*. To minimize this propagation, trains can be rerouted or their schedule may be changed with respect to the one originally planned in the timetable so as to obtain suitable passing orders. Multiple sets of constraints characterize the problem. First of all, time concerning constraints: a train cannot be operated earlier than its arrival in the *control area* (or than its scheduled departure from a platform), and it must occupy each *track-circuit* along one *route* for its *running time* and *clearing time*, with the possible addition of a delay due to traffic. If the *control area* includes a station and trains with passenger transfers are scheduled (trains in connection), then their arrival and departure times must be coherent. Second, constraints due to the change of rolling stock configuration may have to be imposed. In particular, the arrival and departure times of trains resulting from the turnaround, join or split of one another must be coherent. Third, capacity constraints require that at most one train utilizes a *block section* at a time. For ensuring this, the *blocking-time stairway* is typically modeled. In the literature, two granularities have been used to interpret the *microscopic* infrastructure representation. Specifically, when rough granularity is used, only *block sections* are considered, while their decomposition into *track-circuits* is ignored. In the *blocking-time stairway* this translates in the simultaneous release of all *track-circuits* of a *block section*. If using fine granularity, also *track-circuits* are modeled and they can be released progressively as the train exits them.

The MILP model at the basis of RECIFE-MILP is one of the very few approaches considering fine granularity. This allows exploiting the *route-lock sectional-release interlocking* system. The full model is detailed in Appendix A. Non-negative continuous variables repre-

sent times. In particular, they account for the start and end times of **track-circuit** utilization by a train and for the start of its occupation along a particular **route**. Binary variables model train routing and train scheduling decisions. For the routing decisions, the binary variables define the choice of a particular **route** for a train, among its alternatives. For the scheduling decisions, the binary variables define the order in which two trains utilize a **track-circuit** belonging to both their **routes**. The model includes different sets of constraints, which can be classified in three distinct groups:

1. Constraints concerning the traveling of the trains in the **control area**. Given that a train uses exactly one of its **routes** to traverse the **control area**, these constraints impose the minimum entrance times in the **control area** itself and the minimum departure times from stations, considering the scheduled times and possible primary delays. They also impose the coherence of travel times on all **track-circuits**. This travel time includes **running time**, **clearing time** and delay. Delay must be accounted for considering the whole time in which a part of a train is on a specific **track-circuit**, even when trains are longer than **track-circuits** and delays touch several of them concurrently;
2. Constraints concerning the change of rolling stock configuration. To consider turnaround, join or split of trains, the model includes sets of constraints that impose time and space coherence between concerned trains. In particular these constraints model the minimum separation time required between the trains arrival and departure. Moreover, both have to happen on the same **track-circuit**;
3. Constraints concerning the capacity of the **control area**. These constraints model the **route-lock sectional-release interlocking** system through the scheduling variables. They are disjunctive constraints including a big- M parameter.

All three groups of constraints depend on the routing binary variables. In the first group, a set of constraints models how each train uses exactly one **route** to travel in the **control area**. Furthermore, the travel time on a **track-circuit** depends not only on the **track-circuit** itself, but also on the **route** along which it is used. For example, a train with a particular **route** could be required to brake on a **track-circuit** due to the crossing of a switch in a certain position, while this may not happen for all the other **routes** of this train, even if they include the same **track-circuit**. Thus, the binary variables indicating the routing decision appear in the constraints concerning the times, setting them to 0 along all the not chosen **routes**. In the second group of constraints, the relation between the **routes** of the arrival and the departure trains has to be satisfied. In particular, the last **track-circuit** of the arriving train **route** has to be the same of the first **track-circuit** of the departing train one. In the third group of constraints, the use of the binary variables stating the routing decision is due to

the fact that, indeed, the utilization time is a function of the travel time, which necessitates of these variables. The proposed model is the only one existing in the literature capable of optimizing routing and scheduling simultaneously, providing a proof of convergence to the optimum in reasonable time for relevant instances, as it will be discussed in the following. Moreover, it is one of the extremely few dealing with changes of rolling stock configurations and with features as trains and *track-circuits* length.

The objective function considered in RECIFE-MILP is the minimization of the total delays suffered by trains at their exit from the *control area* and at their intermediate stops. However, this objective function can be modified as desired: for example, in Pellegrini et al. (2014) we minimize also the maximum *secondary delay* suffered by a train.

As most algorithms for the *rtRTMP*, RECIFE-MILP implements the so-called *fixed-speed model*. Here, *running times* and *clearing times* are precisely considered when no traffic perturbs the train movement. Specifically, if brakes and accelerations take place in a *track-circuit*, due for example to the presence of a switch, they are precisely considered in the input values. Instead, when they are due to traffic conditions, for example if a train needs to brake for a yellow signal to let another train pass, speed variation dynamics are neglected: the train can brake in no space and no time and re-accelerate in the same way. This choice is very common, mostly due to the complexity which would be brought by the consideration of the alternative *variable-speed model*, which requires the consideration on non-linear constraints.

In RECIFE-MILP, the solution of the above described *MILP* model is included in a two-step optimization process. In the first step, an optimization of the only scheduling problem is performed, considering the *routes* originally planned in the timetable. This step returns either the optimal solution or a feasible one if a given time limit is reached. This solution is used to initialize the search in the second step, where routing is also optimized for a given computational time. After this time, the best solution found is returned, unless the search stops earlier after managing an optimality proof. Moreover, depending on the objective function considered, the first-step solution is also used to suitably reduce the value of the big-M parameter, so possibly strengthening the model. This two-step optimization process has shown to strongly improve the performance of the algorithm.

Another contribution to this performance improvement is given by the backward shift of all reference times. We decrease all the values representing entrance, stop and scheduled exit times so that the first reference time is equal to zero, and all time differences are respected. Such a backward shift allows the *MILP* solver to deal with smaller quantities and it amplifies the impact of the decrease of the big-M parameter.

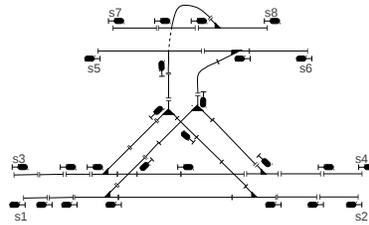
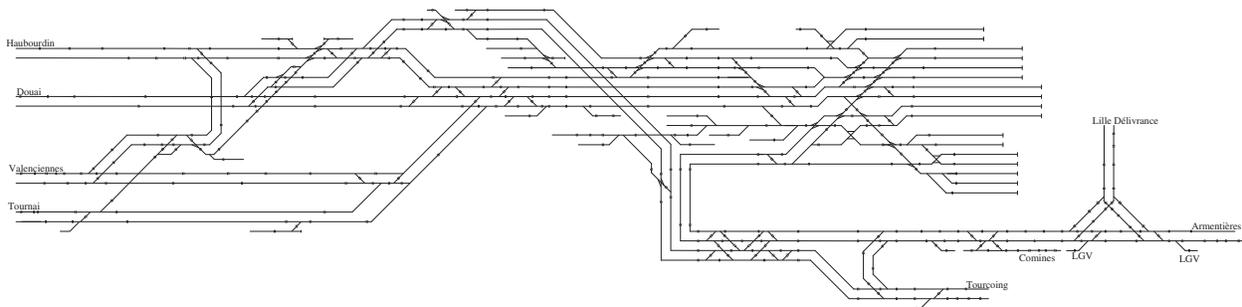
Moreover, we try to reduce as much as possible the number of scheduling variables. In Pellegrini et al. (2015) we propose a first way for doing so. Specifically, by exploiting the infrastructure topology it is often possible to identify sequences of *track-circuits* on which

the order of two trains necessarily needs to be preserved. Think, for example, of a sequence of **track-circuits** on a single track line. Hence, only one binary variable can be defined for capturing the precedence relation on all these **track-circuits**. In a further evolution of the same idea, in Pellegrini et al. (2017a) we push this reasoning forward proposing a reformulation of the RECIFE-MILP model. In this reformulation, we further reduce the number of scheduling variables by including in the disjunctive constraints concerning capacity also variables representing specific train routing decisions. This allows submitting the condition of necessary preservation of precedence relation to the use of specific **routes**, hence permitting a further reduction of the number of binary variables.

Recently, in the PhD thesis of Kaba Keita (Section C.2.3) (Keita et al., 2017), we assess the performance of Benders decomposition on the RECIFE-MILP model. The classical decomposition does not allow an improvement of the performance of the algorithm. However, a novel approach we propose based on the idea of a three-sub-problem decomposition manages in some cases to outperform RECIFE-MILP. The first of the three sub-problems is a version of the classical Benders restricted master problem, in which only binary variables are considered. Specifically, it only includes routing variables. The second is the scheduling problem which we obtain by setting the **routes** as decided in the master problem. This problem includes then continuous variables related to times and binary variables related to order relations, as well as the big-M constraints of the original model. It finds the optimal solution for the given **routes**. The third sub-problem only includes continuous variables and is used to create optimality cuts for the restricted master problem: these cuts indicate the quality of the solution achievable with a set of **routes**. The algorithm consists in iteratively solving the three sub-problems for a limited computational time, progressively adding cuts to the first one. Although in some cases the performance of RECIFE-MILP appears worst than the one of the proposed algorithm, what are the conditions for which this holds is still under study.

Case studies

Since the proposal of RECIFE-MILP, we have applied it to several case studies. We started with the study of instances representing traffic in the **control areas** known as Triangle of Gagny and Lille Flandres station, depicted in Figures 3.7 and 3.8, respectively. The former is a small area where eight **routes** connect eight origin-destination pairs: no rerouting is possible. It includes 32 **track-circuits** organized in 26 **block sections**. This translates into one-hour instances of RECIFE-MILP including about 60 trains, 2 250 continuous variables, 1 530 binary ones and 8 650 constraints. The Lille Flandres **control area** includes links to seven regional, national and international lines and 17 platforms. A total of 2 409 **routes** exist and they are composed by 299 **track-circuits** and 829 **block sections**. It covers an area of

Figure 3.7: Infrastructure representation of the Triangle of Gagny [control area](#)Figure 3.8: Infrastructure representation of the Lille Flandres [control area](#)

about 12 km, where more than 500 trains arrive or depart every day. This translates into one-hour instances including about 45 trains, 20 150 continuous variables, 26 400 binary ones and 26 500 constraints. Randomly perturbed scenarios are tackled. In particular, starting from the original timetable, we impose a delay to 20% of trains which do not represent shunting movements: we randomly select the trains to be delayed and we randomly draw their delay in the interval 5 – 15 min. Both these random selections are based on uniform probability distributions. By replicating the random assignment of train [primary delay](#) several times we obtain different perturbed one-day timetables. For each of them we get one-hour instances including all trains which enter the [control area](#) within a 60 minute interval starting a different times. We use this procedure for generating randomly perturbed instances in all [control areas](#) tackled. On these two [control areas](#) we assess the importance of the possibility of modeling the [route-lock sectional-release interlocking](#) system, compared to the more commonly studied [route-lock route-release](#) one. In Pellegrini et al. (2014) we show that solutions which are actually feasible in the practice are deemed unfeasible in the latter system, and this has a statistically significant worsening effect on the quality of the routing and scheduling choices returned.

In a following study (Pellegrini et al., 2015) we tackle, in addition to the Lille Flandres [control area](#), the two cases of the Pierrefitte-Gonesse junction and the line around Rouen-

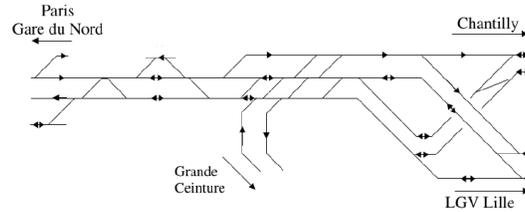


Figure 3.9: Infrastructure representation of the Pierrefitte-Gonesse control area

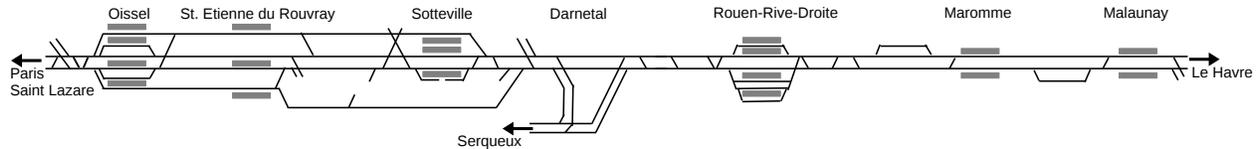


Figure 3.10: Infrastructure representation of the Rouen control area

Rive-Droite station, illustrated in Figures 3.9 and 3.10, respectively. The former is a junction covering an area of about 15 km, including 80 track-circuits, 174 block sections and 39 routes. A peculiarity of this case is the intense mixed traffic: the junction is crossed by high-speed and conventional passenger trains, as well as freight ones. The one-hour instances in Pierrefitte-Gonesse include about 14 trains, 11 000 continuous variables, 9 000 binary ones and 35 000 constraints. The Rouen control area includes 27 km of line and six stations, with two to six platforms. The 190 track-circuits compose 189 block sections and 11 347 routes. Also here traffic is mixed. The main source of difficulty of the Rouen instances is the very high number of routes available for the trains. Here, one-hour instances include about 10 trains, 117 000 continuous variables, 78 000 binary ones and 364 000 constraints. We use the three control areas to show the robustness of RECIFE-MILP in Pellegrini et al. (2015). Specifically, we test several variants of the algorithm and we select the best one through an automatic algorithm configuration approach named SMAC. The chosen variant, described above in this section, always achieves very high quality results, often getting to the optimal solution within a three-minute computation despite the very different characteristics of the three cases.

We add tests in the St. Lazare control area in Paris to show the good performance of the reformulation of the RECIFE-MILP model reducing the number of scheduling binary variables (Pellegrini et al., 2017a). It is a terminal station area covering slightly more than 4 km, with 27 platforms represented in Figure 3.11. It includes 212 track-circuits, 197 block sections and 154 routes. A one-hour instance contains about 101 trains, 24 300 continuous variables, 12 150 binary ones and 114 600 constraints.

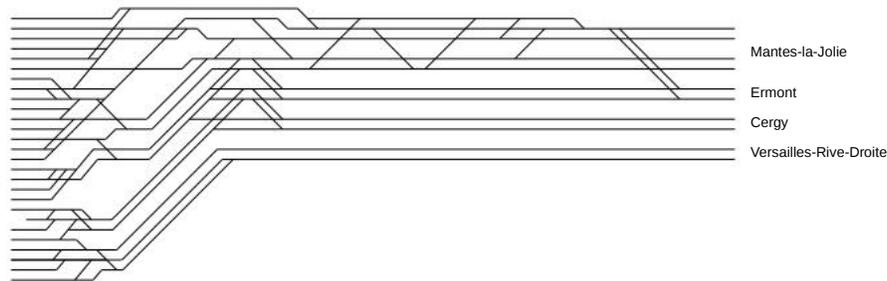


Figure 3.11: Infrastructure representation of the St. Lazare control area

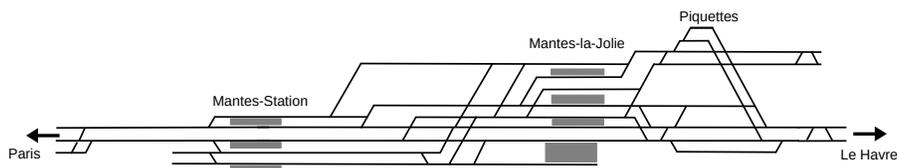


Figure 3.12: Infrastructure representation of the Mantes-la-Jolie control area

As deeper experimental analyses, let us mention the ones carried out within two research projects. These two analyses have the peculiarity of including microscopic simulation in the experimental set-up. The former is the one belonging to the SIGIFret project (Section B.2.1), in the control areas of Rouen and Mantes-la-Jolie. The latter, shown in Figure 3.12, is a critical area along the Paris-Le Havre line, as Rouen. It covers 7 km and includes two stations and one line bifurcation, with its 117 track-circuit, 129 block sections and 735 routes. A one-hour instance contains about 47 trains, 3 450 continuous variables, 19 728 binary ones and 19 700 constraints. In the SIGIFret project we collaborate with SNCF Réseau to define realistic and relevant perturbation scenarios on the two control areas. On these scenarios, we perform an empirical analysis to assess the actual impact that an optimization-based decision support tool may have on traffic management: we design an open-loop of optimization and simulation, based on the interaction of RECIFE-MILP and the OpenTrack microscopic simulator. To assess the impact of the optimization, we compare the train delays after the simulation of the traffic management decisions made according to different strategies. First of all, we consider RECIFE-MILP when rerouting is either forbidden or allowed. Then, we simulate the first-come-first-served (FCFS) strategy, in which the first train claiming a track section is the first one which is allowed to go through it. Furthermore, we take into account the traffic management strategy currently preconized in France and in many European countries: between two trains claiming a track section, the most punctual train is favored and the already delayed one is stopped or slowed down. Finally, for three

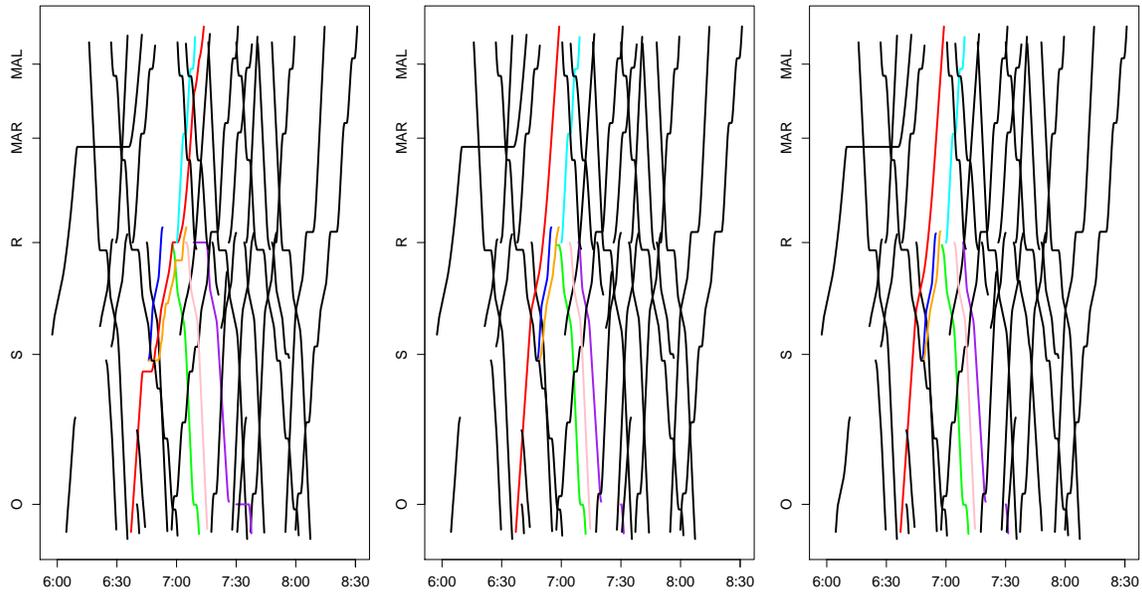


Figure 3.13: Space-time diagram representing traffic in a scenario tackled in the SIGIFret project. Representation of dispatcher decisions (left), RECIFE-MILP with no rerouting (center) and RECIFE-MILP with rerouting (right).

perturbation scenarios in the Rouen [control area](#), we also deal with the decisions which were actually made by the dispatcher. The experimental framework implemented is called open-loop because no information is shared between simulation and optimization once the traffic management decisions are initially made. Hence, a possible unpredicted change of the situation is not detected by the optimization and the decisions are never re-assessed.

To the best of our knowledge, in the literature, in the few papers in which actually occurred scenarios are tackled, only aggregated results are described, with no focus on the specific decisions. In our eyes, analyses as the one proposed in this work and detailed in (Pellegrini et al., 2016) are the best way for supporting the claim that optimization should be used in the traffic management practice.

The results of the experiments show that a major improvement in terms of [secondary delay](#) can be achieved through optimization, compared to all other strategies tested. The average improvements for different types of perturbed scenarios and [control areas](#) go from about 50 to 90% of total [secondary delay](#). To give an example of these results, let us illustrate one of the three scenarios in Rouen which actually took place, and for which hence we know the dispatcher decisions which were implemented. The results are shown in Figures 3.13 and 3.14. The former shows the space-time diagrams representing the traffic evolution corresponding to the application of three strategies: the one defined by the dispatcher (left)

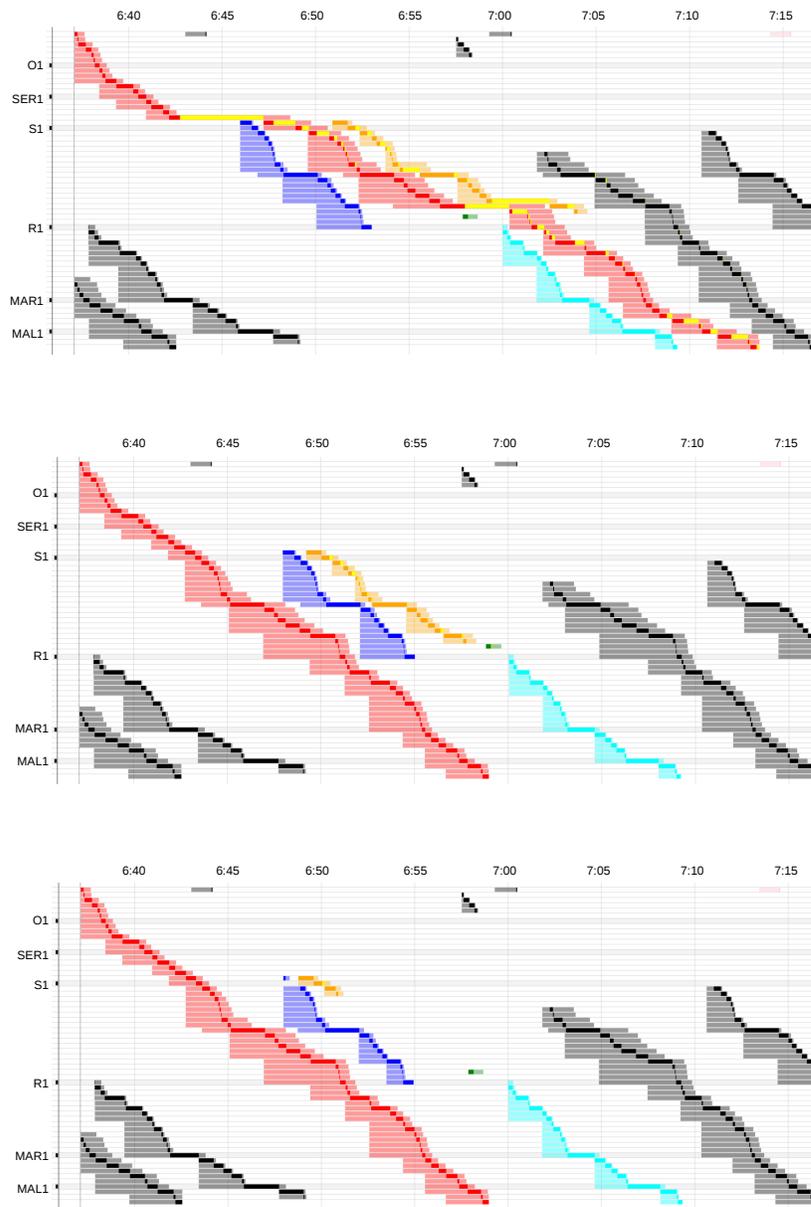


Figure 3.14: Diagram representing **track-circuit** utilization in a scenario tackled in the SIGIFret project. Each line stays for a **track-circuit**: a rectangle indicates a train utilization (occupation in dark, reservation in light, delay in yellow). Representation of dispatcher decisions (top), RECIFE-MILP with no rerouting (middle) and RECIFE-MILP with rerouting (bottom).

and the ones obtained by RECIFE-MILP without (center) and with (right) rerouting. In the

scenario to be tackled, one freight train enters late the **control area**. It is the train represented in red in the figures: it enters the **control area** 6 minutes later than planned. This brings to the emergence of **conflicts** with two local movements (blue and orange) leaving a depot area at Sotteville and directed to Rouen-Rive-Droite to become two commercial passenger trains (orange becoming the purple train, blue becoming the cyan one). Figure 3.14 reports the **track-circuit** utilization diagrams focusing on the critical train of the scenario (the red one). In these diagrams, one for each strategy, the **blocking-time stairway** of the **route** of the critical train is completely shown. Each line represents a **track-circuit**, and a rectangle indicates a train utilization. In dark, the period in which the train occupies the track-circuit. In light, the reservation period. After the dark occupation, a yellow part may indicate that the train stays longer than planned in the **track-circuit**, and hence accumulates a delay. The trains that share only a portion of their **route** with the critical one are shown only for what concerns the shared **track-circuits**. For example, in Figure 3.14 (top) representing the dispatcher’s decisions, we see that a black train on the left of the red one “disappears” between Oissel and shortly past Sotteville because it uses a siding track-circuit not traversed by the red train.

In the practice, the dispatcher (Figures 3.13-left and 3.14-top) decided to have the blue train leaving the depot area at Sotteville two minutes earlier than planned and to let the red train pass between the two local movements. As a consequence, the orange train which was passing last was late, and this implied the late departure (more than 6 minutes) of the resulting purple train at Rouen-Rive-Droite. Moreover, the red train had to slow down to let the blue train and the resulting cyan pass first, and it suffered almost 15 minutes of additional delay. Finally, the blue train running out (ahead) of schedule slightly impacted the trip of the pink one, which had in the end almost 1 minute of delay. Remark that neither the pink nor the purple trains shared any **track-circuit** with the red one: they were only indirectly impacted by this train. Hence, they are not visible in the **track-circuit** utilization diagram in Figure 3.14 (top).

In the strategy proposed by RECIEF-MILP without using rerouting (Figures 3.13-center and 3.14-middle), the red train is allowed passing first, which slightly delays the blue and the orange trains. The delay of the blue train does not have any impact on the departure of the cyan one, thanks to the buffer time available for the service change in the timetable. Instead, the delay of the orange train is partially transferred to the resulting purple one, but the buffer time allows its almost total absorption. The orange train delay, though, creates a **conflict** with the green train, which then suffers about 1 minute of delay.

In addition to allowing the red train to pass first, when using rerouting (Figures 3.13-right and 3.14-bottom) RECIFE-MILP changes the **route** of the orange train: rather than using the upper track between Sotteville and Rouen-Rive-Droite (see Figure 3.10), it is routed through



Figure 3.15: Infrastructure representation of the East Coast Main Line case study

the lower one right after the Darnetal bifurcation. In Figure 3.14-bottom, the orange train “disappears” after traversing a few [track-circuits](#), since the ones belonging to its new [route](#) are not used by the red train. Remark that this [route](#) is available in the optimization since the track is equipped with a signaling system which allows traveling in both directions. By using this track, the orange train does not need to follow the blue one (traveling on the upper track) and gets to Rouen-Rive-Droite in time to let the purple train leave on time and not to create a [conflict](#) with the green one. With this strategy, no [secondary delay](#) emerges due to the initial perturbation.

In another study, we worked on three large European [control areas](#) designing a closed-loop framework. In this framework, a simulator constantly shares information on train positions and expected behavior to the system. Based on the most recent available information, an optimization module periodically re-computes the suitable traffic management strategy to minimize [secondary delay](#). Our study constitutes the first implementation, and to the best of our knowledge the only fully functioning one, of such closed-loop. It was realized within the ON-TIME project (Section B.1.2) and it is detailed in Quaglietta et al. (2016). We consider three case studies, shown in Figures 3.15 to 3.17. The first one is a 79 km long section of the East Coast Main Line (ECML) in the UK. It includes 3 120 [track-circuits](#), 1 558 [block sections](#) and 153 [routes](#). The instances tackled consider time horizons of one to three hours, with about 50 trains entering the [control area](#) per hour. The second case study

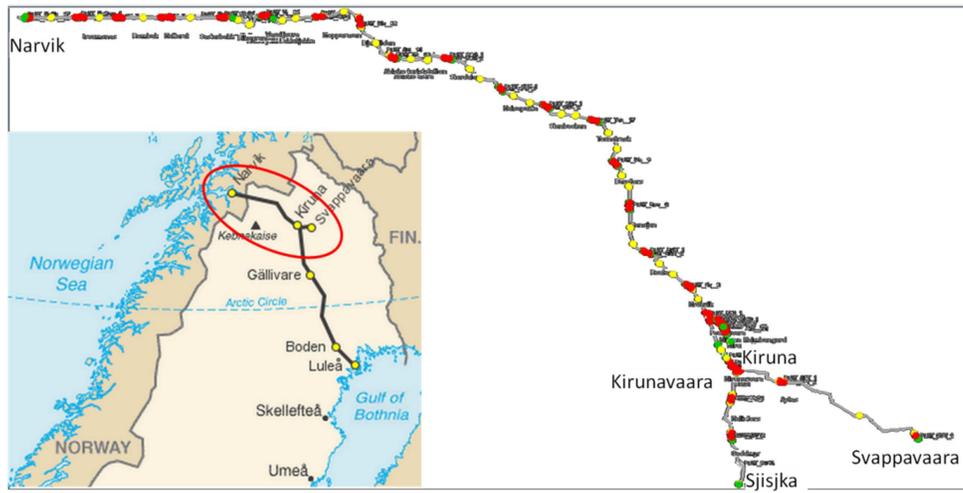


Figure 3.16: Infrastructure representation of the Iron Ore line case study

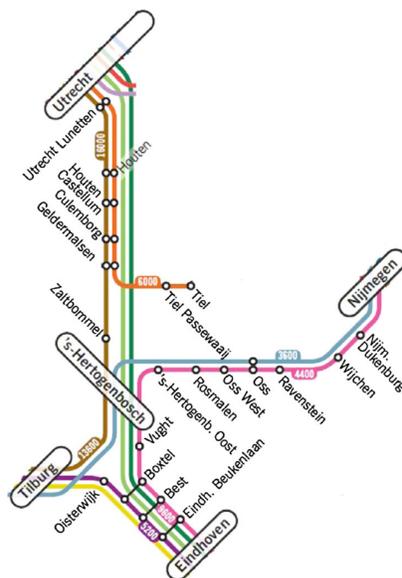


Figure 3.17: Infrastructure representation of the Dutch network case study

is the Iron Ore line which runs between Sweden and Norway. One of its most important features is the fact that it is a single track line 475 km long, intensively used by mixed traffic. Along this line, the Iron Ore trains are quite frequent. They are long (750 m) and they cannot cross with other trains at all stations along the line, due to the insufficient track length at these stations. The **control area** includes 3 771 **track-circuits**, 1 624 **block sections** and 85 **routes**. We tackle seven hour instances where 37 trains traverse the **control area**. Finally, the third case study is a portion of the Dutch network, with its 3 299 **track-circuits**, 864 **block sections** and 80 **routes**. We consider two hour instances with 80 trains. In the experimental setup, we do not consider rerouting possibilities, and we take into account different types of perturbations: entrance delay of one train, entrance delay of multiple trains and temporary speed limitations. To implement the closed-loop framework, every two minutes the optimization module observes the state of the traffic on the infrastructure thanks to the messages sent by the microscopic simulator (Hermes in this study) and decides train orders on common tracks for the next hour. It has a few seconds to make this decision, which is possible thanks to the neglect of rerouting options. Once the decisions are made, they are sent to the simulator which implements them, until it receives possibly different ones coming from subsequent optimization executions. This framework is particularly reactive to unpredicted events. It is what is envisaged to be implemented in the practice, probably integrating a human-machine interface to allow dispatchers validating or not optimization solutions. In a context including human interaction, the loop period will be slightly longer and a computational time of a few minutes is considered reasonable for the optimization: according to **IMs**, it is not conceivable to have dispatchers validating new traffic management solutions every couple of minutes.

In addition to the testing of RECIEF-MILP on extremely large **control areas** in a closed-loop framework, this work has the merit of performing the first comparison between algorithms for the **rtRTMP**. Namely, we compare the performance of RECIFE-MILP and ROMA, its competitor which has been used for the largest number of studies in the literature. The latter uses alternative graphs to formulate the problem considering a **route-lock route-release interlocking** system. The solution process consists in an iterative two-step approach. The first step considers train **routes** as fixed and uses a truncated branch and bound algorithm to identify the train orders and the shifts in departure/arrival times that minimize the maximum **secondary delay**. Once the optimal orders and times are found, the second step employs a tabu search algorithm to identify possible alternative **routes** able to further reduce the maximum delay. If more convenient **routes** are found, another iteration of the two-step approach is performed. This process is repeated until no further improvement of the objective function is found or a computational time limit is reached. As basis for the comparison, following the indications of **IMs**, performances have been evaluated in terms of departure delays, i.e.,

Scenario		Timetable-order	RECIFE-MILP	ROMA
Iron Ore	inst 1	11 352 s	2 436 s	8 625 s
	inst 2	31 630 s	14 994 s	17 983 s
Dutch	inst 1	2 996 s	1 422 s	2 460 s
	inst 2	3 120 s	2 320 s	3 038 s
	inst 3	6 366 s	6 423 s	6 387 s
ECML	inst 1	966 s	9 s	8 s
	inst 2	3 923s	3 300 s	3 466 s

Table 3.1: Results on the three case studies tackled in the ON-TIME project: total delay at main stations. Bold indicates the best result.

Scenario		Timetable-order	RECIFE-MILP	ROMA
Iron Ore	inst 1	6 354 s	4 339 s	4 497 s
	inst 2	15 445 s	15 136 s	10189 s
Dutch	inst 1	3 215 s	1 394 s	2 315 s
	inst 2	2 208 s	1 837 s	1 666 s
	inst 3	5 450 s	4 466 s	4 563 s
ECML	inst 1	2 243 s	1 002 s	1 506 s
	inst 2	3 373s	2 399 s	2 201 s

Table 3.2: Results on the three case studies tackled in the ON-TIME project: maximum consecutive delay. Bold indicates the best result.

the difference between scheduled and actual departure times at a relevant timetable point (e.g., a station, a signal or a junction). Specifically two measures of performance have been considered: the total delay at main stations and the maximum cumulative delay. The total delay at a station is intended as the sum over all trains of their departure delay at that station. To define the maximum cumulative delay we consider the sum over all trains of the departure delay that they have at a given time instant, and we take the maximum value of this sum over all time instants. To some extent, the maximum cumulative delay can be considered as a proxy of the objective function of ROMA, while the total delay is a proxy of RECIFE-MILP's one.

The results obtained are summarized in Tables 3.1 and 3.2 for the two performance indicators described: total delay at main stations and maximum cumulative delay. As a benchmark representing the current practice we consider the timetable order: no decision is

made for changing the originally planned order in the timetable. In bold we indicate the best result achieved. As it can be seen in the results, both RECIFE-MILP and ROMA clearly outperform the timetable order. Moreover, RECIFE-MILP is definitely the best performing algorithm when the total delay at main stations is considered, winning in five over seven instances, and losing for one second in another one. When the maximum cumulative delay is taken into account, the difference is less marked but still in favor of RECIFE-MILP.

In addition to being a first application of the closed-loop framework integrating optimization and simulation, this study somehow places RECIFE-MILP as part of the state of the art for the solution of the **rtRTMP**. After the ON-TIME project, other studies have confirmed its better performance with respect to other approaches proposed in the literature (e.g., Samà et al. (2017b)) and a variant of our algorithms has been proposed to deal with large traffic disruptions, as the interruption of a line for several hours, by a research group at the Technical University of Delft, in the Netherlands (Ghaemi et al., 2017).

Indeed, despite this good performance, it remains possible to find instances which are too difficult to be effectively solved by RECIFE-MILP. Specifically, it is often not possible to solve instances including a very large number of alternative **routes** per train. To improve the performance on these instances, we propose to suitably reduce the size of the instance by solving another combinatorial optimization problem, the **real-time Train Routing Selection Problem**, as described in the next section.

3.5.2 ACO-TRSP

The work on ACO-TRSP first appeared in Samà et al. (2016). It has been mainly carried out as part of the PhD thesis of Marcella Samà (Section C.2.1). It studies the problem of selecting the best subset of routing alternatives for each train among all possible ones. These routing alternatives are the only ones to be considered when solving the **rtRTMP**, to limit its search space to a treatable size.

The common practice of solving the **rtTRSP** is to follow some pre-determined directives given by **IMs** on which **route** subset should be considered for each train in real-time, to help dispatchers when dealing with traffic perturbations. These directives are general, while intuitively a case-to-case solution is required during operations. Indeed, a dynamic selection of the **route** subsets may improve the quality of the **rtRTMP** solution. However, their definition subsets requires to address the following trade-off. On the one hand, considering small subsets would reduce the number of variables to be set in the **rtRTMP**, in principle increasing the chances of finding good quality solutions in a short computational time. On the other hand, considering large subsets would increase the probability of preserving the optimal mix of train **routes** in the search space of the **rtRTMP**, but finding the global optimum might

require a too high computational time.

This work, first of all, formalizes the **rtTRSP**. To precisely describe this problem, let us name a *train route assignment* as the assignment of a **route** to a train among the alternative ones. Moreover, let the train **route** assignments for a pair of trains be coherent in two cases: i) there are no rolling stock constraints between the two trains; ii) the two trains have a rolling stock constraint and the train **route** assignment of the first train has the exit point in the same **track-circuit** in which the one of the second train has the entry point. The latter case is needed to preserve the feasibility of turnaround, join or split constraints. A combination of train **route** assignments is feasible if they are coherent for all pairs of trains. The **rtTRSP** is the problem of defining a set of combinations of feasible train **route**. To assess the influence of the selection of a subset of routing alternatives for each train on the overall **rtRTMP**, the **rtTRSP** evaluates them by using the concept of potential delays: they are the estimation of the propagation of train delays in the network if the given train **route** assignments are chosen. These estimations consider implicitly the train timing and scheduling decisions. Finding the optimal solution of the **rtTRSP** consists of selecting the train **route** subsets with minimal potential delays. The potential delay is defined so as to be coherent with the objective function of the **rtRTMP**, since the **rtTRSP** solution is an input for the former. In this work, potential delays are based on **secondary delays** as the **rtRTMP** objective which we consider is the minimization of their sum.

We model the **rtTRSP** by means of a construction graph. Each node is a train **route** assignment: the construction graph is formed by as many disjoint subsets of nodes as the number of trains in the instance. Each of these subsets represents the routing alternatives for a train. A non-oriented link connecting two nodes exists if the two corresponding train **route** assignments are coherent. A cost is associated to each node and link, representing the potential delays due to their choice. A feasible solution of the **rtTRSP** on this graph is a set of cliques of cardinality equal to the number of trains, and its cost is equal to the total cost of these cliques.

We investigate different strategies to compute node and link costs, based on the potential delay computed for each train **route** assignment. We define the potential delays based on train routing and scheduling decisions, which characterize the **rtRTMP**. These two types of decisions contribute independently on the definition of the potential delays. The potential delay due to a routing decision is immediately linked to a train **route** assignment, and hence it is the cost of a node. It is computed as the non-negative difference between the travel time of the train when it uses this **route** and when it uses the one planned in the timetable. The potential delay due to a scheduling decision is based on the decisions possible given a pair of train **route** assignments: the potential delay is computed based on the **secondary delays** measured when the one train or the other passes first on the possibly existing common

[track-circuits](#).

As a further contribution, we propose an ACO algorithm to tackle the [rtTRSP](#) so modeled: ACO-rtTRSP. ACO is a meta-heuristic inspired by the foraging behavior of ant colonies. Solutions are incrementally constructed by each ant of a colony. At each step of the solution construction process, an ant selects a new node probabilistically using the random proportional rule, which is based on pheromone trails and heuristic information. These are the colony's shared knowledge and a greedy measure on the quality of a node which may be added to the current partial solution. Once all the ants of the colony have built a feasible solution, the best one is improved through a local search: a node in the solution is replaced by another one such that they refer to the same train, the latter has a link connecting to each of the other node in the solution, and it minimizes the clique cost. Then the solution is used for updating pheromone, i.e., for increasing the trail on the links used and having some of it evaporating from the others. This process is repeated iteratively until the available computational time has elapsed. A number of the best solutions built are stored in an ordered set as follows. The position of a solution in the set can be based on two ordering criteria: 1) its clique cost, being the best solution the one with minimum clique cost; 2) a lexicographic bi-objective function: the first objective is the minimization of the clique cost, the second is the minimization of the number of sequences of [track-circuits](#) on which trains may meet given the combination of train [route](#) assignments, being the best solution the one with minimum number. The reason behind the choice of ACO for our problem is two-fold: 1) the [rtTRSP](#) is similar to a subset selection problem, for which this meta-heuristic is known to be well performing; 2) ACO fits particularly well the real-time and combinatorial nature of the [rtTRSP](#) and computes multiple good quality solutions in a very short computational time.

The input to the [rtRTMP](#) will be the set of alternative [routes](#) for each train which correspond to nodes included in one of the cliques in the ordered solution set returned by the ACO algorithm. Hence, one shall fix the size of this set larger than cardinality of sets of alternative [routes](#) desired, to account for repetitions.

We test the ACO algorithm on instances representing traffic in two [control areas](#) introduced in Section 3.5.1: the 27-km line around the station of Rouen-Rive-Droite and the 12-km Lille Flandres station area. In the construction graphs representing instances, the average number of nodes and links is 597 and 152 441 for the former [control area](#), and 3 881 and 6 902 867 for the latter, respectively. In a preliminary analysis detailed in Samà et al. (2016), we select the most appropriate strategy to set node and link costs, and we apply an automatic tuning procedure (IRace) to set the values of the parameters of the algorithm. Then, to assess the performance of our algorithm, we perform a whole solution process including [rtTRSP](#) and [rtRTMP](#), comparing different approaches:

- *all routes*: All routing alternatives are given in input to RECIFE-MILP (Section 3.5.1) that returns the best **rtRTMP** solution found within 180s. The **route** planned in the timetable is set as the starting routing alternative for each train;
- *rnd-rtTRSP*: An **rtTRSP** solution with the desired number of routing alternatives for each train is generated by fixing the starting routing alternative for each train to the **route** planned in the timetable, and by randomly selecting the remaining routing alternatives. This **rtTRSP** solution is given in input to the RECIFE-MILP, that returns the best **rtRTMP** solution found within 180s;
- *ACO-rtTRSP*: an **rtTRSP** solution with the desired number of routing alternatives for each train is computed by the ACO-rtTRSP algorithm with a time limit of 30s. This **rtTRSP** solution is given in input to RECIFE-MILP that returns the best **rtRTMP** solution found within 150s. For each train, the **route** in the best ACO-rtTRSP clique is set as starting routing alternative.

The results show that an improvement of the total **secondary delay** in the final solution is obtained for both **control areas** when passing from *all routes* to *rnd-rtTRSP*, underlining the pertinence of the problem tackled here. A further improvement of 10 to 36% is obtained using *ACO-rtTRSP* rather than the random approach. Moreover, the analysis suggests that selecting small subsets of **routes** as solution of the **rtTRSP** is the best choice, although the optimal routing alternatives are more likely to be preserved when considering large subsets. Indeed, with small subsets RECIFE-MILP often manages to converge, eventually reaching a good sub-optimum, and this is typically better than getting stuck in a too large search space.

In a subsequent study, detailed in Samà et al. (2017a), we try to identify the best moment to tackle the **rtRTMP**, comparing two alternatives. In the first one, it is tackled in the **operational phase** as described above. In the second alternative, it is tackled in the **tactical phase**. In this case the problem is not a real-time one anymore, and somehow integrates the tactical timetabling and the operational **rtRTMP**. The selection of **route** subsets is done by a slight variation of the ACO algorithm described above, based on records of past perturbed traffic: for each of them we obtain a series of train **route** assignment combinations. The **routes** available for each train are then ordered based on how frequently they are included in these subsets. The ordered sets are finally passed to the **rtRTMP**. The first **routes** in the subset of each train which are feasible in the traffic situation to be tackle are then used. The solution of the problem in the **tactical phase** allows the allocation of longer computational time with respect to the real-time case. The limited computational time available in the **operational phase** is entirely left for the solution of the **rtRTMP**. Indeed, the two alternative moments represent two different ways of addressing the trade-off between abundant computational time and specific information on the perturbation to be tackled.

To identify the best moment, we perform an extensive computational analysis on the same **control areas** as above, considering both disturbed and disrupted instances. The disturbed instances are affected by perturbations which, even if not predictable, have a similar nature to the perturbations recorded, which may be used for solving the problem in the **tactical phase**. These disturbed instances are characterized by train entrance delays. The disrupted instances are instead affected by infrastructure unavailability, possibly not recorded or considered as outlier in the past records, such as track malfunctions. We consider these two groups of instances to assess the impact of the perturbation predictability on alternative possible moments in which the problem can be solved.

The results of the analysis allow concluding that when the traffic situation to be tackled is comparable to the ones recorded in the historical traffic data, solving the problem in the **tactical phase** is more effective. Solving it in the **operational phase** as a sub-problem of the **rtRTMP** is instead the best choice when the traffic disturbance is strong and the train delays are different from the ones considered in the historical traffic data. From a practical perspective, this could be seen as proposing to dispatchers the following procedure. As a standard practice, the problem is solved in the **tactical phase**. As soon as a strong traffic disturbance arises, switch the process to solve the **rtTRSP**. When the traffic situation is re-established, return to use the pre-computed **route** subsets.

Once routing and scheduling decisions are made, several speed profiles may be adopted to meet them. In the next section we describe our work on the problem of properly defining these profiles.

3.5.3 TDRC-MILP

In the study on energy consumption in the **operational phase**, object of the PhD thesis of Teresa Montrone (Section C.2.5) and detailed in Montrone et al. (2017), we focus on the **real-time Energy Consumption Minimization Problem**. As discussed in Section 3.3, trains use suitable driving regimes to follow speed profiles compatible both with the infrastructure characteristics and the timetable. In the **operational phase**, they must also be appropriate for traffic conditions. Indeed, energy consumption depends on the driving regimes followed by the trains. The **rtECMP** finds the driving regime combination which minimizes energy consumption in real-time. These combinations consider as an input the routing and orders of trains of an **rtRTMP** solution and comply with them. The objective of the problem is the minimization of the weighted sum of energy consumption and total delay. As in Section 3.3, we assume that the possible driving regimes to be used by the trains are maximum acceleration, cruising, coasting and maximum braking. Moreover, each train can change the driving regime in predefined positions, called switching points, within each **block section**. In

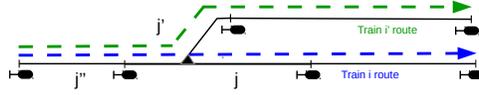


Figure 3.18: Example of incompatible **block sections** used for explaining traffic related constraints in the **rtECMP**.

particular, each **block section** is divided into a fixed number of subsections in which the train follows one of the four possible regimes.

As a first contribution, we formalize the **rtECMP** as a **MILP** model. Here, the continuous variables represent the times at which trains enter each **block section** of their **route** and their total delay. The binary variables indicate whether a driving regime combination is used in a **block section** or not. Other variables handle the stop duration at red signals and the braking at yellow signals, to account for traffic and **interlocking** system, as explained in Section 1.2.2. Exploiting these variables, probably the most original constraints in the model are those ensuring that a train enters a **block section** with a yellow signal when traffic imposes it, and will hence stop at the end of it¹. This is the case when it has to give precedence to one or more other trains. In particular, the signal will be yellow if there is at least one of these trains which is traversing or is still to traverse a **block section** that is incompatible with the one following the **block section** opened by the signal itself, i.e., that shares with it one or more **track-circuits**. Figure 3.18 illustrates the rationale for these constraints, where we consider train i and **block section** j'' . The latter is followed by j on the **route** of train i . Block section j' belongs to the **route** of train i' and it is incompatible with j . Train i' has the precedence in j' with respect to i in j , according to the **rtRTMP** solution considered. If i is traversing j'' before i' releases j' , i must have entered with a yellow signal and it will have to stop at the end of j'' (red signal) to guarantee safety. We model these constraints using a big- M approach.

After the formalization, we propose an algorithm for this problem, named TDRC-MILP, TDRC staying for Train Driving Regime Combination. The algorithm starts with the calculation of the travel times and the energy consumption for all trains in each **block section** of their **route**, considering all the feasible initial speeds and driving regime combinations. Indeed, this calculation can be made in a precomputation phase, since it depends on the train and infrastructure characteristics but not on the traffic condition to be dealt with. Then, in real-time, TDRC-MILP creates the **MILP** model and solves the optimization with an exact solver (CPLEX) for a limited amount of time. After this time, the best solution found is

¹We suppose that a driver will see the actual aspect of the following signal only when it will have reached it: the visibility distance is zero.

returned. We include in the algorithm the possibility of choosing a constraining option which enables a procedure to reduce the number of feasible train driving regime combinations. In particular, if this option is enabled, the procedure deletes the combinations that do not respect a given criterion. This criterion assures that each regime can be only followed by one that consumes less or equal energy. Precisely, any regime can follow the maximum acceleration, while only maximum braking can follow itself. Moreover, the cruising can be followed by cruising, coasting or maximum braking, while coasting only by coasting or maximum braking. The MILP model will then be generated in real-time considering the reduced set of feasible driving regime combinations.

We test TDRC-MILP on instances representing traffic in the Pierrefitte-Gonesse **control area**, also used in Section 3.5.1. We consider one hour scenario at the morning peak hour and a traffic perturbation in which some trains arrives in the **control area** with a delay between five and fifteen minutes. The instance includes 16 trains. We obtain 50 **rtECMP** instances by finding alternative feasible **routes** and precedence constraints through RECIFE-MILP (Section 3.5.1). The computational time limit for TDRC-MILP is alternatively 900 or 30 seconds of wall clock time. The latter is a computational time which may be considered for a real-time application, where a time limit of few minutes needs to be shared between the **rtRTMP** solver and the **rtECMP** one. As discussed in Section 3.5.1, three minutes is an often considered time for this whole process, which may allow devoting 30 seconds to the solution of the **rtECMP**. We test different weighs of energy consumption and total delay in the objective function, to study their influence on the optimal solution, driving regime combinations and computational time. Moreover, we study the influence of the number of subsections in which the **block sections** are split. In particular, we consider three or four subsections of equal length for each **block section**, alternatively. When this number is three, we suppose at first that all feasible combinations are considered. Then we enable the constraining option in TDRC-MILP, so the driving regime combinations considered are only the ones in which each regime is followed by one that consumes less or equal energy. When the number of subsections is four, we always enable the constraining option. Indeed, in a preliminary analysis, we noted that with four subsections the instances become too large if we do not enable this option, and TDRC-MILP is unable to find a feasible solution due to lack of memory.

The results show that when the constraining option is not enabled, the problem is more difficult due to the high number of driving regime combinations: in average, TDRC-MILP requires more time to find the best solution, In particular, when the time limit is 30 seconds, the algorithm is unable to find even a feasible solution for 23 out of 50 instances. Whatever the configuration, TDRC-MILP finds very good solutions when the time limit is 900 seconds. Indeed, the average percentage optimality gap of the solutions returned is always zero up to the second decimal digit. When the time limit is 30 seconds, the same holds quite often.

Furthermore, we observe that the problem seems to be more difficult when the weight of total delay in the objective function is small with respect to the one of energy consumption, regardless of the number of subsections. Indeed, the algorithm requires more time to find the optimal solution. The reason for this difficulty may be that there are many combinations with similar values of energy consumption, which is the only really relevant quantity in this case. Therefore, TDRC-MILP finds it more difficult to effectively explore the solution space.

In general, as expected, the best results are obtained when the time limit is larger regardless of the number of subsections. However, the improvement is not really remarkable. Moreover, the algorithm finds the best solutions when the number of subsections per **block section** is lower and the sequence of driving regimes is not completely free. This may be counter-intuitive because, in principle, a higher number of possible driving regime combinations should allow the trains to better handle all possible unexpected events. However, apparently the instances become too difficult to be solved to optimality: although the average percentage optimality gap is always very small, it is indeed strictly positive. The use of a problem-specific heuristic may hence be suitable to fully exploit the existing possibilities.

3.6 Conclusions

In this chapter we summarized our main contributions in the field of rail transport. They all aim to the solution of difficult combinatorial optimization problems for effectively exploiting infrastructure capacity. Specifically, we worked on all phases of the capacity utilization planning process, starting from the **strategic phase** taking place years in advance, up to the **real-time phase** taking place during operations.

A peculiarity of the research described in this chapter consists in the consideration of the infrastructure represented **microscopically**, going to the finest granularity ever considered in the literature for capacity utilization problems. We deem this consideration extremely important, for being able to fully exploit the available infrastructure capacity. Indeed, this comes at the cost of a larger amount of data necessary to define instances, and in general to a larger amount of variables and constraints in the models.

Despite this, we show in our research that optimal solutions of relevant problems can be found in reasonable computational times, in coherence with the phase of the process considered: while a few hours can be available for solving an instance of a problem in the **strategic phase**, this time reduces to few minutes in the **real-time phase**. However, with appropriate models, the existing **MILP** solvers often achieve optimality, or in any case good quality solutions, in all the case studies tested.

Probably the most relevant contribution reported in this manuscript is the algorithm

named RECIFE-MILP for the `rtRTMP`, which is described in Section 3.5.1. We first proposed this algorithm in 2012 and it is now considered as a relevant part of the state of the art for this problem.

Scientific production

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Chapter 4

Conclusions

In this manuscript we have summarized our main research contributions on the solution of difficult transport problems. Namely, we focused on optimization problems issuing from the fields of air and rail transport.

The problems we modeled and tackled are all focused on the effective use of infrastructure capacity, and they emerge in all phases of the capacity utilization planning process. Indeed, allocating the finite and often scarce capacity to satisfy competing demand is a difficult problem, which is tackled in different ways in the different systems and in the different phases of the process.

We proposed specific models and algorithms to tackle these problems, exploiting as much as possible relations and synergies between the two systems and within each of them. We paid particular attention to the definition of coherent approaches for dealing with the different problems emerging in the subsequent phases of the capacity utilization process in each system. We think this coherence is crucial to achieve good system performances throughout the whole process.

In particular, for the air system we based all our contributions on the consideration of the airport [slot allocation process](#) from a network perspective. This constitutes a major difference with respect to what is done in the literature where each airport is accounted for independently in the [tactical phase](#). However, it is indeed more coherent with the holistic vision of the capacity utilization process, in which in the end the network must necessarily be considered.

In parallel, for the railway system we proposed models and algorithms for problems emerging in all phases of the capacity utilization process, all based on a common fundamental decision. This decision concerns the representation of the infrastructure to be considered in the model. Differently from what most often done in the literature, we decided to consider the [microscopic](#) representation, including very specific details of the infrastructure as it is

in reality. This is necessary, in our eyes, to allow the efficient use of the existing capacity, although it increases the sizes of problem instance representations and formulations. However, we think we showed that dealing with relevant size instances is possible even with this representation, when suitable models and algorithms are defined.

The exploitation of the synergies between the two systems is probably less evident in the manuscript. However, many of the ideas developed in the previous chapters have been motivated and strengthened by the experience gained in the two systems together. We consider that this cross-systems experience has constituted a definite boost for our research in both air and rail problems.

The cross-systems activity is also at the basis of some of the perspectives for future research sketched in the next chapter, with which we conclude the manuscript.

Chapter 5

Research perspectives

In this chapter we propose some hints for future research, following the two streams considered in the rest of the manuscript. In both, the long term perspective is continuing on the started trend of model and solution of difficult problems concerning infrastructure capacity exploitation.

A perspective in air transport is the extension of our most recent model for [primary slot allocation](#) (SOSTA, described in Section 2.2.3). In particular, to even better represent the current system and allow its optimization we need to incorporate a further feature to the model: according to the regulations, airport slots are requested in series, and hence for several weeks in a row. In our model, we consider a single day, hence neglecting different days interdependence. Undoubtedly, integrating this feature in the model is quite simple. However, considering series implies the need of taking into account all requests of a season simultaneously. This raises the number of slots to be dealt with from the few tens of thousands we account for today, to a few millions. Hence, we think that what will be particularly challenging is the design of an effective algorithm to deal with so large instances in reasonable time. Our current idea is to start thinking of an algorithm based on the concept of shifting bottlenecks, which is quite well known in scheduling literature. Once designed and tested an effective algorithm to tackle the extended problem, we will meditate on the most relevant following steps. They may be still linked to the development of approaches for the [slot allocation process](#), for example extending our proposal for the [secondary slot allocation](#). Another option is to start the design of completely novel approaches for the [operational phase](#). If we will decide to focus on the latter option, we think that useful hints will come from the experience gained in rail traffic. Specifically, what may be interesting is bringing into the air transport methods some sort of microscopic representation of the infrastructure, as we do for rail problems.

In rail transport we will focus the same issue in the long term, i.e., deciding if extending

some of the approaches proposed or focusing on yet unexplored problems. In the short term, we will follow a bit of both directions.

On the one side, we will work to keep improving the performance of our algorithm for the [real-time Traffic Management Problem](#) (RECIFE-MILP presented in Section 3.5.1). Moreover, we will extend it to cover very large control areas, reaching the size of national networks. The idea behind this extension is the decomposition of the large instance into smaller local sub-instances to be optimized in a coordinated fashion. An option we will definitely investigate is the design of an iterative process in which we consider alternatively a [microscopic](#) representation of sub-instances and a [macroscopic](#) one of the whole network. Under a different point of view, we will work on the same algorithm to incorporate features which are expected to characterize future rail traffic. Specifically, in a few decades traffic is expected to be operated without the need of [block section](#) definitions, as described in Section 1.2.2. The new system will be based on the so-called moving blocks, in which the precise distance to be maintained between pairs trains to ensure safety will depend on the speeds used. Today our algorithm cannot deal with this new feature, but we are confident we can extend it to do so. Specifically, we will work on this within the X2Rail-2 project (Section B.1.5) and its follow-ups.

On the other side, we will deal with problems which we have not studied yet. Namely, let us mention the problem of managing depot, garage or yard areas. Here, we will deal with the routing of trains and the scheduling of tasks necessary to properly complete the commercial services which are the main focus of the research discussed in this manuscript. In these areas, the tasks are quite different if either passenger or freight trains are concerned. We will deal with passenger trains depot and garage areas in the PhD thesis of Franck Kamenga (Section C.2.6). We will consider freight yards in the OptiYard project (Section B.1.4) thanks to the support of Samuel Deleplanque (Section C.1.2).

Finally, in a more futuristic perspective, we will study a possible change in the paradigm of rail traffic management. As described in Sections 1.4 and 3.5, today traffic is managed in a centralized way by the national IM. Instead, we will focus on the possibility of moving toward a decentralized management, in which trains may negotiate in real-time their right to use portions of infrastructure at given moments. This type of management has already been envisaged in air transport, but it has not attracted much attention in rail one. Indeed, the current centralized management suffers from issues as the fact of somehow limiting the market opening to an actual competition. Some of these issues may be overcome in a decentralized system. A possible modeling may be based on the concept of autonomic system. Such a system is a collection of autonomic elements. They are functionally equivalent and they manage their behavior as a function of politics defined by the system administrator. They do the same for managing the relations with each other and with the environment.

The global behavior of the system corresponds to the emergent behavior which results from the actions and interactions of the elements. In decentralized traffic management, trains may represent the autonomic elements, which choose their route and speed as a function of their state as well as on the state of the whole traffic. These choices will be optimized thanks to adaptive algorithms for decision making in a dynamic environment, and they will be subject to negotiation in case of potential competition. We started investigating this type of modeling through a literature review carried out by Elisa Marcelli (Section C.3.6), through which we identified some possible hints for developments. Indeed, we currently ignore whether a decentralized traffic system may be well performing compared to the centralized one. However, as in most research works, we will need to try and see.

Appendix A

RECIFE-MILP model

RECIFE-MILP is the MILP-based algorithm we propose for the `rtRTMP`. The algorithm and its applications are described in Section 3.5.1. In this appendix we detail the MILP model at its basis.

RECIFE-MILP considers the infrastructure in terms of `track-circuits`. Thanks to this fine representation, the `route-lock sectional-release interlocking` system typically deployed in the practice can be modeled. Specifically, as mentioned in Section 1.2.2, sequences of `track-circuits` are grouped into `block sections`, which are opened by a signal indicating their availability. Before a train can enter (start the occupation of) a block section, all the `track-circuits` belonging to the same `block section` must be reserved for the train itself. In the following, we will name utilization time the sum of reservation and occupation time. If a train starts its trip at null speed from a platform, then we consider the beginning of the occupation to correspond to the moment in which the train starts moving. If it remains still at the platform, its actual utilization will be ensured through reservation. Each `block section` is reserved by the train some time before its entering, to allow the route formation, and it remains reserved after its leaving, to allow the route release.

We define the `routes` in terms of sequences of `track-circuits` and by the intermediate stops. Hence, as an example, a sequence of `track-circuits` defines two or more different `routes` if it can be traversed performing different stop patterns. The `running times` for a `route` with intermediate stops include the appropriate deceleration and acceleration times, but not the dwell times.

In the MILP model, we use the following notation:

$T \equiv$ set of trains,

$w_t \equiv$ weight associated to train t 's delay,

$ty_t \equiv$ type corresponding to train t (indicating train characteristics),

$init_t, sched_t \equiv$ earliest time at which train t can be operated given the timetable and the

primary delay, and earliest time at which train t can reach its destination given $init_t$, the route assigned to t in the timetable and the intermediate stops,

$i(t', t) \equiv$ indicator function: 1 if trains t' and t use the same rolling stock and t results from the turnaround, join or split of train t' , 0 otherwise,

$ms \equiv$ minimum separation time between the arrival of a train and the departure of another train which uses the same rolling stock,

$R_t, TC_t \equiv$ set of routes and track-circuits which can be used by train t ,

$TC^r \equiv$ set of track-circuits composing route r ,

$OTC_{ty,r,tc} \equiv$ set of consecutive track-circuits preceding tc which are occupied by t traveling along route r if its head is on tc , depending on t 's and tc 's length,

$TC(tc, tc', r) \equiv$ set of track-circuits between tc and tc' along route r ,

$p_{r,tc}, s_{r,tc} \equiv$ track-circuits preceding and following tc along route r ,

$rt_{ty,r,tc}, ct_{ty,r,tc} \equiv$ running time and clearing time of tc along r for a train of type ty ,

$ref_{r,tc} \equiv$ reference track-circuit for the reservation of tc along route r , depending on the interlocking system,

$e(tc, r) \equiv$ indicator function: 1 if track-circuit tc belongs to an extreme (either the first or the last) block section on route r , 0 otherwise,

$bs_{r,tc} \equiv$ block section including track-circuit tc along route r ,

$for_{bs}, rel_{bs} \equiv$ formation time and release time for block section bs ,

$S_t, TCS_{t,s} \equiv$ set of stations where train t has a scheduled stop and set of track-circuits that can be used by t for stopping at station s ,

$dw_{t,s}, arr_{t,s}, dep_{t,s} \equiv$ minimum dwell time, scheduled arrival and scheduled departure times for train t at station s ,

$M \equiv$ large constant.

The MILP model includes the following non-negative continuous variables:

- for all triplets of train $t \in T$, route $r \in R_t$ and track-circuit $tc \in TC^r$:

$o_{t,r,tc}$: time at which t starts the occupation of tc along r ,

$l_{t,r,tc}$: longer stay of t 's head on tc along route r ,

due to dwell time and scheduling decisions (delay);

- for all pairs of train $t \in T$ and track-circuit $tc \in TC_t$:

$sU_{t,tc}$: time at which tc starts being utilized by t ;

$eU_{t,tc}$: time at which tc ends being utilized by t ;

- for all pairs of train $t \in T$ and **track-circuit** $tc \in TC_t : tc = tc_\infty$ or $\exists s \in S_t, tc \in TCS_{t,s}$:

$D_{t,tc}$: delay suffered by train t when arriving in tc .

In addition the MILP formulation includes the following binary variables:

- for all pairs of train $t \in T$ and **route** $r \in R_t$:

$$x_{t,r} = \begin{cases} 1 & \text{if } t \text{ uses } r, \\ 0 & \text{otherwise,} \end{cases}$$

- for all triplets of train $t, t' \in T$ such that the index t is smaller than the index t' , and **track-circuit** $tc \in TC_t \cap TC_{t'}$:

$$y_{t,t',tc} = \begin{cases} 1 & \text{if } t \text{ utilizes } tc \text{ before } t' (t \prec t'), \\ 0 & \text{otherwise } (t \succ t'). \end{cases}$$

The objective function to be minimized is the total weighted delays suffered by trains at the intermediate stops and at their exit from the infrastructure:

$$\min \sum_{t \in T} w_t \sum_{tc \in TC_t : tc = tc_\infty \vee \exists s \in S_t, tc \in TCS_{t,s}} D_{t,tc}. \quad (\text{A.1})$$

The sets of constraints considered impose the following conditions:

- A train t cannot be operated earlier than $init_t$:

$$o_{t,r,tc} \geq init_t x_{t,r} \quad \forall t \in T, r \in R_t, tc \in TC^r. \quad (\text{A.2})$$

- The start time of **track-circuit** occupation along a **route** is zero if the **route** itself is not used:

$$o_{t,r,tc} \leq M x_{t,r} \quad \forall t \in T, r \in R_t, tc \in TC^r. \quad (\text{A.3})$$

- A train starts occupying **track-circuit** tc along a **route** after spending in the preceding **track-circuit** its **running time**, if the **route** is used, and its longer stay.

$$o_{t,r,tc} = o_{t,r,p_r,tc} + l_{t,r,p_r,tc} + rt_{r,ty_t,p_r,tc} x_{t,r} \quad \forall t \in T, r \in R_t, tc \in TC^r; \quad (\text{A.4})$$

remark that these constraints imply that $l_{t,r,p_r,tc}$ equals 0 if t does not use r .

- A train t with a scheduled stop at station s and using **route** r does not enter the **track-circuit** following tc before the scheduled departure time from s if tc is in $TCS_{t,s}$:

$$o_{t,r,sr,tc} \geq \sum_{s \in S_t: tc \in TCS_{t,s} \cap TC^r} dep_{t,s} x_{t,r} \quad \forall t \in T, r \in R_t, tc \in \bigcup_{s \in S_t} TCS_{t,s}. \quad (\text{A.5})$$

- A train t with a scheduled stop at station s and using **route** r has a longer stay in tc of at least $dw_{t,s}$ if tc is in $TCS_{t,s}$:

$$l_{t,r,sr,tc} \geq \sum_{s \in S_t: tc \in TCS_{t,s} \cap TC^r} dw_{t,s} x_{t,r} \quad \forall t \in T, r \in R_t, tc \in \bigcup_{s \in S_t} TCS_{t,s}. \quad (\text{A.6})$$

- A train t must use exactly one **route**:

$$\sum_{r \in R_t} x_{t,r} = 1 \quad \forall t \in T. \quad (\text{A.7})$$

- The value of a delay $D_{t,tc}$ cannot be less than the difference between the actual and the scheduled arrival times at the exit of the infrastructure or at a station:

$$D_{t,tc_\infty} \geq \sum_{r \in R_t} o_{t,r,tc_\infty} - sched_t \quad \forall t \in T; \quad (\text{A.8})$$

$$D_{t,tc} \geq o_{t,r,tc} + rt_{r,ty_t,tc} x_{t,r} - \sum_{s \in S_t: tc \in TCS_{t,s} \cap TC^r} arr_{t,s} x_{t,r} \quad \forall t \in T, r \in R_t,$$

$$tc \in \bigcup_{s \in S_t} TCS_{t,s}. \quad (\text{A.9})$$

- A minimum separation time ms must separate the arrival and departure of trains using the same rolling stock:

$$\sum_{\substack{r \in R_t, tc \in TC^r: \\ pr,tc=tc_0}} o_{t,r,tc} \geq \sum_{\substack{r \in R_{t'}, tc \in TC^r: \\ sr,tc=tc_\infty}} o_{t',r,tc} + (ms + rt_{r,ty_{t'},tc}) x_{t',r}$$

$$\forall t, t' \in T : i(t', t) = 1. \quad (\text{A.10})$$

- If trains t' and t use the same rolling stock and t results from the turnaround, join or split of train t' , the **track-circuit** tc where the turnaround, join or split takes place must be utilized for the whole time between t' 's arrival and t 's departure. Thus, tc starts being reserved by t at the latest when t' ends its utilization:

$$\sum_{tc \in TC_t: \exists r \in R_t, pr,tc=tc_0} sU_{t,tc} \leq \sum_{tc \in TC_{t'}: \exists r \in R_{t'}, sr,tc=tc_\infty} eU_{t',tc} \quad \forall t, t' \in T : i(t', t) = 1. \quad (\text{A.11})$$

Here, the inequality must be imposed since, in case of a join, two trains arrive and are connected to become a single departing one. The utilization of the departing train must then immediately follow the utilization of the first train arriving, being strictly smaller than the one of the second train.

- A train's utilization of a **track-circuit** starts as soon as the train starts occupying the **track-circuit** $ref_{r,tc}$ along one of the **routes** including it, minus the **formation time**:

$$sU_{t,tc} = \sum_{r \in R_t: tc \in TC^r} \left(o_{t,r,ref_{r,tc}} - for_{bs_{r,tc}} x_{t,r} \right) \quad (\text{A.12})$$

$$\forall t \in T, tc \in TC_t : (\nexists t' \in T : i(t',t) = 1) \vee (\forall r \in R_t : ref_{r,tc} \neq s_{r,tc_0}).$$

Constraints (A.12) are imposed as inequalities (\leq) when they concern a **track-circuit** of the first **block sections** of the **route** ($ref_{r,tc} = s_{r,tc_0}$) and the train t results from the turnaround, join or split of one or more other trains. This fact is a consequence of the need of keeping platforms utilized. Indeed, if train t results from the turnaround of train t' , Constraints (A.11) ensure that the **track-circuit** where the turnaround takes place starts being reserved by t as soon as t' arrives. As a consequence, Constraints (A.11) impose that t 's reservation of the **track-circuit** starts much earlier than its occupation. Indeed, t needs to wait at least for a time ms before departing and, in order to guarantee the coherence with the constraints imposed by (A.4) on the occupation variables and the **running time**, the occupation of the **track-circuit** starts only on t actual departure.

- The utilization of a **track-circuit** tc lasts till the train utilizes it along any **route**, plus the **release time**:

$$eU_{t,tc} = \sum_{r \in R_t: tc \in TC^r} o_{t,r,ref_{r,tc}} + rel_{bs_{r,tc}} x_{t,r} + ul_{t,r,tc} \forall t \in T, tc \in TC_t. \quad (\text{A.13})$$

Here $ul_{t,r,tc}$ is the total utilization time:

$$ul_{t,r,tc} = \sum_{tc' \in TC(ref_{r,tc}, tc, r)} (rt_{r,ty_t,tc'} x_{t,r} + l_{t,r,tc'}) + \sum_{tc' \in TC_t: tc \in OTC_{ty_t, r, tc'}} l_{t,r,tc'} + ct_{r,ty_t,tc} x_{t,r}.$$

It includes: the **running time** of all **track-circuits** between $ref_{r,tc}$ and tc , the longer stay of the train's head on each of these **track-circuits** $l_{t,r,tc}$ and the **clearing time** of tc . Moreover, it includes the longer stay on all **track-circuits** tc' such that $tc \in OTC_{ty_t, r, tc'}$. As mentioned in the definition of $OTC_{ty_t, r, tc'}$, if the head of the train is on one of these **track-circuits**, then its tail has not yet exited tc : the train is longer than tc' , or of the sequence of **track-circuits** between tc and tc' . Hence, if the train suffers a longer stay when its head is on one of these **track-circuits**, such a longer stay must be counted in the utilization time of tc .

- The **track-circuit** utilizations by two trains must not overlap.

$$\begin{aligned}
 eU_{t,tc} - M(1 - y_{t,t',tc}) &\leq sU_{t',tc} \quad \forall t, t' \in T, \text{idx } t < \text{idx } t', tc \in TC_t \cap TC_{t'} : \\
 i(t, t') \sum_{r \in R_t} e(tc, r) &= 0 \wedge i(t', t) \sum_{r \in R_{t'}} e(tc, r) = 0, \quad (\text{A.14})
 \end{aligned}$$

$$\begin{aligned}
 eU_{t',tc} - My_{t,t',tc} &\leq sU_{t,tc} \quad \forall t, t' \in T, \text{idx } t < \text{idx } t', tc \in TC_t \cap TC_{t'} : \\
 i(t, t') \sum_{r \in R_t} e(tc, r) &= 0 \wedge i(t', t) \sum_{r \in R_{t'}} e(tc, r) = 0. \quad (\text{A.15})
 \end{aligned}$$

Appendix B

Research projects and initiatives

In this appendix, we list the research projects and formal initiatives to which we contributed. The research presented in this manuscript does not touch all of them.

Namely, the CATS European (Section B.1.1) and the industrial Gronda Sud di Milano (Section B.3.1) projects are omitted. They represent the first steps in the field of air and rail transport problems, whose study is discussed here. However, the perspective considered in the two projects is not really optimization and it is hence slightly out of the scope of this manuscript.

The same holds for the more recent Capacity4Rail European project (Section B.1.3), neglected here for its absence of optimization. Nonetheless, its focus on rail automation is strictly linked with the research discussed in Chapter 3.

Finally, the personal project on meta-heuristic tuning (Section B.4.1) is also not dealt with. It is connected to the design and configuration of optimization algorithms. This is the focus of the research preceding the contributions in this manuscript and constitutes somehow a first step toward the use of optimization in difficult transportation problems.

B.1 European projects and initiatives

B.1.1 CATS

2007-2010 Contract-based Air Transportation System (CATS)
TREN/07/FP6AE/S07.75348/036889.

The target addressed through this project is the proposal of an innovative Air Traffic Management solution able to face the challenge of traffic growth and improve efficiency of the European Air Transport System. Two high-level target concepts are considered: Highly Cost-Efficient Air Transport System and Highly Time-Efficient Air Transport System.

The aim is to propose a new **ATM** paradigm, based on an innovative operational concept: the Contract of Objectives. This concept introduces an innovative way of managing **ATM** by mutually agreed objectives leading to a market driven Air Transportation System. It addresses the entire air transport supply chain by reconciling operational links between air and ground services. This functional and operational continuity between ground and air will enhance efficiency by increasing system predictability.

Our contribution to this project consists in the proposal of a multi-criteria analysis to assess the validity of the Contract of Objective. We use an analytic hierarchy process to assess the opportunity of implementing this concept by considering the views of experts.

B.1.2 ON-TIME

2011-2014 Optimal Networks for Train Integration Management across Europe (ON-TIME)
 FP7-SCP0-GA-2011-265647.

The objective of this project is a step-change in railway capacity by reducing delays and improving traffic fluidity. This is aimed to be achieved by a partnership between railway industry experts, system integrators, small dynamic knowledge led companies and academic researchers.

There are four levels of work:

L1: High level principles, definitions and requirements to direct research

L2: Methods and algorithms derived from L1 that improve capacity and reduce delay

L3: Functional components using L2 methods and algorithms to show improvement in capacity and delay; and architecture linking the functional components, including information definitions, to distribute those components across environments and countries.

L4: Demonstrators to show that the functional components can be built into industrial-strength systems

The project draws on previous research projects and national trials. Previously, railways have improved their own networks to remove bottlenecks and increase fluidity. Such changes have generally been done “ad hoc” so results and best practice have not been shared. Previous relevant academic research has, in general, been based on algorithm development. To apply the results of such research needs an understanding of the practical operating principles and the nature of delay initiation and propagation. This project addresses both issues and delivers research-based results that can be freely applied to commercial traffic management and traffic planning tools.

Our contribution to this project concerns the adoption of the RECIFE-MILP algorithm in the proposed demonstrator for coping with traffic perturbations. This is the object of a whole work package (WP4) in which we compare RECIFE-MILP with a very well known alternative algorithm named ROMA developed at the University of Delft. This work is shortly described in Section 3.5.1.

B.1.3 Capacity4Rail

2013-2017 Capacity4Rail - Increasing Capacity 4 Rail networks through enhanced infrastructure and optimised operations (CAPACITY4RAIL)
FP7-SST-2013-RTD-1-605650.

In 2011, the White Paper on European Transport reasserted how fundamental transport was for society, for the mobility of European citizens and for the growth and vitality of the European economy. CAPACITY4RAIL produces research that is innovative, prepares rail for the future and takes into account results from previous research projects and programmes. The project builds on previous useable results and delivers both technical demonstrations and system wide guidelines and recommendations that will be the basis for future research and investment, increasing the capacities of rail networks in the future.

The time used for infrastructure monitoring, maintenance and renewal means “down time”. New concepts for low maintenance infrastructure, using standardized and “plug-and-play” concepts are proposed. Non-intrusive innovative monitoring techniques or self-monitoring infrastructure are investigated, allowing low or no impact on train operations.

The fragility of some key component of the infrastructure system (especially in extreme weather conditions) such as switches may impact the efficiency of the whole system. The resilience of switches to any kind of known failure is reinforced, as well as the ability of the operation system to recover from incidents. Capacity enhancements are also achieved by higher speed freight vehicles, allowing an optimized interleaving of freight trains into mixed traffic, and improved planning models for operation. Intermodal integration within the global transport system is improved through enhanced transshipment of passengers and freight.

CAPACITY4RAIL also looks towards 2030/2050, by proposing guidelines for future deployments in the mid-term, recommendations for technologies to be developed and deployed in the long term and investigating the key opportunities for funding these within national and EU funding schemes.

Our role in the project is to contribute and lead a work package. Specifically, we work on WP3.3 on *Optimal strategies to manage major disturbances*, within the sub-project 3 *Operations for Enhanced Capacity*. The content of the work package is centered on the

study of possible improvements of the process implemented in Europe for coping with traffic disruptions, mostly through automation increase.

B.1.4 OptiYard

2017-2019 Optimised Real-time Yard and Network Management (OptiYard)
H2020-S2RJU-OC-2017-777594.

The Commission’s 2011 White Paper states that by 2050, rail should substantially expand its modal share over medium and long distances. This is consistent with the Policy goals of expanding rail capacity, both cited in the Horizon 2020 and Shift2Rail (S2R) calls. Considering the ambitious Horizon 2020 Key Performance Indicator (KPI) calling for a surge in the utilization of capacity within a range 70 – 90%, yards, hubs and terminals play a key role in facilitating this step-change by contributing to a competitive, reliable and safe freight transport.

To meet the needs of S2R and Horizon 2020, OptiYard designs a decision support tool for yard managers that will help them to optimize processes and manage their yards more efficiently. The processes must be performed in real-time and with interaction with the relevant network, to guarantee on-time delivery and operational efficiency, in particular, for single wagon transport.

OptiYard addresses critical operational points of the transport chain (both rail marshaling yards or as transfer points to other modes) to improve capacity and reliability. OptiYard will facilitate real-time interaction between yard and relevant network IT systems that allow for software based planning and ultimately optimization of single wagonload and blocktrain operational processes.

Building on the current state of the art and practice, the ambition of OptiYard is to provide a fully functional software module where real-time yard management, interaction with the network and “ad hoc” timetable planning are simulated in real-time. The optimization module and algorithms are proven for large and complex freight transport networks, and integrate well with S2R IP5 activities towards automation, e.g., intelligent assets and automated shunting and mainline operations.

Our contribution in this project consists in participating and lead a work package. Specifically, we work on WP5 *Process optimization*. We develop the optimization based decision-support tool for yard managers, completing a closed-loop with a microscopic simulator. This work is the object of future research, as mentioned in Chapter 5.

B.1.5 X2RAIL-2

2017-2020 Enhancing railway signalling systems based on train satellite positioning, on-board safe train integrity, formal methods approach and standard interfaces, enhancing Traffic Management System functions (X2RAIL-2)
S2R-CFM-IP2-01-2017-777465.

X2RAIL-2 represents the second proposal of the Shift2Rail members in the IP2 “Advanced Traffic Management & Control Systems” domain.

The pillar (IP2) challenge is to increase functionalities of the existing signaling and automation systems and related design and validation processes providing a more competitive, flexible, real-time, intelligent traffic management and decision support system, and maintaining backward compatibility to the existing European Rail Traffic Management System (ERTMS) and especially its European Train Control System component (ETCS).

The X2RAIL-2 project aims to research and develop four selected key technologies to foster innovations in the field of railway signaling and automation systems within the following Technology Demonstrators:

Fail-Safe Train Positioning - To achieve a significant reduction of the use of traditional train detection systems by means of the attainment of an absolute and safe train positioning system based on a multi-sensor concept, where GNSS is the preferred technology.

On-Board Train Integrity - To achieve the safe On-board Train Integrity to allow the application of new signaling train separation concepts (e.g., Moving Block or Virtual Block) based on the train self-localization rather than on traditional train detection systems.

Formal Methods - To innovate and standardize processes and interfaces in the evolution phases of a signaling project (e.g., design, implementation, test & commissioning, operation & maintenance) to rationalize the approach and to reduce time-to-market costs.

Traffic Management Evolution - To improve standardization and integration of Traffic Management processes with the aim to achieve flexibility and scalability within the choice of functional service module managed by Traffic Management System.

The X2RAIL-2 project aims at reaching TRL5/6¹ demonstrators.

Our contribution to this project consists in participating to the definition of methods and principles for future traffic management. This work is part of a work package entitled *Traffic management evolution* (WP6).

¹Technology Readiness Level

B.1.6 ENGAGE

2018-2021 European network for the ATM community (Engage)
H2020-EU.3.4.7. - SESAR JU - 783287

Engage is a Knowledge Transfer Network proposed for European air traffic management, building on the solid foundation of previous actions, and introducing novel features and actions. Previous attempts to involve industry in the earlier maturity phases of *ATM* research have only partly been successful. We recognize that additional actions and incentives are necessary. With a balanced consortium, permeating all features of our proposal is the pronounced and active engagement of industry partners. At the core of the network are thematic challenges, supported by dedicated workshops. Catalyst funding will support focused projects, thus stimulating the transfer of exploratory research results towards *ATM* application-oriented research. This approach is enabled by the budget released through our lean management and compact consortium team. The network will establish a knowledge hub, in which members across the research community are continuously involved. This will include an observatory and undertake the role of devising and maintaining the long-term roadmap development of innovative and interdisciplinary *ATM* concepts beyond *Single European Sky ATM Research (SESAR) 2020*. The knowledge hub will be the one-stop, go-to source for information in Europe. Our vision of the network is that of an enduring partnership between academic, operational and industrial partners exchanging needs, ideas and information to ensure the relevance and applicability of research and uptake of new concepts and methods.

Our role within this Knowledge Transfer Network consists in bringing the connection with the rail transport world.

B.2 National projects

B.2.1 SIGIFret

2013-2015 Simulation of an innovative freight traffic management (SIGIFret - Simulations d'une gestion innovante des circulations fret)
Programme de REcherche et D'Innovation dans les Transports terrestres (PREDIT).

The objective of this project is the quantification of economic gains which are possible through effective traffic management. This traffic management must cope with the simultaneous presence in the network of passenger and freight trains.

The second objective is the deliver of a reliable basis for making decisions on how such a traffic management system can be tested in the perspective of an actual deployment. The study is based on the integrated use of an optimization and a simulation tool.

Third, a new optimization model is designed to assess the capacity of a network through saturation, to suitably assess the capacity consumption of freight trains in a context of mixed traffic.

Our contribution to this project consists, first of all, in assessing the gain allowed by the RECIFE-MILP algorithm compared to classic traffic management strategies. This work is summarized in Section 3.5.1. Second, we design RECIFE-SAT to solve the saturation problem, as described in Section 3.2.

B.3 Industrial projects

B.3.1 Gronda Sud di Milano

2006 Study on the transportation and economic system in the areas interested by the project “Gronda Sud di Milano” (Studio trasportistico sull’assetto economico e logistico delle aree interessate dal progetto della Gronda Sud di Milano)

Rete Ferroviaria Italiana SpA (RFI)

The objective of the project is the production of a feasibility study of the modification of the railway network circling around the Milan region in Italy. The aim of the modification is easing freight traffic circulation in the area. The economic convenience of the modification is also studied.

B.4 Personal projects

B.4.1 Metaheuristics tuning

2010 On-line meets Off-line Tuning: A novel approach for tuning the parameters of ant colony optimization and other metaheuristics

//AMG/VLD/WBI.WORLD/doh/2010/14511, Belgium.

The main objective of this project is to develop and empirically analyze a novel approach to tuning the parameters of meta-heuristics. Meta-heuristics, and among the others ant colony optimization, are well known techniques for tackling combinatorial optimization

problems. Their performance is influenced by a set of categorical and numerical parameters. Great attention has been devoted to the development of methods for tuning these parameters in order to boost the performance of meta-heuristics. The scientific community typically considers two separate research directions. Several authors suggest tuning the value of the parameters on the basis of a training set of instances, and to keep them unchanged throughout the solution process. This first approach goes under the name of off-line tuning. Other authors propose some methods for adapting the values of the parameters during each solution process itself. This second approach goes under the name of on-line tuning.

Within this research project we design a novel tuning approach that combines the benefits of the off-line and of the on-line approaches. A relationship between the experimental conditions and the opportunity offered by each of them can intuitively be identified. For making the most of the hybridization of the two tuning approaches, we identify the conditions that favor one of them against the other based on a wide experimental analysis: we first study how the experimental conditions impact on the relative performance of on-line and off-line tuning. Then, we use the understanding gained in this study for proposing a new tuning approach that combines the two classical ones.

Appendix C

Post-doctoral researchers, PhD, master and bachelor students supervision

As in the presentation of the research projects (Appendix B), the work of some of the students and researchers mentioned in the following is not mentioned in the manuscript. Namely the Master thesis of Gianpiero Francesca (Section C.3.1) is omitted because out of the scope of the discussed research. Other Master and Bachelor thesis supervised (Sections C.3.2-C.3.5) are not specifically mentioned in the manuscript because they did not bring to major realizations, although being an important support for the research reported.

C.1 Post-doctoral researchers

C.1.1 Rahimeh Neamatian-Monemi

Supervision rate: 70%

In 2014-2015, Rahimeh Neamatian-Monemi worked on the SIGIFret project (Section B.2.1) for one year. The topic of her post-doctoral contract was *Multi-objective optimization for the quantification of capacity of railway nodes*.

C.1.2 Samuel Deleplanque

Supervision rate: 70%

In 2017, Samuel Deleplanque joined our research team, for working for two years on the OptiYard project (Section B.1.4). The topic of his post-doctoral contract is *Real-time man-*

agement of railway yards. The collaboration mostly constitute the object of future research, as discussed in Chapter 5.

C.2 PhD students

C.2.1 Marcella Samà

Supervision rate: 30%

In 2014 Marcella Samà joined our research team for six months in the context of her PhD work at Università Roma 3, in Italy. She defended her thesis entitled *Development of models and algorithms for public transports* in 2016. The collaboration is still ongoing on the [rtTRSP](#) and the main realizations are presented in Section 3.5.2.

C.2.2 Diego Arenas

Supervision rate: 50%

Between 2013 and 2016 Diego Arenas has been PhD student at Railenium, a French IRT with focus on railway research. The title of his thesis is *Timetable re-optimization in case of maintenance activities on the railway infrastructure*, and the main contribution brought is described in Section 3.4. Diego Arenas now is employed at Railenium and the collaboration is expected to continue through common research projects.

C.2.3 Kaba Keita

Supervision rate: 80%

Between 2014 and 2017, Kaba Keita has been PhD student at IFSTTAR. The title of his thesis is *Decomposition of large-scale problems in the operational management of railway traffic* and its main results are reported in Section 3.5.1.

C.2.4 Nicola Coviello

Supervision rate: 30%

In 2015 Nicola Coviello joined our research team for six months in the context of his PhD work at Università La Sapienza, in Italy. He defended his thesis entitled *Evaluating railway capacity through timetable analysis: methodologies and application cases* in 2017. The collaboration is still ongoing, on the topics described in Section 3.2.

C.2.5 Teresa Montrone

Supervision rate: 60%

Teresa Montrone has been a PhD student at Università del Salento, Italy, between 2014 and 2017. The supervision of her work is motivated by the strong link between the treated topic and the research discussed in Chapter 3, for which the first contacts started in 2015. Her thesis is entitled *Energy consumption minimization on a railway network* and it makes the object of Section 3.5.3 and part of Section 3.3. The collaboration is still ongoing.

C.2.6 Franck Kamenga

Supervision rate: 70%

Since 2017 Franck Kamenga is a PhD student at SNCF and IFSTTAR. His work on *Local integrated optimization of rolling stock rostering and train movements* will make the object of future research, as mentioned in Chapter 5.

C.3 Advanced training, Master and Bachelor students

C.3.1 Gianpiero Francesca

In 2010 Gianpiero Francesca obtained his Master degree at Università degli Studi del Sannio, in Italy, in Computer Science Engineering. He completed a six-month internship at the IRIDIA-CoDE laboratory in Bruxelles, Belgium. His final report is entitled *A Study on Operator Selection for a Memetic Algorithm Applied to the QAP*.

C.3.2 Guillaume Douchet

In 2013 Guillaume Douchet completed a three-month internship at IFSTTAR during his Bachelor degree in Computer Science at Université Lille 1, in France. He participated to the work discussed in Section 3.5.1 with a study entitled *CPLEX parameter tuning to boost the performance of a heuristic algorithm for the real-time railway traffic management problem*.

C.3.3 Cecilia Negri

In 2015 Cecilia Negri spent six months at IFSTTAR to produce her final dissertation for the obtainment of a Master degree in Transport Engineering at Università La Sapienza, in Italy. She worked in the context of the Capacity4Rail project sketched in Section B.1.3, on which

she produced a work entitled *Analysis of the interoperability and of the automatism of big perturbations of railway traffic*.

C.3.4 Martino Marangon

In 2016 Martino Marangon completed a six-month internship at IFSTTAR for finalizing his Master degree in Computer Science Engineering at Università di Trieste, in Italy. The title of his work was *First steps toward the analysis of the impact of speed variation dynamics on the optimization of the real-time railway traffic management problem*.

C.3.5 Cristina Bernardis

In 2016 Cristina Bernardis spent six months at IFSTTAR for completing her Master dissertation entitled *Analysis of the impact of speed variation dynamics on the optimization of the real-time railway traffic management problem*. She obtained a Master degree in Management and Production Engineering at Università di Trieste, in Italy.

C.3.6 Elisa Marcelli

Between 2017 and 2018 Elisa Marcelli joined our research team for six months for an advanced training funded by Università di Camerino, in Italy, following her Master degree in Mathematics and Application. The title of her work is *State of the art and modeling of railway traffic as autonomous or autonomic system*. This work opens some research perspectives discussed in Chapter 5.

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Acronyms

ANSP Air Navigation Service Provider. 5, 10, 11, *Glossary: ANSP*

ATM Air Traffic Management. 1, 3, 4, 11, 78, 82, 96, *Glossary: ATM*

European Rail Traffic Management System European Rail Traffic Management System. 8, *Glossary: European Rail Traffic Management System*

GA Genetic Algorithm. *Glossary: genetic algorithm*

IATA International Air Transport Association. 9, 97–99

IM Infrastructure Manager. 8, 12, 56, 58, 69, *Glossary: infrastructure manager*

IPCS Installations Permanentes de Contre-Sens. *Glossary: Installations Permanentes de Contre-Sens*

MA Maintenance Activity. *Glossary: maintenance activity*

MILP Mixed-Integer Linear Programming. 31–33, 41, 44, 46, 62–65, *Glossary: mixed-integer linear programming*

PESP Periodic Event Scheduling Problem. *Glossary: periodic event scheduling problem*

RFF Réseau Ferré de France. *Glossary: Réseau Ferré de France*

rtECMP real-time Energy Consumption Minimization Problem. 30, 62–64, *Glossary: real-time Energy Consumption Minimization Problem*

rtRTMP real-time Railway Traffic Management Problem. 30, 31, 43, 44, 46, 56, 58–65, 71, *Glossary: real-time Traffic Management Problem*

rtTRSP real-time Train Routing Selection Problem. 30, 58–62, 86, *Glossary: real-time Train Routing Selection Problem*

RU Railway Undertaking. 8, 12, *Glossary:* railway undertaking

SESAR Single European Sky ATM Research. 82, *Glossary:* SESAR

SNCF Société Nationale des Chemins de fer Français. *Glossary:* Société Nationale des Chemins de fer Français

TDS Track Detection Section. *Glossary:* track detection section

TTP Train Timetabling Problem. *Glossary:* train timetabling problem

Glossary

- accommodated flight** A flight to which the requested number of [slots](#) is allocated during the [slot allocation process](#).. [18–20](#), [23](#), [24](#)
- airline** A company that provides air transport services for traveling passengers and freight. [4](#), [9](#), [10](#), [15–20](#), [24–27](#), [96–98](#)
- airport** A physical system including several subsystems as [runways](#), [taxiways](#), [apron stands](#) and [terminals](#). [2–5](#), [8](#), [9](#), [11](#), [16–25](#), [27](#), [95–99](#)
- airway** Specific paths along which aircraft may be routed within a [sector](#). [4](#), [99](#)
- apron stand** A portion of airport infrastructure where aircraft stop. [2](#), [95](#)
- block section** A section of track which a train may enter only when it is not utilized by other trains. [6–8](#), [44](#), [47–50](#), [54](#), [56](#), [62–65](#), [69](#), [71](#), [72](#), [75](#), [96–99](#)
- blocking-time** Time interval during which a [track-circuit](#) is utilized by a train.. [7](#), [95](#)
- blocking-time stairway** Representation of a train-path on a space-time diagram, indicating the [blocking-time](#) of [track-circuits](#) along the train route.. [7](#), [8](#), [31](#), [44](#), [53](#)
- clearing time** Time interval during which the head of a train has exited a [track-circuit](#) but its tail still physically occupies it. [44–46](#), [72](#), [75](#), [97](#)
- conflict** In timetabling, a conflict exists when two trains travelling at the planned speed would concurrently require the same track segment. [13](#), [31](#), [32](#), [42](#), [44](#), [51](#), [53](#), [54](#)
- control area** Portion of railway infrastructure on which a dispatcher is in charge of regulating traffic. [5](#), [44–51](#), [54](#), [56](#), [60](#), [61](#), [64](#)
- coordinated** Qualification of an [airport](#) the capacity of which is saturated during normal operations. The access to such [airport](#) is granted by a [coordinator](#). A coordinated [airport](#) is also called level 3. [9](#), [10](#), [15](#), [23](#), [96](#)

coordinator Organization in charge of granting access to a [coordinated airport](#). 9, 10, 15, 16, 20, 95, 97, 98

displacement cost Cost that [airlines](#) bear due to [schedule displacement](#). 16–18, 20, 23–25

EUROCONTROL Intergovernmental organization with 41 Member and 2 Comprehensive Agreement States. It is committed to building, together with its partners, a Single European Sky that will deliver the [ATM](#) performance required for the twenty-first century and beyond.. 3, 10

European Rail Traffic Management System System of standards for management and interoperation of signaling for railways by the European Union (EU).. 8

facilitated Qualification of an [airport](#) the capacity of which is saturated at peak-times. The access to such [airport](#) is validated by a [facilitator](#). A facilitated [airport](#) is also called level 2. 9, 10, 15, 23, 96

facilitator Organization in charge of validating access to a [facilitated airport](#). 10, 96

fixed-speed model Model of train speed variation dynamics neglecting brake and acceleration curves in case of unpredicted deviation from the planned speed profile.. 46

formation time Time interval necessary for forming the [block section](#) of interest by possibly setting its movable parts, and for the driver to see the signal and react. 7, 72, 75

grandfather right Historical right of an [airline](#) on the use of a [slot](#) at an [airport](#) if it has used the corresponding [slot](#) in the preceding equivalent season at least 80% of the times. 15–18, 23, 24, 26, 27, 96

incumbent Qualification of an [airline](#) which holds one or more [grandfather rights](#) at an [airport](#). 15

infrastructure manager Body or firm responsible for establishing, managing and maintaining railway infrastructure, including traffic management, control-command and signaling. 8

interlocking Arrangement of signal apparatus that prevents conflicting train movements through an arrangement of tracks. 5–7, 12, 31, 44, 45, 48, 56, 63, 71, 72, 97, 98

interval Time at which a [slot](#) is exercised. 20–22, 99

- junction** Part of the railway network where multiple lines cross. 5, 6, 97, 99
- macroscopic** Level of representation of the railway infrastructure: the network includes nodes, representing [junctions](#), and links, representing lines.. 5, 31, 41, 69
- microscopic** Level of representation of the railway infrastructure: the network includes tracks split in [block sections](#) and [track-circuits](#), the access to which is regulated through the [interlocking system](#).. 5–7, 31, 41, 44, 65, 66, 69
- mixed-integer linear programming** Is a very general framework for capturing problems with both discrete decisions and continuous variables. 31
- new entrant** Qualification of an [airline](#) which requests a series of [slots](#) at an [airport](#) on any day where, if the request were accepted, it would hold fewer than five slots. 15
- occupation time** Time interval during which a [track-circuit](#) is physically occupied by a train, including [running time](#) and [clearing time](#). 7, 98
- operational phase** Phase of the capacity utilization planning process which takes place from few days before the day of operations up to the end of operations themselves. iv, 2, 5, 10, 12, 61, 62, 68, 97, 98
- pre-operational phase** Phase of the capacity utilization planning process typically included in the [operational phase](#) which takes place few days before the day of operations. iv, v, 2, 10, 12, 30, 40, 41
- primary delay** Delay in the railway system not due to traffic evolution but to external causes, as the late arrival of a train driver. 13, 35, 44, 48, 72
- primary slot allocation** First phase of the airport [slot allocation process](#) in Europe. It takes place about five months before the start of the season, when the [airlines](#) submit formal requests for slots to airport [coordinators](#), who decide how to allocate scarce capacity. It terminates at the [IATA](#) conference. 10, 15, 16, 18–20, 23–26, 68
- railway undertaking** any public or private entity that provide services for the transport of goods and/or passengers by rail. 8
- real-time Energy Consumption Minimization Problem** Sub-problem of the [real-time Traffic Management Problem](#), aiming at optimally selecting train speed profiles to minimize delay and energy consumption while meeting previously made routing and scheduling decisions. 30, 44, 62

- real-time phase** Phase of the capacity utilization planning process typically included in the [operational phase](#) which takes place during operations. [iv](#), [v](#), [2](#), [11](#), [12](#), [30](#), [65](#), [98](#)
- real-time Traffic Management Problem** Problem emerging in the [real-time phase](#): train rerouting and rescheduling for minimizing delay propagation. [30](#), [43](#), [69](#), [97](#), [98](#)
- real-time Train Routing Selection Problem** Sub-problem of the [real-time Traffic Management Problem](#), aiming at optimally reducing instance size by selecting a proper subset of alternative [routes](#) for each train. [30](#), [44](#)
- release time** Time interval necessary for unlocking a [block section](#) after the passage of a train. [7](#), [72](#), [75](#)
- reservation time** Time interval during which a [track-circuit](#) is reserved for a train and it is hence not accessible to any other. It precedes the [occupation time](#). [7](#)
- route** Sequence of [track-circuits](#) traversed by a train within a portion of infrastructure. [12](#), [13](#), [30–34](#), [37–39](#), [41–50](#), [53](#), [54](#), [56](#), [58–64](#), [71–75](#), [95](#), [98](#)
- route-lock route-release** Type of [interlocking](#) system in which all [track-circuits](#) in a [block sections](#) are released simultaneously. [7](#), [48](#), [56](#)
- route-lock sectional-release** Type of [interlocking](#) system in which the [track-circuits](#) in a [block sections](#) are released sequentially. [7](#), [31](#), [44](#), [45](#), [48](#), [71](#)
- running time** Time interval during which the head of a train physically occupies a [track-circuit](#). [44–46](#), [71–73](#), [75](#), [97](#)
- runway** A portion of airport infrastructure that aircraft use for land or take-off. [2–5](#), [95](#), [99](#)
- schedule displacement** Difference between the requested and assigned [slot times](#) during the [slot allocation process](#). [16](#), [17](#), [23](#), [96](#)
- secondary delay** Delay in the railway system due to the emergence of conflicts. It is also named knock-on delay. [13](#), [35](#), [44](#), [46](#), [51](#), [54](#), [56](#), [59](#), [61](#)
- secondary slot allocation** Second phase of the airport [slot allocation process](#) in Europe, which takes place after the [IATA](#) conference. In this phase, [airlines](#) exchange slots under the supervision of [airport coordinators](#). [10](#), [16](#), [24–27](#), [68](#)
- sector** A portion of en-route space managed by an air traffic controller. [2–5](#), [10](#), [11](#), [17](#), [18](#), [22](#), [24–27](#), [95](#), [99](#)

- series** Sequence of at least five [slots](#) at an [airport](#), requested for the same time on the same day-of-the-week, distributed regularly in the same season.. [15](#)
- signaling system** Set of semaphores governing the entrance to [block section](#). [5](#), [6](#), [30](#)
- slot** Permission given to an airline to use the full range of [airport](#) infrastructure necessary to operate on a specific date and time for landing or taking-off at a congested [airport](#). [4](#), [5](#), [9](#), [10](#), [15–27](#), [95–99](#)
- slot allocation process** Process implemented in Europe to allocate [airport](#) capacity in the [tactical phase](#) of the planning process, regulated by [IATA](#) and the European Commission. [9](#), [10](#), [15](#), [27](#), [66](#), [68](#), [95](#), [97](#), [98](#)
- station** Particular [junction](#) where trains may stop for passengers to get on and off. [5](#), [6](#)
- strategic phase** Phase of the capacity utilization planning process which takes place years before the day of operations. [iv](#), [v](#), [2](#), [4](#), [5](#), [9](#), [11](#), [29](#), [65](#)
- subinterval** Time period equal to the difference of two consecutive [intervals](#)' start times. [20–22](#)
- tactical phase** Phase of the capacity utilization planning process which takes place months before the day of operations. [iv](#), [v](#), [2](#), [4](#), [5](#), [9](#), [11](#), [15](#), [27](#), [29](#), [61](#), [62](#), [66](#), [99](#)
- taxiway** A portion of airport infrastructure that aircraft use for reaching and leaving [runways](#). [2](#), [95](#)
- terminal** A building at an airport where passengers transfer between ground transportation and airport facilities. [3](#), [95](#)
- time supplement** Time margin added to the expected traveling time during the timetable design for increasing robustness. [8](#), [36](#)
- track-circuit** A section of a track where the presence of a train can be automatically detected. [6](#), [7](#), [31](#), [42](#), [44–50](#), [52–54](#), [56](#), [59](#), [60](#), [63](#), [71–76](#), [95](#), [97](#), [98](#)
- variable-speed model** Model of train speed variation dynamics precisely computing brake and acceleration curves in case of unpredicted deviation from the planned speed profile.. [46](#)
- way-point** Points [sector](#) borders along [airways](#), to be crossed for entering and exiting the [sector](#). [4](#)



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Education

2003–2007 **PhD in Economics, in the field of Mathematical Economics,**
Università Ca' Foscari Venezia, Venice, Italy,
Thesis title: *ACO: parameters, exploration and quality of solutions.*

1999–2003 **Master Degree in Business Economics,**
Università Ca' Foscari Venezia, Venice, Italy,
Thesis title: *Behavioral Model of an Ant Colony for a Problem of Distributive Logistics with multiple time windows: the case study Polo SpA (in Italian).*

Research interests

Optimization, modeling, integer linear programming, metaheuristics, swarm intelligence, transportation, logistics, air traffic management, railway traffic management, autonomous agents, multi-agent systems, parameter tuning.

Summary of scientific production

Nature of the contribution	total	since 2014
Articles published on international journals (peer-reviewed)	25	12
Book chapters	2	0
Articles published in the proceedings of international conferences (peer-reviewed)	40	21
Abstracts published in the proceedings of international conferences and workshops	40	18
Technical reports	22	6

Work experience

Research

2014–now **Researcher, IFSTTAR, COSYS-LEOST,** (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux), Lille, France.

- 2011–2014 **Post-doctoral researcher**, *IFSTTAR, COSYS-ESTAS*, (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux), Lille, France.
- 2010–2011 **Post-doctoral researcher**, *IRIDIA*, (Institut de Recherches Interdisciplinaires et de Développements en Intelligence Artificielle), Université Libre de Bruxelles, Bruxelles, Belgium.
- 2009–2010 **Post-doctoral researcher**, *Dipartimento di Matematica Applicata*, Università Ca' Foscari Venezia, Venice, Italy.
- 2008–2009 **Post-doctoral researcher**, *Dipartimento di Elettrotecnica, Elettronica e Informatica*, Università di Trieste, Trieste, Italy.
- 2005–2006 **Visiting researcher**, *IRIDIA*, (Institut de Recherches Interdisciplinaires et de Développements en Intelligence Artificielle), Université Libre de Bruxelles, Bruxelles, Belgium.
- 2004–2005 **Visiting researcher**, *Department of Systems and Industrial Engineering*, University of Arizona, Tucson, USA.

Industry

- 2010–now **Member of the board of directors**, *GP Pellegrini SpA*, Venice, Italy, <http://www.pellegrini.it>.
- 2010–2017 **Member of the board of directors**, *GP Dati Hotel Service SpA*, Venice, Italy, <http://www.gpdati.com>.
- 2010–2011 **Consultant for the development of a revenue management software tool**, *GP Dati Hotel Service SpA*, Venice, Italy, <http://www.gpdati.com>.
- 2007–2008 **Project manager for the development of printing and management software**, *GP Pellegrini SpA*, Venice, Italy, <http://www.pellegrini.it>.
- 2003 **Trainee involved in the the development of a logistic software tool**, *Pollo S.p.A.*, Padua, Italy, <http://www.poloristorazione.it>.

Teaching experience

- 2016 Invited lecturer on Models and solution of the real-time Railway Traffic Management Problem (master course in Optimization models, 4 hours). Department of Engineering and Architecture. Università di Trieste, Trieste, Italy.
- 2016 Invited lecturer on Railway Traffic Management in Europe: current practice and academic research (undergraduate course in Transportation, 2 hours). Faculty of Architecture. IUAV University of Venice, Venice, Italy.
- 2016 Invited lecturer on RECIFE-MILP: an effective heuristic for the real-time Railway Traffic Management Problem (master course in Optimization in public services, 6 hours). Faculty of Engineering. Università la Sapienza, Rome, Italy.
- 2015 Invited lecturer on Models and solution of the real-time Railway Traffic Management Problem (master course in Optimization models, 4 hours). Department of Engineering and Architecture. Università di Trieste, Trieste, Italy.
- 2015 Invited lecturer on Railway Traffic Management in Europe: current practice and academic research (undergraduate course in Transportation, 2 hours). Faculty of Architecture. IUAV University of Venice, Venice, Italy.
- 2009–2010 Teaching assistant of Mathematics (undergraduate course, 27 hours), Università Ca' Foscari Venezia, Venice, Italy.
- 2008–2009 Teaching assistant of Mathematics (undergraduate course, 7.5 hours) and Logistics (undergraduate course, 15 hours), Università Ca' Foscari Venezia, Venice, Italy.

2006–2007 Lecturer of Elements of Informatics for Economics (undergraduate course, 30 hours), teaching assistant of Mathematics (undergraduate course, 7.5 hours) and Microeconomics II (PhD course, 15 hours), Università Ca' Foscari Venezia, Venice, Italy.

Invited talks

- November 2017 **RECIFE-MILP for real-time railway traffic optimization: main results and current research**, *Talk given at the Department of Science and Technology, Linköping University, Norrköping, Sweden.*
- May 2016 **On the actual impact of real-time railway traffic management optimization**, *Talk given at the Railway Operations Research Seminar: 'Put Passengers First', Leuven, Belgium.*
- November 2012 **Forecasting hotel demand: mathematical models and algorithms available to the revenue manager**, *Talk given at the Web Hotel Revenue Seminar 2012, Rome, Italy.*
- November 2012 **Forecasting of the demand: one of the most interesting challenges of revenue management: What mathematics can and cannot do**, *Talk given at the Web Hotel Revenue Seminar 2012, Rome, Italy.*
- April 2012 **Yield management and forecasting: How the revenue manager can profit from models and algorithms**, *Talk given at the GP Days Seminar 2012, organized by GP Dati Hotel Service SpA, Venice, Italy.*
- November 2011 **Mathematics and yield management: How the revenue manager can profit from models and algorithms**, *Talk given at the Web Hotel Revenue Seminar 2011, Rome, Italy.*
- June 2011 **Swarm Intelligence**, *Talk given at the Danish Pavilion at the 54th Venice Biennale, Venice, Italy.*

Invited lectures

- March 2015 **Real-time Railway Traffic Management**, *RailTokyo2015, 6th International Conference on Railway Operations Modelling and Analysis, Tokyo, Japan.*
- October 2011 **Mathematical methods for the yield management in the hospitality industry**, *GP Dati Hotel Service SpA, Venice, Italy.*
- May 2009 **Revenue management in air traffic management**, *Lecture given during the course of Quantitative methods for decision making in tourism. Faculty of Economics. Università Ca' Foscari Venezia, Venice, Italy.*
- November 2008 **Application of ant colony optimization to real-world problems**, *Lecture given during the course of Optimization models. Faculty of Engineering. Università di Trieste, Trieste, Italy.*
- November 2008 **Introduction to metaheuristics**, *Lecture given during the course of Optimization models. Faculty of Engineering. Università di Trieste, Trieste, Italy.*
- March 2008 **Revenue management in air traffic management**, *Lecture given during the course of Quantitative methods for decision making in tourism. Faculty of Economics. Università Ca' Foscari Venezia, Venice, Italy.*

Awards

- 2017 Best paper award, 7th International Conference on Railway Operations Modelling and Analysis - RailLille2017. [32]

Personal fellowships

- 2012 Configuring algorithms: A novel framework, three-year mandate of *chargé de recherches* F.R.S. - FNRS, A 4/5 - MCF/DM - 11191, Belgium. (Fellowship awarded but not accepted.)
- 2010 On-line meets Off-line Tuning: A novel approach for tuning the parameters of ant colony optimization and other metaheuristics, //AMG/VLD/WBI.WORLD/doh/2010/14511, Belgium.

Research project and initiative participation

- 2018–2021 Engage - European network for the ATM community, H2020-EU.3.4.7. - SESAR JU - 783287
- 2017–2020 X2RAIL-2 - Enhancing railway signalling systems based on train satellite positioning, on-board safe train integrity, formal methods approach and standard interfaces, enhancing Traffic Management System functions, S2R-CFM-IP2-01-2017-777465.
- 2017–2019 Optimised Real-time Yard and Network Management (OptiYard), H2020-S2RJU-OC-2017-777594. Lead of Work Package 5.
- 2013–2017 Capacity4Rail - Increasing Capacity 4 Rail networks through enhanced infrastructure and optimised operations (CAPACITY4RAIL), FP7-SST-2013-RTD-1-605650. Lead of Work Package 3.3.
- 2013–2015 Simulation of an innovative freight traffic management (SIGIFret - Simulations d'une gestion innovante des circulations fret), Programme de REcherche et D'Innovation dans les Transports terrestres (PREDIT).
- 2011–2014 Optimal Networks for Train Integration Management across Europe (ON-TIME), FP7-SCP0-GA-2011-265647.
- 2008–2009 Contract-based Air Transportation System (CATS), TREN/07/FP6AE/S07.75348/036889.
- 2006 Study on the transportation and economic system in the areas interested by the project "Gronda Sud di Milano" (Studio trasportistico sull'assetto economico e logistico delle aree interessate dal progetto della Gronda Sud di Milano), Rete Ferroviaria Italiana SpA (RFI).

Conference organization

- 2018 Member of the program committee of ANTS 2018 - 11th International Conference on Swarm Intelligence.
- 2018 Member of the program committee of EvoCOP 2018 - the 18th European Conference on Evolutionary Computation in Combinatorial Optimisation.
- 2017 Member of the program committee of ATMOS 2017 - the 17th Workshop on Algorithmic Approaches for Transportation Modeling, Optimization, and Systems.
- 2017 Member of the program committee of EvoCOP 2017 - the 17th European Conference on Evolutionary Computation in Combinatorial Optimisation.
- 2016-2017 Member of the organization committee of RailLille 2017 - 7th International Conference on Railway Operations Modelling and Analysis.
- 2016 Member of the program committee of ANTS 2016 - 10th International Conference on Swarm Intelligence, track on ant colony optimization and other non-PSO optimization methods.

- 2015 Member of the program committee of GECCO 2015 - Genetic and Evolutionary Computation Conference, track on ant colony optimization and swarm intelligence.
- 2013 Member of the program committee of GECCO 2013 - Genetic and Evolutionary Computation Conference, track on evolutionary combinatorial optimization and metaheuristics.
- 2013 Participant to the organization of XXVI EURO - INFORMS Joint International Conference, at Sapienza University, Rome, Italy.
- 2012 Member of the program committee of GECCO 2012 - Genetic and Evolutionary Computation Conference, track on evolutionary combinatorial optimization and metaheuristics, and of ANTS 2012 - Eighth International Conference on Swarm Intelligence.
- 2011 Member of the program committee of GECCO 2011 - Genetic and Evolutionary Computation Conference, track on combinatorial optimization and metaheuristics.
- 2010 Member of the program committee of GECCO 2010 - Genetic and Evolutionary Computation Conference, track on Combinatorial Optimization and Metaheuristics, and of ANTS 2010 - Fifth International Workshop on Ant Colony Optimization and Swarm Intelligence.
- 2009 Member of the program committee of GECCO 2009 - Genetic and Evolutionary Computation Conference, track on combinatorial optimization and metaheuristics, and of SLS 2009 - Engineering Stochastic Local Search Algorithms: Designing, Implementing and Analyzing Effective Heuristics.
- 2007 Member of the program committee of GECCO 2007 - Genetic and Evolutionary Computation Conference, track on ant colony optimization, swarm intelligence, and artificial immune systems.
- 2004 Participant to the organization of The Tenth International Conference on Stochastic Programming, at the University of Arizona, Tucson, USA.
- 2003 Participant to the organization of the 34th AIRO conference, at Università Ca' Foscari di Venezia, Venice, Italy.

Editorial Activity for International Journals

Editorial board membership

Journal of Advanced Transportation

Participation to guest editorial board for special issues

Simulation and Optimization for Railway Operations Management, *Journal of Advanced Transportation*, 2018

Referee activity

Annals of Operations Research, Artificial Life journal, Complexity, Computers and Mathematics with Applications, Computers & Graphics, Computers & Industrial Engineering, Constraints Journal, European Journal of Operational Research, Expert Systems, IEEE Computational Intelligence Magazine, IEEE Transactions on Evolutionary Computation, IEEE Transactions on Systems Man and Cybernetics, IEEE Transactions on Vehicular Technology, European Journal of Transport and Infrastructure Research, IET Intelligent Transport Systems, Information Sciences, International Journal of Geographical Information Science, International Journal of Rail Transportation, Journal of Air Transport Management, Journal of Artificial Intelligence Research, Journal of Experimental & Theoretical Artificial Intelligence, Journal of Global Optimization, Journal of Rail Transport Planning & Management, Journal of the Operational Research Society, Journal of Zhejiang University Science C (Computers & Electronics), Mathematical Problems in Engineering, Nonlinear Processes in Geophysics, Optimization Letters, Swarm and Evolutionary Computation, Swarm Intelligence, Transactions on Parallel and Distributed Systems, Transportation Research Part A, Transportation Research Part B, Transportation Research Part C, Transportation Research Part E.

Referee Activity for Scientific and Research Institutions

- 2018 Doctoral committee member: Nadjla Ghaemi, TU Delft, the Netherlands.
- 2017 Doctoral committee member: Stefano Costanzo, Università di Trieste, Italy.
- 2010 Research project reviewer: The Netherlands Organisation for Scientific Research (NWO).

Research supervision

Post-doctoral researchers supervision

- 2017-now Supervision of Samuel Deleplanque, COSYS-ESTAS, IFSTTAR, France: *Real-time management of railway yards.*
- 2014-2015 Supervision of Rahimeh Neamatian-Monemi, COSYS-ESTAS, IFSTTAR, France: *Multi-objective optimization for the quantification of capacity of railway nodes.*

PhD students supervision

- 2017-now Supervision of Frank Kamenga, COSYS-ESTAS, IFSTTAR, France: *Local integrated optimization of rolling stock rostering and train movements.*
- 2014-2017 Supervision of Kaba Keita, COSYS-ESTAS, IFSTTAR, France: *Decomposition of large-scale problems in the operational management of railway traffic.*
- 2015-2017 Supervision of Teresa Montrone, Università del Salento, Italy: *Energy consumption minimization on a railway network.*
- 2015-2017 Supervision of Nicola Coviello, Università La Sapienza, Italy: *Evaluating railway capacity through timetable analysis: methodologies and application cases.*
- 2014-2016 Supervision of Diego Arenas, COSYS-ESTAS, IFSTTAR, Railenium, France: *Timetable re-optimization in case of maintenance activities on the railway infrastructure.*
- 2014-2016 Supervision of Marcella Samà, Università Roma 3, Italy: *Development of models and algorithms for public transports.*

Master students supervision

- 2017 Supervision of the advanced training of Elisa Marcelli, Università di Camerino, Italy: *State of the art and modeling of railway traffic as autonomous or autonomic system.*
- 2016 Supervision of the Master thesis of Cristina Bernardis, Università di Trieste, Italy: *Analysis of the impact of speed variation dynamics on the optimization of the real-time railway traffic management problem.*
- 2016 Supervision of the Master thesis of Martino Marangon, Università di Trieste, Italy: *First steps toward the analysis of the impact of speed variation dynamics on the optimization of the real-time railway traffic management problem.*
- 2015 Supervision of the Master thesis of Cecilia Negri, Università La Sapienza, Italy: *Analysis of the interoperability and of the automatism of big perturbations of railway traffic.*
- 2013 Supervision of the final internship for the bachelor of science degree of Guillaume Douchet, Université Lille 1, France: *CPLEX parameter tuning to boost the performance of a heuristic algorithm for the real-time railway traffic management problem.*
- 2010 Supervision of the Master thesis of Gianpiero Francesca, Università degli Studi del Sannio, Italy: *A Study on Operator Selection for a Memetic Algorithm Applied to the QAP.*

Personal skills

Languages

Italian	native language
English	excellent (spoken and written)
French	fluent (spoken and written)

Computer skills

Programming languages	ASP, SQL, Visual Basic, R, Bash, Mosel, C and C++
Modeling languages	SysML, RailML
Software	Microsoft office, xIPrint Paris, xIPrint Miami, Kofax Ascent, OpenTrack
Operating systems	Windows, Linux

Publications

Journals

- [1] D. Arenas, P. Pellegrini, S. Hanafi, and J. Rodriguez. Timetable rearrangement to cope with railway maintenance activities. *Computers and Operations Research*, 2018. To appear.
- [2] P. Pellegrini, G. Marlière, and J. Rodriguez. RECIFE-SAT: a MILP-based algorithm for the railway saturation problem. *Journal of Rail Transport Planning & Management*, 7(1-2):19–32, 2017.
- [3] P. Pellegrini, T. Bolić, L. Castelli, and R. Pesenti. SOSTA: an effective model for the Simultaneous Optimisation of airport Slot Allocation. *Transportation Research Part E: Logistics and Transportation Review*, 99:34–53, 2017.
- [4] M. Samà, P. Pellegrini, A. D’Ariano, J. Rodriguez, and D. Pacciarelli. On the tactical and operational train routing selection problem. *Transportation Research Part C: Emerging Technologies*, 76:1–15, 2017.

- [5] P. Pellegrini, G. Marlière, and J. Rodriguez. A detailed analysis of the actual impact of real-time railway traffic management optimization. *Journal of Rail Transport Planning & Management*, 6(1):13–31, 2016.
- [6] M. Samà, P. Pellegrini, A. D’Ariano, J. Rodriguez, and D. Pacciarelli. Ant colony optimization for the real-time train routing selection problem. *Transportation Research Part B: Methodological*, 85:89–108, 2016.
- [7] E. Quaglietta, P. Pellegrini, R.M.P. Goverde, T. Albrecht, B. Jaekel, G. Marlière, J. Rodriguez, T. Dollevoet, B. Ambrogio, D. Carcasole, M. Giaroli, and G. Nicholson. The ON-TIME real-time railway traffic management framework: A proof-of-concept using a scalable standardised data communication architecture. *Transportation Research Part C: Emerging Technologies*, 63:23–50, 2016.
- [8] P. Pellegrini, G. Marlière, R. Pesenti, and J. Rodriguez. RECIFE-MILP: an effective MILP-based heuristic for the real-time railway traffic management problem. *Intelligent Transportation Systems, IEEE Transactions on*, 16(5):2609–2619, 2015.
- [9] P. Pellegrini, G. Marlière, and J. Rodriguez. Optimal train routing and scheduling for managing traffic perturbations in complex junctions. *Transportation Research Part B: Methodological*, 59C:58–80, 2014.
- [10] P. Pellegrini, F. Mascia, T. Stützle, and M. Birattari. On the sensitivity of reactive tabu search to its meta-parameters. *Soft Computing*, 18(1):2177–2190, 2014.
- [11] A. Ellero and P. Pellegrini. Are traditional forecasting models suitable for hotels in Italian cities? *International Journal of Contemporary Hospitality Management*, 26(3):383–400, 2014.
- [12] F. Mascia, P. Pellegrini, T. Stützle, and M. Birattari. An analysis of parameter adaptation in reactive tabu search. *International Transactions in Operational Research*, 21(1):127–152, 2014.
- [13] P. Pellegrini and J. Rodriguez. Single European Sky and Single European Railway Area: A system level analysis of air and rail transportation. *Transportation Research Part A: Policy and Practice*, 57:64–86, 2013.
- [14] R. Chevrier, P. Pellegrini, and J. Rodriguez. Energy saving in railway timetabling: A bi-objective evolutionary approach for computing alternative running times. *Transportation Research Part C: Emerging Technologies*, 37:20–41, 2013.
- [15] P. Pellegrini, L. Castelli, and R. Pesenti. Metaheuristic algorithms for the simultaneous slot allocation problem. *IET Intelligent Transport Systems*, 6(4):453–462, 2012.
- [16] P. Pellegrini, T. Stützle, and M. Birattari. A critical analysis of parameter adaptation in ant colony optimization. *Swarm Intelligence*, 6(1):23–48, 2012.
- [17] L. Castelli, P. Pellegrini, and R. Pesenti. Airport slot allocation in Europe: economic efficiency and fairness. *International Journal of Revenue Management*, 6(1/2):28–44, 2012.
- [18] P. Pellegrini and D. Favaretto. Quantifying the exploration performed by metaheuristics. *Journal of Experimental & Theoretical Artificial Intelligence*, 24(2):247–266, 2012.
- [19] P. Pellegrini, L. Castelli, and R. Pesenti. Secondary trading of airport slots as a combinatorial exchange. *Transportation Research Part E: Logistics and Transportation Review*, 48(5):1009–1022, 2012.
- [20] A. Ellero and P. Pellegrini. Computer language efficiency via data envelopment analysis. *Advances in Operations Research*, 2011. ID 154516.
- [21] L. Castelli and P. Pellegrini. An AHP analysis of air traffic management with target windows. *Journal of Air Transport Management*, 17(2):68–73, 2011.
- [22] P. Pellegrini and E. Moretti. A computational analysis on a hybrid approach: quick-and-dirty ant colony optimization. *Applied Mathematical Sciences*, 3(23):1127–1140, 2009.
- [23] M. Birattari, P. Pellegrini, and M. Dorigo. On the invariance of ant colony optimization. *IEEE Transactions on Evolutionary Computation*, 11(6):732–742, 2007.
- [24] D. Favaretto, E. Moretti, and P. Pellegrini. Ant colony system for a VRP with multiple time windows. *Journal of Interdisciplinary Mathematics*, 10(2):263–284, 2007.
- [25] D. Favaretto, E. Moretti, and P. Pellegrini. An ant colony system approach for variants of the traveling salesman problem with time windows. *Journal of Information and Optimization Sciences*, 27(1):35–54, 2006.

Book chapters

- [26] T. Stützle, M. López-Ibáñez, P. Pellegrini, M. Maur, M. A. Montes de Oca, M. Birattari, and M. Dorigo. Parameter adaptation in ant colony optimization. In Y. Hamadi, E. Monfroy, and F. Saubion, editors, *Autonomous Search*, pages 191–215. Springer, Berlin, Germany, 2012.
- [27] P. Pellegrini and M. Birattari. Out-of-the-box and custom implementation of metaheuristics. A case study: the vehicle routing problem with stochastic demand. In M. Köppen et al., editor, *Intelligent Computational Optimization in Engineering: Techniques & Applications*, volume 366 of *Studies in Computational Intelligence*, pages 273–295. Springer, Berlin, Germany, 2011.

Conference proceedings

- [28] T. Montrone, P. Pellegrini, and P. Nobili. A MILP algorithm for the minimization of train delay and energy consumption. In A. Sforza and C. Sterle, editors, *Optimization and Decision Science: Methodologies and Applications. ODS 2017. Springer Proceedings in Mathematics & Statistics*, volume 217, pages 485–493. Springer, Cham, 2017.
- [29] P. Pellegrini, G. Marlière, R. Pesenti, and J. Rodriguez. A MILP reformulation for train routing and scheduling in case of perturbation. In A. Sforza and C. Sterle, editors, *Optimization and Decision Science: Methodologies and Applications. ODS 2017. Springer Proceedings in Mathematics & Statistics*, volume 217, pages 495–503. Springer, Cham, 2017.
- [30] P. Pellegrini, T. Bolić, L. Castelli, and R. Pesenti. Optimizing the slot allocation on a network of airports. In *INFORMS Transportation and Logistics Society - TSL2017, Chicago, USA.*, 2017.
- [31] M. Samà, P. Pellegrini, A. D’Ariano, J. Rodriguez, and D. Pacciarelli. Ant colony optimization for train routing selection: operational vs tactical application. In *2017 Models and Technologies for Intelligent Transportation Systems (IEEE MT-ITS 2017), Naples, Italy*, 2017.
- [32] D. Arenas, P. Pellegrini, S. Hanafi, and J. Rodriguez. Timetable optimization during railway infrastructure maintenance. In *7th International Conference on Railway Operations Modelling and Analysis - RailLille2017, Lille, France*, pages 1093–1112, 2017.
- [33] N. Coviello, P. Pellegrini, S. Sobieraj Richard, and J. Rodriguez. Stability of saturated timetables: the influence of buffer times. In *7th International Conference on Railway Operations Modelling and Analysis - RailLille2017, Lille, France*, pages 243–259, 2017.
- [34] K. Keita, P. Pellegrini, and J. Rodriguez. A benders decomposition algorithm for the real-time railway traffic management problem. In *7th International Conference on Railway Operations Modelling and Analysis - RailLille2017, Lille, France*, pages 486–504, 2017.
- [35] T. Montrone, P. Pellegrini, and P. Nobili. A real-time energy consumption minimization problem in railway networks. In *7th International Conference on Railway Operations Modelling and Analysis - RailLille2017, Lille, France*, pages 1399–1412, 2017.
- [36] P. Pellegrini, G. Marlière, R. Pesenti, and J. Rodriguez. Boosting the performance of railway traffic management through the reformulation of RECIE-MILP. In *7th International Conference on Railway Operations Modelling and Analysis - RailLille2017, Lille, France*, pages 505–520, 2017.
- [37] M. Samà, P. Pellegrini, A. D’Ariano, J. Rodriguez, and D. Pacciarelli. The potential of the routing selection problem in real-time railway traffic management. In *7th International Conference on Railway Operations Modelling and Analysis - RailLille2017, Lille, France*, pages 566–584, 2017.
- [38] T. Montrone, P. Pellegrini, and P. Nobili. Energy consumption minimization problem in a railway network. *Transportation Research Procedia*, 22:85–94, 2017. 19th EURO Working Group on Transportation Meeting “Simulation and Optimization of Traffic and Transportation Systems”, EWGT 2016, 05-07 October 2016, Istanbul, Turkey.
- [39] D. Arenas, P. Pellegrini, S. Hanafi, and J. Rodriguez. Train timetabling during infrastructure maintenance activities. In *IEEE International Conference on Intelligent Rail Transportation - ICIRT 2016*, 2016.
- [40] P. Pellegrini, G. Marlière, and J. Rodriguez. RECIFE-MILP for real-time railway traffic optimization: main results and open issues. In *WCRR 2016, 11th World Congress of Railway Research, Milan, Italie*, 2016.

- [41] T. Montrone, P. Pellegrini, P. Nobili, and G. Longo. Energy consumption minimization in railway planning. In *16 IEEE International Conference on Environment and Electrical Engineering*, 2016.
- [42] P. Pellegrini, G. Marlière, and J. Rodriguez. Real-time railway traffic management optimization and imperfect information: preliminary studies. In *Proceedings of the International Conference on Industrial Engineering and Systems Management (IEEE-IESM'2015)*, pages 55–60. International Institute for Innovation, Industrial Engineering and Entrepreneurship (I⁴e²), 2015.
- [43] M. Samà, P. Pellegrini, A. D'Ariano, J. Rodriguez, and D. Pacciarelli. A routing filter for the real-time railway traffic management problem based on ant colony optimization. *Transportation Research Procedia*, 10:534–543, 2015. 18th meeting of the Euro Working Group on Transportation - EWGT 2015, Delft, The Netherlands.
- [44] P. Pellegrini, G. Marlière, and J. Rodriguez. Analysis of the robustness of real-time railway traffic management optimization. In *RailTokyo 2015, 6th International Seminar on Railway Operations Modelling and Analysis, Tokyo, Japan, 2015*.
- [45] E. Quaglietta, R.M.P. Goverde, T. Albrecht, B. Jaekel, G. Marlière, P. Pellegrini, J. Rodriguez, T. Dollevoet, B. Ambrogio, D. Carcasole, M. Giaroli, and G. Nicholson. Optimal management of railway perturbations by means of an integrated support system for real-time traffic control. In *RailTokyo 2015, 6th International Seminar on Railway Operations Modelling and Analysis, Tokyo, Japan, 2015*.
- [46] G. Marlière, P. Pellegrini, and J. Rodriguez. Simulation of an innovative management of freight trains. In *International Symposium of Transport Simulation - ISTS2014*, 2014.
- [47] P. Pellegrini, G. Marlière, and J. Rodriguez. Optimal train routing and scheduling in case of traffic perturbations: improving solution time through parameter tuning. In *TRA2014 Transport Research Arena 2014*, 2014.
- [48] J. Rodriguez, P. Pellegrini, G. Marlière, S. Hu, and S. Sobieraj Richard. Improvement of real-time traffic management by using optimization tools. *Procedia - Social and Behavioral Sciences*, 160:465–473, 2014. XI Congreso de Ingeniería del Transporte - CIT 2014.
- [49] P. Pellegrini, G. Marlière, and J. Rodriguez. Boosting the performance of a MILP formulation for railway traffic management in complex junctions. In *MT-ITS 2013, Models & Technologies for Intelligent Transportation Systems, Dresden, Germany*, pages 419–428, 2013.
- [50] R. Chevrier, P. Pellegrini, and J. Rodriguez. A better train timetabling for a better energy management: Computing alternative running times for helping timetable-makers. In *WCRR 2013, 10th World Congress of Railway Research, Sydney, Australia*, 2013.
- [51] P. Pellegrini, G. Douchet, G. Marlière, and J. Rodriguez. Real-time train routing and scheduling through mixed integer linear programming: Heuristic approach. In *IESM 2013, 5th International Conference on Industrial Engineering and Systems Management, Rabat, Morocco*, 2013.
- [52] P. Pellegrini, G. Marlière, and J. Rodriguez. A mixed-integer linear program for the real-time railway traffic management problem modeling track-circuits. In *RailCopenhagen 2013, 5th International Seminar on Railway Operations Modelling and Analysis, Copenhagen, Denmark*, 2013.
- [53] R. Chevrier, P. Pellegrini, and J. Rodriguez. Computing multiple running times for railway timetabling: a speed-level based model for constructing alternative speed profiles. In *5th International Seminar on Railway Operations Modelling and Analysis, RailCopenhagen 2013, Copenhagen, Denmark*, 2013.
- [54] P. Pellegrini, G. Marlière, and J. Rodriguez. Real time railway traffic management modeling track-circuits. In Delling D. and Liberti L., editors, *12th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems*, volume 25 of *OpenAccess Series in Informatics (OASICs)*, pages 23–34, Dagstuhl, Germany, 2012. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik.
- [55] G. Francesca, P. Pellegrini, T. Stützle, and M. Birattari. Off-line and on-line tuning: A study on operator selection for a memetic algorithm applied to the QAP. In M. Peter and J.-K. Hao, editors, *EvoCOP 2011*, volume 6622 of *LNCS*, pages 203–214. Springer, Heidelberg, Germany, 2011.
- [56] L. Castelli, P. Pellegrini, and R. Pesenti. Ant colony optimization for allocating airport slots. In *MT-ITS 2011*, 2011.
- [57] A. Libardo, P. Pellegrini, and G. Salerno. Capacity in railway junctions and optimal route management. In *RAILROAD 2011*, 2011.

- [58] P. Pellegrini, T. Stützle, and M. Birattari. Off-line and on-line tuning: a study on MAX-MIN ant system for TSP. In M. Dorigo et al., editor, *ANTS 2010*, volume 6234 of *LNCS*, pages 239–250. Springer, Heidelberg, Germany, 2010.
- [59] D. Favaretto, E. Moretti, and P. Pellegrini. On the explorative behavior of MAX-MIN ant system. In T. Stützle et al., editor, *SLS 2009*, volume 5752 of *LNCS*, pages 115–119. Springer, Heidelberg, Germany.
- [60] L. Castelli, E. Padoano, P. Pellegrini, and A. Ranieri. Analysis of a collaborative decision making concept in air traffic management: an airline perspective. In *EWGT 2009*, 2009.
- [61] P. Pellegrini, D. Favaretto, and E. Moretti. Exploration in stochastic algorithms: An application on MAX-MIN ant system. In N. Krasnogor et al., editor, *NICSO 2008*, volume 236 of *Studies in Computational Intelligence*, pages 1–13, Berlin, Germany, 2009. Springer Verlag.
- [62] P. Pellegrini and A. Ellero. The small world of pheromone trails. In M. Dorigo et al., editor, *ANTS 2008*, volume 5217 of *LNCS*, pages 387–394. Springer, Heidelberg, Germany, 2008.
- [63] P. Pellegrini, D. Favaretto, and E. Moretti. Multiple ant colony optimization for a rich vehicle routing problem: A case study. In B. Apolloni et al., editor, *KES 2007*, volume 4693 of *LNCS*, pages 627–634. Springer, Heidelberg, Germany, 2007.
- [64] P. Pellegrini and M. Birattari. Implementation effort and performance. A comparison of custom and out-of-the-box metaheuristics on the vehicle routing problem with stochastic demand. In T. Stützle et al., editor, *SLS 2007*, volume 4638 of *LNCS*, pages 31–45. Springer, Heidelberg, Germany, 2007.
- [65] P. Pellegrini and E. Moretti. Quick-and-dirty ant colony optimization. In D. Thierens et al., editor, *GECCO 2007*, page 178. ACM, New York, NY, USA, 2007.
- [66] P. Pellegrini, D. Favaretto, and E. Moretti. On MAX-MIN ant system's parameters. In M. Dorigo et al., editor, *ANTS 2006*, volume 4150 of *LNCS*, pages 203–214. Springer, Heidelberg, Germany, 2006.
- [67] M. Birattari, P. Pellegrini, and M. Dorigo. On the invariance of ant system. In M. Dorigo et al., editor, *ANTS 2006*, volume 4150 of *LNCS*, pages 215–223. Springer, Heidelberg, Germany, 2006.

Conference abstracts

- [68] S. Deleplanque, P. Pellegrini, and J. Rodriguez. Optimiser une gare de triage en temps réel, 2018. 19th conference ROADEF of the French society of operations research et decision aid, Lorient, France.
- [69] K. Keita, P. Pellegrini, and J. Rodriguez. A three-step Benders decomposition approach for re-routing and rescheduling trains in case of perturbation, 2018. 19th conference ROADEF of the French society of operations research et decision aid, Lorient, France.
- [70] P. Pellegrini, T. Bolić, L. Castelli, and R. Pesenti. Integrating series in the simultaneous allocation of airport slots on a network of airports, 2017. *INFORMS 2017*, Huston, USA.
- [71] G. di Tollo, R. Pesenti, and P. Pellegrini. Scheduling ships and tugs within a harbour: the port of Venice, 2017. *AIRO 2017*, Salerno, Italie.
- [72] T. Bolić, L. Castelli, P. Pellegrini, and R. Pesenti. A simultaneous slot allocation on a network of airports, 2017. *AIRO 2017*, Salerno, Italie.
- [73] A. Marín, L. Cadarso, R. Garcia-Rodenas and P. Pellegrini, and J. Rodriguez. Integrate macro-micro real-time railway traffic management, 2017. 21st Conference of the International Federation of Operational Research Societies (IFORS2017), Quebec City, Canada.
- [74] K. Keita, P. Pellegrini, J. Rodriguez, and A. Marín. A benders algorithm for real-time train routing and scheduling including effective inequalities, 2017. 21st Conference of the International Federation of Operational Research Societies (IFORS2017), Quebec City, Canada.
- [75] K. Keita, P. Pellegrini, and J. Rodriguez. A decomposition approach for the real time railway traffic management problem, 2017. 18th conference ROADEF of the French society of operations research et decision aid, Metz, France.
- [76] D. Arenas, P. Pellegrini, J. Rodriguez, and S. Hanafi. Train timetable rearrangement facing infrastructure maintenance activities, 2017. 18th conference ROADEF of the French society of operations research et decision aid, Metz, France.

- [77] B. Jaekel, P. Pellegrini, S. Sobieraj Richard, and J. Rodriguez. Sysml formalization of the disruption management process in european railways, 2017. TRB 2017, Washington, D.C., USA.
- [78] K. Keita, P. Pellegrini, and J. Rodriguez. Benders decomposition for the real-time railway traffic management, 2016. EURO 2016, Poznan, Poland.
- [79] M. Samà, P. Pellegrini, A. D’Ariano, J. Rodriguez, and D. Pacciarelli. Ant colony optimization for the real-time train routing selection problem, 2016. EURO 2016, Poznan, Poland.
- [80] M. Samà, P. Pellegrini, A. D’Ariano, J. Rodriguez, and D. Pacciarelli. Train routing selection for the real-time railway traffic management problem, 2016. Dagstuhl Seminar 16171, Dagstuhl, Germany.
- [81] D. Arenas, P. Pellegrini, J. Rodriguez, and S. Hanafi. Timetable optimization to cope with railway infrastructure maintenance, 2016. 17th conference ROADEF of the French society of operations research et decision aid, Compiègne, France.
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