UNIVERSITÀ DEGLI STUDI
DI GENOVA

Università degli Studi di Genova

XXXIII CICLE IN COMPUTER SCIENCE AND SYSTEMS ENGINEERING

Dipartimento di Informatica, Bioingegneria, Robotica ed Ingegneria dei Sistemi

PhD Thesis

Simulation and Control of Groups of People in Multi-modal Mobility

María Asunción del Cacho Estil-les

Supervisor: Prof. Chiara Bersani

ACKNOWLEDGEMENT

II would like to say my best thanks to everyone who supported me in my work and helped me along with my whole PhD study, being a fundamental support for me throughout these years.

First, I owe my sincere gratitude to my supervisor Chiara Bersani, for her patient leading, collaboration, for her constructive criticism, support, and help; especially for guiding my research to this topic and motivating me throughout the doctoral program.

Next, I would like to thank Roberto Sacile for patiently guiding me, teaching me to conduct scientific research, and providing support to finish my thesis.

I also wish to express my gratitude to the entire DIBRIS department of the University of Genoa, for giving me the opportunity to do this PhD and grow professionally and personally.

Finally, I want to thank my family and friends for all the support they have given me and continue to give me. A special thanks to my husband, Paolo, constant source of support and encouragement, and my children Álvaro and Pablo. “Gracias”.

Abstract

Tourism and transport are constantly growing and, with it, the movements of travellers. This entails two fundamental effects on which we must focus: control of mass tourism and the organization of transport.

Good transport organization and travel planning avoid crowds and therefore mass tourism. This allows promoting sustainable tourism in which it is sought to offer a quality service to tourists taking care of the environment.

In this thesis the objective is to manage the flow of groups of people through means of transport. This control of groups of people is aimed at customer satisfaction by offering quality tourism.

On the one hand, the study focuses on the problem to mitigate the negative effects due to mass arrivals in touristic locations. A TEN network has been developed to define the optimal tours for different groups of tourists. A related mixed integer quadratic optimization model has been developed with three main objectives: it minimizes the maximum value of occupancy in the selected destinations to limit mass tourism, reduces the divergence between the proposed visit tour and one required by the tourist group and the overall duration of their visit, and a heuristic approach has been introduced.

On the other hand, it has been implemented a railway scheduling and rescheduling problem introducing optimization-based and min-max approaches on the regional and high-speed railway network. The scheduling model defines the best schedules for a set of trains considering costumers' demand and the priority of the trains to cover the rail sections in case of conflict on the railway lines. Consecutively, the generated feasible timetables are used to minimize possible consequences due to events that may negatively affect the real time traffic management. The main contribution of this section is the introduction in the second approach the innovative concept to prioritize the train that can access on the block section in case of conflicts on the network.

LIST OF CONTENTS

LISTS OF FIGURES

LIST OF TABLES

Chapter 1. Introduction

1.1 Background

In the last decades, tourism and transport have developed in such a way that they have allowed a considerable increase in displacement between cities, countries, and continents. According to World Travel and Tourism Council in 2018, the Travel & Tourism sector experienced an important growth, outpacing that of the global economy for the eighth consecutive year [1].

There are different factors that have caused this increase in tourism. Improvements in communication, whether technological, through transport, advertising, etc., have caused the massification of the number of people looking to travel for leisure, not for work. The new technologies make it possible to organize a trip very easily, with hardly any help from an external agent [2]. This aspect has contributed to the increase in tourism but above all that of so-called mass tourism.

Mass tourism is one where a high volume of vacationers, a group of tourists, is concentrated in a single destination, which causes the receptor capacity of the place to be exceeded. This brings with it damage to the natural and cultural resources that the place has and therefore to the people who inhabit it.

This type of tourism also affects large cities, cultural destinations, and even natural areas far from the main tourist magnets.

That is why so-called sustainable tourism is becoming increasingly important. In [3], sustainability is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The needs of future generations can be approached from different points of view. In this case, the study of sustainable tourism will focus on two fundamental aspects: preserving the natural environment, especially that which includes protected areas; and guarantee both the inhabitants and the visitors of the place quality tourism. That is sustainable tourism in both environmental and social commitment.

Tourism planning contributes to the reduction of discomfort caused at the destination of tourists [4]. In literature, several studies focus on describing sustainable tourism [5] and planning it for a better future, focusing on different aspects related to tourism. The study in [6] introduces the development of scenario planning for sustainable tourism since the 1970s. In [7], sustainable tourism is listed as a part that encompasses sustainable development.

Research in [8] introduces an innovative analysis of tourist traffic based on survey techniques to estimate the environmental impact of tourism in a destination, developed in this case in Italy's South Tyrol Region. The environmental impact is also a problem focused on study [9]. Research aims to improve the tourism planning process by identifying the impacts and limits of it. One of the last tools identified in transport policy to address environmental, social, and economic issues is the Sustainable Urban Mobility Plan (SUMP) [10].

Another aspect that favours tourism is the increase in the speed of means of transport, whether private or public transport, and their low cost in recent decades.

When talking about sustainable tourism, it is inevitable to talk about sustainable transport as they are directly related. The word tourism is linked to the verb travel and, to travel it is necessary to use the means of transport. Sustainable transport contributes to the good development of sustainable tourism, especially in the environmental impact it produces.

Sustainable transport is a concept that encompasses both economic sustainability and medium-time sustainability, influence of transport in the environment. Below are the different types of sustainable transport: walking, bicycle, electric car, and public transport.

Obviously, walking is the most sustainable transport together with the bicycle. Emissions are reduced to zero and provide benefits in health who use these media. Electric cars are propelled by an electric motor and employ rechargeable batteries, thus avoiding CO2 emissions.

Focusing on the ecological aspect, the benefits of public transport are very high. The pollution that originates cities would be reduced considerably if most citizens move by public transport. To make citizens change their customs and prefer public transport to private, services should improve offering higher quality, practicality, and comfort. Public transport must be safe, reliable, and efficient.

There are numerous studies focused on sustainable transport by relating it with sustainable tourism, as [11]. In the public transport group, we find, among others, the train. This means of public transport by land is one of the most sustainable. If, for example, the number of emissions produced by a train to go from point A to point B and those produced by a particular vehicle is compared, traveling by rail is convenient, since the vehicle's emissions would have to multiply them by the number of passengers traveling on the train. It is, therefore, evident the convenience of this means to travel which also increases citizens quality of life [12], and respects the environment [13].

Public transport in general works better and better and is well organized in terms of respecting schedules. That is why users, in many circumstances, prefer to travel by public transport. Although it should be noted that, in the case of trains on European railway lines, punctuality and customer satisfaction are not usually one of its strengths. Which causes a decrease in the use of the train to get around. Some studies focus on identifying the key points that railway lines must guarantee to obtain greater customer satisfaction [14]. In this way, public transport would have to be integrated effectively into the lives of citizens in order to compete with individual transport [15].

It is difficult to plan a train journey in the knowledge that there will probably be delays and the scheduled time will not be respected. Quality tourism depends on the proper functioning of transport. Therefore, it is concluded that to plan a trip, different aspects must be taken into account in which the points of interest, the tourist and the means of transport used are the main points to take into account.

1.2 Research aims

The main objective of this thesis is the management of the flow of people through the different means of transport to achieve a higher quality of service. The research objectives of this dissertation are described below.

- The control mass tourism, programming the access times of tourists to the localities, avoiding exceeding the capacity, thus being able to contribute to the development of sustainable tourism.
- Improve punctuality in the train schedule. Through the development and implementation of mathematical scheduling and rescheduling models, conflicts in the network and between trains are detected and resolved to restore normality in the shortest possible time.
- A robust train rescheduling model must be achieved in which the maximum delay caused by problems in the railway network is minimized. To achieve this goal, a rescheduling algorithm with a min-max approach is proposed.
- The planning and control of the traffic of the different means of transport must be approached during a window of time of several hours since the problems found in the network can be extended in time considerably.

1.3 Contributions

The main contributions of this thesis are described below.

- **Sustainable Tourism.** Most studies based on the tourism planning do not consider a fundamental factor when organizing trips. This factor is the environmental impact of mass tourism in the place that is visited. Mass tourism is considered a type of tourism with the aim of visiting the greatest number of points of interest in a single day. It is tourism without the intention of extending the stay in the tourist place for more than one day and that has negative environmental and social consequences. This type of tourism has destructive effects on local societies as well as on the natural resources of the place, contributing irremediably to the climate change that the planet is suffering.

To minimize the environmental impact and that which affects the inhabitants of the points of interest of mass tourism with a stay of less than one day, the development of a Time Expanded Network based on the Tourist Trip Design Problem is proposed. The main objective is to distribute tourist visits without crowding the places of interest, thus increasing the quality of tourism. The structure of the problem offers the best scheduling for tourist trips in a set of points of interest. To find out how the problem of mass tourism has been approached, see Chapter 3.

- **Train Priority in case of conflict.** In rail transport there are different categories of trains, generally classified according to their speed: the faster the train reaches, the higher its category. Based on this type of classification and other factors such as the number of passengers transported by the train, the concept of priority is introduced. This concept, when an optimal train timetable is scheduled, is necessary to avoid conflicts between two or more trains.

Is defined as conflict the moment when two or more trains want to enter the same block section at the same time. In this case, the alternative arcs are activated (explained later) and one of the trains gets the preference to enter the required block section. In the case of a conflict between two or more trains, the train with the highest priority is given way.

The priority can be defined in several ways. In the case of a network with trains of the same level, such as a network composed solely of regional trains, the priority is given by the number of passengers on board at the time of the conflict. The train with the highest number of passengers will be awarded the highest priority.

In the case of a network made up of trains with different priority levels, preference would be given to the train with the highest priority, regardless of the number of passengers onboard the train.

The priority of trains is developed in the three chapters dedicated to scheduling and rescheduling of regional trains (Chapter 4) and high-speed trains (Chapter 5). In Chapter 6, which includes the concept of priority, a robust model for high-speed trains is introduced.

1.4 Thesis structure

The outline of the thesis is as follows.

- **Chapter 2.** An overview of literature focused on travel planning is presented, with special emphasis on those points related to the research developed in this work. The three fundamental points are shelled: Tourist Trip Design Problem, the Train Scheduling and Rescheduling Problem, and, as part of this last point mentioned, the Conflict Resolution Problem is presented.
- **Chapter 3.** This chapter focuses on the study of the problem to mitigate the negative effects due to mass arrivals in touristic locations. Have been defined the optimal tours for different groups of tourists, which have planned short stays to visit a set of touristic destinations.
- **Chapter 4.** This chapter presents regional train scheduling and rescheduling models based on the generation of an alternative graph of the railway network, to solve the conflicts that can be generated between two or more trains.
- **Chapter 5.** Chapter 5 is the continuation of the study developed in the previous chapter. In this case, the research focuses on high-speed trains, with the special characteristics that this entails. The models that are presented consider the demand of the passengers, considering as the main objective the minimization of the travel time of each group of passengers. The case study is applied to the high-speed train network in Northern Italy.
- **Chapter 6.** To finish with the research related to the scheduling and rescheduling of high-speed trains, this chapter develops an evaluation of the models based on the minimum-maximum method.
- **Chapter 7.** The last chapter develops the conclusions obtained after completing the research and some of the possible future lines on which to continue with the study.

Chapter 2. Literature review

2.1 Introduction

This work is divided into two parts in which travel planning plays a fundamental role, being the basis of the research. In the first part, the study is based on the planning of the tourist visit of a group of people trying to avoid mass tourism and guarantee sustainable tourism. In the second part, the train journey of different groups of people is planned with the aim of minimizing travel time and satisfying the user.

But first, let see what travel planning is, with a literature review, and how it integrates with the scheduling problem.

Travel planning is defined as a problem in which a user, group of users, or means of transport travels from the departure point to the arrival point [16]. These two points are usually different, although they could be the same, starting and ending travel at the same point. The objective is to carry out this travel at the lowest possible cost. According to the demands and circumstances of the user, the cost can be based on travel time, distance, consumed energy, etc. That is, travel planning consists of a set of travel points, travel feature set and requirements set. This type of problem allows us to know what actions to take to travel.

To plan a travel, it is also possible to focus on when to carry out these actions. For this, it is necessary a job-shop scheduling problem. A scheduling problem includes machines (everything that works) and jobs (work that must be done). As a result of this problem, a feasible solution is obtained, satisfying all the constraints.

Many times, travel planning and scheduling are analysed together since it is necessary to know both what and when the actions are carried out.

It is essential to guarantee the user a quality service. Good travel planning, which includes scheduling planning of the transport, contributes to customer satisfaction. Several research focus on the study of tourist trip travel planning with the aim of increasing the quality of service [17]. In article [18], focused on Malta for the development of the case study, the possibility of using a mobile application to plan the stay in the country is proposed. The objective is to achieve a sustainable trip that adapts to the client's needs.

In the same way, in study [19], a system is developed in which travel itineraries are recommended to guarantee quality tourism. The proposed itinerary is marked by parameters such as personal preferences, a database with expert recommendations, travel restrictions… Based on these data, the client can orient himself and select what best suits him, modifying the suggested itinerary.

Next, a summary of some of the most outstanding research in the field of travel planning is included, focusing on the two lines in which the research work is carried out.

2.2 Tourist Trip Design Problem (TTDP)

There are various studies that focus on demand-based touristic itineraries planning considering the visitors' utilities, travel distances, or costs [20]. In general, the problem addressing the definition of the best tours for travellers according to their preferences is classified as a Tourist Trip Design Problem (TTDP) [21].

The TTDP is based on travel planning for those tourists interested in visiting more than one Point of Interest (PoI) during the day. The travel must be organized to satisfy the tourist considering several aspects: visiting time at each PoI, the distance between the different points, visiting hours, means of transport… To satisfy the user, the routes are usually personalized based on their preferences, many times considering the user experience of those who have already visited the POI [22].

Currently, the best tool for planning a trip is the smartphone, with searches through the Internet or applications developed for this purpose. A good electronic tourist guide must be able to recommend to the tourist, based on their preferences, the points of interest and the route to visit them [23].

In [21], the authors investigated models, algorithmic approaches, and methodologies concerning the TTDP for single or multiple tour TTDP. In the TTDP context, the Orienteering Problem (OP) has the objective to maximize the total profit of visited nodes guarantying that the paths respect the time allowed for sightseeing the nodes in a single day [24] [25].

In [26], the authors proposed a heuristic approach, which aims at defining the tour routes for heterogeneous tourist groups balancing the total utility of the group and the fairness of individual members.

Besides, in [27], the authors solved the TTDP considering the individual preferences of the tourists about points of interest and the concept of mutual social relationship between the different tourists. They compared the solution of the TTDP for four cases: the generation of single tours where each tourist have one trip plan; the generation of tours for each subgroup of tourists built considering to aggregate the tourists with common preferences; a joint trip plan for all tourists considering the social relations of each pair of tourists; and, finally, a combined solution in which some parts of the itineraries may be shared by tourists with similar interests while other parts of the tour may be personalized based on the single individual preferences.

In [28], the authors solved a TTDP implementing a time-dependent shortest path through a fixed sequence of nodes. Given the predefined large size of the time-dependent network, the authors proposed a decomposition approach to solve a sequence of smaller subproblems in reasonable computation times.

In [29], the authors developed a mathematical model - as well as related efficient algorithms - to solve a TTDP with the objective to design a tour trip to visit the most desirable tourists' sites subject to various budget and time constraints. In [30], the authors proposed an approach to generate dynamic routes for shared buses in the last mile scenarios considering travel requirement prediction and dynamic routes planning. In [31], a time dependent TTDP has been solved in large urban areas for different groups of people. The authors define a chronological sequence of attractive points to be visited during a specific period via several modes of transportation. A large survey about models, algorithmic approaches, and methodologies concerning TTDP is presented in [21].

2.3 Train Scheduling and Rescheduling Problem

In the next future, probably train schedules will be modelled based on passenger demand, especially for high-speed trains. Currently, passengers require to travel and move quickly through the main cities of the country. On the other hand, railway companies always seek to meet the needs of passengers [32]. To achieve this objective, the scheduling of the network traffic ensuring maximum customer satisfaction may be applied. In this area, the train scheduling problem is to find an optimal timetable that allows passengers to reach their destination in the shortest time.

The assessment of the train timetable, which defines the times for departure, stop, or arrival for each train on each line of the rail network, represents the train scheduling planning. A train scheduling problem is usually performed to satisfy customers' needs in terms of rail quality service.

Train scheduling (TS) allows defining the planning of the arrival and departure times of trains at the rail stations. The TS general objective is to minimize the completion time or/and delays of the planned train services [33]. So, the main issue is to determine the best feasible timetable for a set of trains to satisfy restrictive operational constraints related to the track capacity, maximum travel speed, and to avoid possible conflicts on the rail network in using every single track.

If some disturbance on the network appears at the operation or real-time decisional level, a train rescheduling problem must be solved timely. Further, in case of disturbances on the network, the travel time of the train or its dwell time at stations can be increased [34]. The time it takes to restore normality to the network is uncertain. Therefore, through scheduling and rescheduling algorithms, it is necessary to minimize the propagation of the delay due to unexpected disturbances [35]. The main objective of rescheduling is to restore the original schedule for trains within a limited time horizon minimizing operational costs. A large literature is dedicated to train scheduling and rescheduling problems [36].

From a performance-based viewpoint, TS problems can be investigated on three different levels, which depend on the increased data required for the analysis: microscopic, macroscopic, and mesoscopic representation [37].

- **Microscopic representation:** computes the TS according to a deep analysis of each infrastructure component such as safety signals and dynamic information, as in [38], considering a model based on a detailed railway network (including track section level).

- **Macroscopic representation:** The macroscopic approach can optimize operations at network level [39], providing a high-level infrastructure representation (track sections are typically ignored) [40]. In the last decades, there is some literature dedicated to train scheduling and rescheduling problems at a macroscopic level [41].

Here are some works developed around the subject of train scheduling in different context.

In [42], the authors investigate the joint optimization model for train scheduling, train stop planning, and passenger distribution by considering the passenger demands over each origin and destination pair on a high-speed railway corridor.

The study in [43], focused on the transport by rail of hazmat, proposes an approach to show how variations of the timetable can sensibly decrease the average and maximum exposure.

In [44], the authors presented a study based on the integration of train scheduling and rolling stock circulation planning under time-varying passenger demand for an urban rail transit line.

In [45], the problem of scheduling a set of trains traveling through a given railway network consisting of single tracks, sidings and stations is considered.

Those proposed algorithms have as main objective to offer the best quality of services to fit customers’ needs.

- Mesoscopic representation: the optimization is addressed to a fine-tuning train routing among the main corridors on the network, likely to optimize energy efficiency [46].

Studying the problem from another point of view, in literature, the TS problem has been classified into three main categories [47]: classic, real-time, and robust TS.

The Classic TS problem finds the timetable for high or medium speed trains on a single or double track set of railway sections minimizing the makespan of the overall train activities [48], the railway throughput [49], or train fuel consumption [50].

The real-time TS problem is based on the current position of trains proposing dynamic solutions in case of disturbances on the railway infrastructures and solving, in real-time, forthcoming conflicts [51] minimizing, for example, eventual delays as in [52] or [53]. The research [54] proposes a real-time scheduling model, avoiding propagating delays without degrading the quality of service to passengers. In [51], a branch and bound model introduces an approach to the conflict between two trains using alternative graphs. The work in [55] describes four methods to solve the problem of a conflict in a single, double, and multi-tracks railway lines. The study in [56] defines a TS problem taking also into account the crew scheduling and possible changes to the network.

Finally, works on the robust TS show robust optimization techniques on delay management problems [57] and on the control of the distance between two successive trains [41].

In a modern view, the rail managers have also to adapt the train schedule to customer requirements, ensuring an adequate number of trains to meet the passenger needs in terms of demand for each destination, assuring speed and punctuality [57]. In this context, the definition of the robustness level of the system network may be relevant to offer the best service. In addition to the timetable efficiency, a robust TS must have the ability to avoid delay propagation in case of disturbances on the network usually caused by operational problems, design errors, or changes in functional parameters, minimizing the primary delays in respect to the nominal scheduling [58].

Different approaches in literature focus on the study of TS robustness [59]. A robustness index may represent the expected probabilistic increase in passenger discomfort when a delay occurs [60] or the measure in which a nominal timetable may absorb the upcoming disturbances [47].

In [61] the authors solved a TS problem integrating the microscopic and macroscopic framework. In this case, at the microscopic level, a stable timetable has been generated by considering train running and headway times at the local level. The macroscopic model, applied to the overall network, defines the timetable including robust methods to estimating delay propagation.

Another approach [62] proposed the performance measure of timetable robustness as the percentage of the process completed within the scheduled time or as a percentile of the process time. As a general approach to improving the timetable robustness, the TS planner extends the arrival instant of the train with a buffer time to deal with the possible deviation in time with respect to the scheduled departure in order to prevent delay propagation to the following trains, so-called secondary delay [63]. One of the methods to carry out robust optimization is the min-max approach, in which a feasible solution is calculated by optimizing the worst-case given a set of scenarios. In [64], a min-max method is used to optimize the organized and balance use of train station tracks while in [65] the authors optimized the passenger robustness, which aims to minimize the total travel time of the passengers when possible delays affect the network.

2.3.1 Conflict Resolution Problem (CRP)

The railway systems are composed of large numbers of sub-systems with complex interactions. The rail tracks are divided into block sections, which are segments of track separated by two signals.

The signalling system uses track circuits to detect the presence of trains on each track section. According to the signal at the beginning of the block, the signalling system communicates to the train driver three different status of the next blocks. The train can proceed on the block because no criticism exists on the following sections or the train should proceed with “caution” at limited speed because the following blocks are still busy and, finally, the train must stop because another train is present in the next block section [41]. By the railway signal control system, the line capacity is managed as each track section may be safely occupied only by one train [66].

In [51], the authors tackle a train scheduling problem faced by railway infrastructure managers giving special attention to real-time Conflict Resolution Problem (CPR) [67]. A conflict appears on the network when two or more trains require covering the same block section at the same time.

Many authors formulated the train rescheduling problem based on the Alternative Graph [68] where each node represents a logistic operation and alternative arcs might model the constraint related to CRP at the nodes. Authors in [69] implement the alternative graph model in the context of the real-time railway traffic management system. In [70] and [71], the same authors introduce different disturbances on the network creating delay scenarios and solving the problems by graph-based solutions. In [72], the authors investigate the train scheduling and rescheduling problems introducing a new bottleneck approach focused on a case study based on part of the UK railway network.

Chapter 3. Optimal travel planning of short stays in mass tourist destinations

3.1 Introduction

This chapter proposes a methodological approach to manage the mass tourist flows based on the tourism carrying capacity assessment at the destinations. The positive and negative impacts of tourism on the economic, environmental, and social perspectives must be considered.

Based on the research literature, Sustainable Tourism Development (STD) and the level of the quality of life in the touristic location have a reciprocal link [73]. In general, STD aims at minimizing the negative impacts on cultural heritage and the environment. In the meantime, it should provide positive benefits for the local economy contributing to the improvement of local community services and infrastructures. The UNESCO World Heritage and Sustainable Tourism Programme defined some strategies to prevent and manage touristic threats and impacts [74]. STD cannot be achieved if touristic locations are affected by mass tourism without adequate integrated sustainability measures [75]. From this perspective, the STD analysis should consider the demand factor, above all, in the case of small touristic destinations [76].

In this part of the study, the objective is to present an approach to promote STD for close and small touristic locations. Specifically, the STD aspects considered are related to the tourist short stays (less than one day) resulting in peaks of tourist density which may affect safety.

The contribution of this approach is twofold. Firstly, a particular structure of the TTDP model gives the best scheduling for touristic tours in a set of strategically attractive destinations. The objective is to reduce the peaks of touristic demand considering three aspects: maximization of tourists' satisfaction; optimization of the use of the available transport resources; respecting a threshold of maximum touristic carrying capacity in each location.

Secondly, from a methodological viewpoint, the problem has been modelled on a Network Flow Problem (NFP) [77] solved by a Time Expanding Network (TEN) methodology [78]. The advantage of the TEN approach is to build a static representation of the original network for each discrete time interval and then to solve the NFP for each of them [79]. The TEN approach has been used to solve many flow network problems with applications to evacuation problems [77], multi-depot bus scheduling [80], optimal capacity utilizations for intelligent transportation management of traffic coordination systems [81], reducing air traffic delay [82], and for solving resource-constrained shortest-path problems [83].

The proposed TEN based TTDP model has been implemented with the objective to define the optimal travel planning for different groups of tourists (GTs) to visit attractive locations. The model supports the GT wished list of locations to be visited (irrespective of their order), the length of each visit, and the transport modes for the transfers. The proposed model maximizes the tourist satisfaction, while minimizing the deviation of the visiting time for each location with respect to the planned visit duration. A min max approach is presented in the objective function to minimize the maximum value of touristic occupancy of the locations.

In the existing literature, the TTDP is modelled from the tourists' viewpoint. In those cases, the solutions generate the daily tourist tours according to parameters and constraints associated only to the tourist satisfaction. This means that the classical objectives of the TTDP are the optimization of the tourists' profit in terms of economic costs, visiting time, distance travelled, duration of the transits, or service transport availability.

The main innovative element of the proposed approach is the different viewpoint used to solve the TTDP. In our context, the local authorities of attractive locations aim at defending their territories, particularly environmentally and historically sensitive, affected by a massive flow of tourists. The proposed model has the objective to protect the locations to be visited minimizing the peak of touristic massive arrival without affecting the planned visiting time of the users.

This chapter addresses the need of the Cinque Terre National Park (Liguria Region, north-western Italy) to manage and promote a STD in the five small villages of the Ligurian coast.

3.2 Time Expanded Network (TEN)

A Time Expanded Network (TEN) is considered as a comprehensive model to represent complex systems in the framework of dynamic network optimization problems. In literature, one of the main traditional approaches for network optimization, in different context of applications, such as transportation, logistics or communication, are the class of network flow models. In many real-life applications, where the transfer of the flow from a node to another is not instantaneous, the classical static network flow approaches need to be modified introducing the time factor to model the flows transition in the network. Ford and Fulkerson [84] introduced this kind of models considering flow variations over time. In [31] a review about path and flow problems in generalized networks is presented. In detail, the TEN represents a copy of the static flow network replicated in each time interval of the time horizon [85].

Let $Z = (N, A)$ be a network (Figure 1): where N is the set of nodes representing the locations, and A is the set of arcs representing the infrastructure connections (e.g., train, ship, …) between such locations (Figure 1a). For a given time set $T = \{t_1, t_2, \dots t_T\}$, the corresponding $TEN\ Z^T = (N^T, A^T)$ (Figure 1b) is defined as follows. For each node $c_i \in N$ of the network, a copy of that node has to be created for each time interval of the time horizon, labelled as c_{it} that is:

$$N^T := \left\{ c_{it_s} \middle|_{\substack{t_{s \in T,} \\ i = 1, \dots, N}} \right\} \quad \textit{Equation 1}$$

For each arc $a_{ij} = (c_i, c_j) \in A$ of the network, if a mean of transport exist at that instant, there will be an instance of that arc $a_{ij}(t_s t_d)$, connecting nodes c_{it_s} to c_{jt_d}. In addition, the TEN also consists of holdover arc $(c_{it_s}, c_{it_{s+1}})$ for each $c_i \in N$ of the static network. These arcs allow holding the flows on the same nodes for more than one-time interval.

The set of arcs is defined as follows:

$$A^T := \left\{ a_{ij}(t_s t_d) = (c_{it_s}, c_{jt_d}) \middle| \begin{array}{c} a_{ij} = (c_i, c_j) \in A, \\ t_s, t_d \in T \\ t_d > t_s \end{array} \right\} \quad \textit{Equation 2}$$

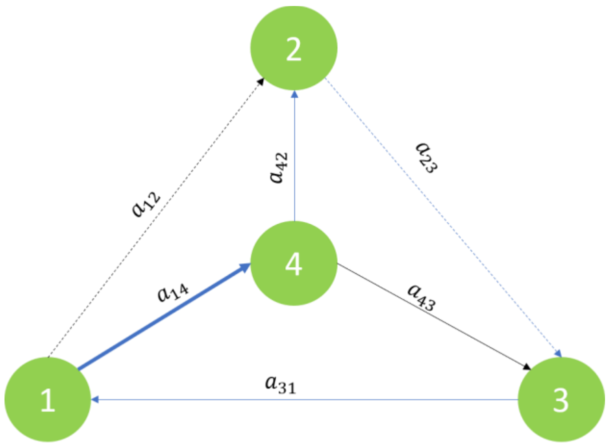


Figure 1a

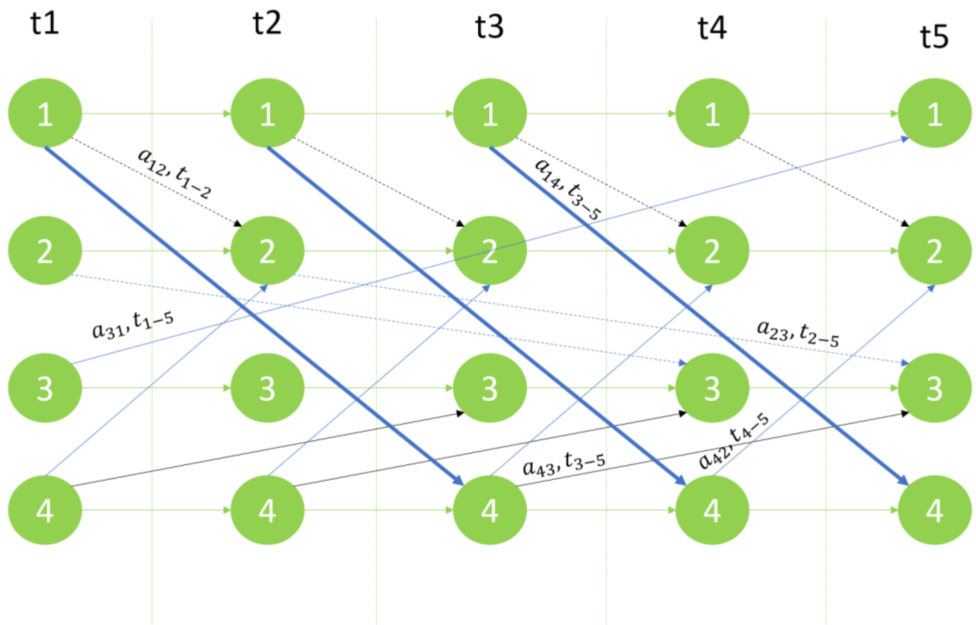


Figure 1b

Figure 1. (1a) Network G with 4 nodes and 6 arcs. (1b) TEN GT with time horizon t=5

3.3 Carrying Capacity of a Tourist Destination

To adopt STD strategies balancing the requirements for the conservation and the attractiveness of touristic locations, a tourist carrying capacity (TCC) analysis has to be done.

Here, a TCC is mainly referred to the definition proposed by World Trade Organization as "The maximum number of people that may visit a tourist destination at the same time, without causing destruction of the physical, economic, socio-cultural environment and an unacceptable decrease in the quality of visitors' satisfaction" [86] [87]. More recently, this definition has been integrated considering the impact of touristic flows which has not to affect negatively the quality of life of community residents [88].

The goal of this paragraph is to present a suitable methodology to compute the maximum threshold value for the TCC for small sensible locations on the coastal areas. In literature, the methodologies to compute TCC are based on physical, biological, and management conditions of the selected locations [89]. Such three characteristics are defined as three connected indices: the physical carrying capacity (PCC), the real carrying capacity (RCC), the effective carrying capacity (ECC) [90].

The following indices can be computed as in [90]:

$$PCC = Area\ Au\ Rf \qquad \text{Equation 3}$$

where,

- $Area$ is the size of the physical area visited by tourists.
- Au represents the minimum space required by each tourist.
- Rf, is the rotation factor which means the number of times the selected location can be visited per day.

The RCC is determined by reducing the PCC though correction factors associated to environmental features (sunshine, rainfall, soil erosion, biological disturbance):

$$RCC = PCC\ \Pi\ cfi\ ki = 1 \qquad \text{Equation 4}$$

The correction factor is normalized using Equation 5

$$cfi = 1 - (Lmi\ Tmi)\ i = 1, .., k \qquad \text{Equation 5}$$

where Lmi is the limiting magnitude of *i-th* environmental factor, and Tmi is its total magnitude.

Finally, ECC is equal to RCC times the parameter mc which is associated with the quality of the management and infrastructures given by the visited location ($mc \leq 1$).

$$ECC = RCC * mc \qquad \text{Equation 6}$$

3.4 TEN Based TTDP Model formulation

In this section, the proposed TEN based TTDP model is presented to find the optimal planning and the temporal sequences of attractive locations to be visited by a set GTs during a specific period by using several modes of transport services. In the static network, the set *N* of touristic locations, are connected by the set *A* of arcs which represent the transport services from location *i-th* to location *j-th* with a specific time transit.

Due to the dynamic nature of the proposed problem, a TEN expanding the static network over the planning horizon for every time interval has been defined. The time intervals are not considered constant, but they are defined according to the travel time for the related transport service between nodes. Each time interval is converted to the timetable of transport services according to the departure and arrival time from origin to destination location. In this way, the number of the time interval to build the TEN is reduced only to the number of actual transport services available in the selected time horizon.

3.4.1 Variables and Parameters of the TEN based TTDP Model

The following variables and parameters are introduced.

- $G = \{1 \ldots g\}$ is the GT set. Each GT must be considered as an indivisible group of persons.
- $NT := \{c_{i,ts} | ts \in T, i = 1 \ldots N\}$ is the set of nodes. Each node represents a specific location in the network, and it has a related $ECCi$ in term of allowed visiting tourists. Two fictitious nodes have also been added: the super source and the super sink, which indicate the virtual starting node of all the visits, before entering the first city to be visited; and the super sink, destination after leaving the last visited node. In the case of fictitious nodes, the $ECCi$ is unlimited.
- $AT = (c_{i,ts}, c_{j,td})$, is the set of arcs of TEN. Each unidirectional arc links two nodes, thus representing a specific means of transport to travel from one node to another.
- Set of time intervals which the time horizon consists of $T = \{t_1, t \ldots tT\}$. The proposed network system has an event-driven dynamic. Each discrete time point $t_1 < t < \cdots < t_k < \cdots < t_T$ represents the occurrence of an event associated to the arrival or departure times of a transport service.
- Set of modes of transport, $M = \{1 \ldots m\}$ available modes of transport are represented by the arcs between nodes of the network. Each mode of transport has a related maximum capacity in number of allowed people to be transported (CAP_m).

The following parameters and decision variables have been introduced.

Parameters

w_g	Number of persons which the g-th GT, $g \in G$
$Start_g$	Planned starting time of the tour of each *g-th* GT, $g \in G$

d_{m,c_i,t_i,c_j,t_j}	Binary parameter equal to 1 if a transit is available by the *m-th* mode of transport between the nodes *ci* and *cj*, from the time instant *ti*, to *tj* with *ti, tj* ∈ *T*, *ci, cj* ∈ *N*, *m* ∈ *M*
ECC_c	Maximum *ECC* allowed in term of visiting tourists at the node *ci*, *ci* ∈ *N*
CAP_m	Capacity (in number of allowed transported persons) of *m-th* mode of transport, *m* ∈ *M*
$\hat{t}_{g,c}$	Planned visiting duration of *g-th* group at the *c-th* node, *g* ∈ *G*, *c* ∈ *N*
O_t	Real time for the event (arrival or departure times of the transport service) associated to the related time instant *ti* ∈ *T*

Decisional Variables

y_{m,g,c_i,c_j,t_i,t_j}	Binary variable equal to 1 if the *g-th* GT uses a transport service by the *m-th* mode of transport at time instant *ti* at the node *ci* to reach the node *cj* at time instant *tj ; ci, cj* ∈ *N*, *m* ∈ *M*, *ti, tj* ∈ *T*, *g* ∈ *G*
yp_{m,g,c_i,c_j,t_i,t_j}	Total number of tourists allocated to a transport service carried out by the *m-th* mode of transport at time instant *ti* at the node *ci* to reach the node *cj*, with *ci, cj* ∈ *N*, *m* ∈ *M*, *ti* , *ti* ∈ *T*, *g* ∈ *G*
$x_{c,t}$	Number of visiting tourists at the node *ci* at time instant *ti*, *ci* ∈ *N*, *ti* ∈ *T*
$STOCK_{c,t}$	Percentage of occupied effective carrying capacity $ECCci$, at the node *ci* at time instant *ti*, *ci* ∈ *N*, *ti* ∈ *T*
$t_{g,c}$	Optimal visiting duration of *g-th* GT at the *c-th* node, *g* ∈ *G*, *c* ∈ *N*
t_g^{end}	Optimal end time of the tour for each *g-th* GT, *g* ∈ *G*

3.4.2 Optimal TEN Based TTDP Model

The multi-objective function of the model considers different aspects of the TTDP problem. It considers the optimization of the tourist satisfaction, the reduction of the maximum available occupancy of the touristic sites to preserve the area from overcrowding, and the minimization of the visit for each group.

a. Objective functions

$$OB_1 = \min \sum_{c,t} STOCK_{c_i,t_i} . (O_{t+1} - O_t)$$

$$OB_2 = \min \sum_{g,c} w_g \cdot \left(\hat{t}_{g,c} - t_{g,c}\right)^2$$

$$OB_3 = \sum_{g} t_g^{end}$$

$$Min\ \alpha \cdot OB_1 + \beta \cdot OB_2 + \gamma \cdot OB_3 \quad \textit{Equation 7}$$

Where α, β, and γ are weight parameters that implement the preference factors that identify the relative importance of objectives.

The OB_1 objective implements a min-max approach by minimizing the maximum value of tourists allocated to each visited location during the overall time horizon in order to prevent massive touristic arrivals.

The second objective OB_2 aims at minimizing the square deviation of the time spent by the GTs to compute their visiting tours in respect to the planned ones.

The third objective OB_3 minimizes the ending time of the tour for each GT in order to guarantee that the tourists cover the path at minimum cost in the network in terms of travel duration.

b. Constraints

$x_{c_i,t_i} = \sum_{g} y_{1,g,c_i,c_j,t_i,t_{i+1}} \cdot w_g$	$c_i = 2, \dots, N-1$ $t_i = 1, \dots, T-1$	*Equation 8*
$\frac{x_{c_i,t_i}}{ECC_{c_i}} \leq STOCK_{c_i,t_i}$	$c_i = 2, \dots, N-1$ $t_i = 1, \dots, T-1$	*Equation 9*

$yp_{m,c_i,c_j,t_i,t_j} = \sum_g y_{m,g,c_i,c_j,t_i,t_j} \cdot w_g$	$m = 1, \dots, M$ $c_{i,}c_j = 2, \dots, N-1$ $t_i t_j = 2, \dots, T-1$	*Equation 10*
$yp_{m,c_i,c_j,t_i,t_j} \leq CAP_m$	$m = 1,..,M$ $c_i, c_j = 2,..,N-1$ $t_i, t_j = 2,..,T-1$	*Equation 11*
$y_{m,g,c_i,c_j,t_i,t_j} \leq d_{m,c_i,t_i,c_j,t_j}$	$g = 1,..,G$ $m = 1,..,M$ $c_i, c_j = 1,..,N$ $t_i, t_j = 1,..,T-1$	*Equation 12*
$t_{g,c_i} = \sum_{m,c_i,t_i,t_j} \left[O_{t_j} - O_{t_i}\right] y_{m,g,c_i,c_i,t_i,t_j}$	$g = 1,..,G$ $c_i = 2,..,N-1$	*Equation 13*
$\sum_{m,c_i \neq c_j,t_i,t_j} y_{m,g,c_i,c_j,t_i,t_j} \leq 1$	$g = 1,..,G$ $c_j = 2,..,C-1$	*Equation 14*
$\sum_{m,c_i,t_i<t_j} y_{m,g,c_i,c_j,t_i,t_j} = \sum_{m,c_h,t_h>t_j} y_{m,g,c_j,c_h,t_j,t_h}$	$g = 1,..,G$ $c_j = 2,..,N-1$ $t_j = 1,..,T$	*Equation 15*
$\sum_{m,c_j,t_i,t_j} y_{m,g,1,c_j,t_i,t_j} = 1$	$g = 1,..,G$	*Equation 16*
$\sum_{m,c_i,t_i,t_j} y_{m,g,c_i,\mathrm{N},t_i,t_j} = 1$	$g = 1,..,G$	*Equation 17*
$\sum_{m,c_i,c_j,t_i,t_j} y_{m,g,c_i,c_j,t_i,t_j} = 0$	$g = 1,..,G$ $t_i < Start_g$	*Equation 18*
$\sum_m y_{m,g,c_i,c_j,t_i,t_j} \,.\, O_{t_j} < t_g^{end}$	$g = 1,..,G$ $c_i, c_j = 1,..,N$ $t_j, t_j = 1..,T$	*Equation 19*

By Equation 8, the number of tourists belonging to the GTs, which visit each node in each time interval, is computed. The TEN is built considering that the stays in each location are implemented by the holding arcs which allow to transit, on the same node, for more than one-time interval. In the proposed model, the transport services given by the first transport mode ($m = 1$), by walking, are realized by the transiting on the holding arcs. Equation 9 implement the min-max decision making which implies minimizing the possible worst scenario in which the ECC_{c_i} is total occupied in each node c_i. The occupancy threshold, which varies between 0 and 1, is identified by the variable $STOCK_{c_i,t_i}$ which is limited by the ratio between the actual number of tourists present in the location in each time interval and the maximum available capacity ECC_{c_i}. By Equation 9 and by minimizing the variable $STOCK_{c_i,t_i}$ in OB_1, it is guaranteed the minimization of the maximum value of occupancy of ECC_{c_i}.

Equation 10 computes, for each transport service, the number of tourists allocated to the transport resources. Equation 11 verifies that the threshold of the maximum capacity of each transport resource is respected. Equation 12 guarantees that the GTs only access to existing arcs and so to available transport services. Equation 13 defines, for each GT, the visit time of each node.

By Equation 14, the model constraints the GT to visit each node only once. Equation 15 realizes the flow conservation at each node of the TEN in each time interval. Equation 16 and Equation 17 manage the touristic flow in the specific case of source and sink nodes. In Equation 18, the model guarantees that each GT cannot start its tour before its planned arrival time in the source node. Equation 19 deals with minimizing the total travel time spent by each GT in the network.

c. Problem complexity

The problem is quadratic in the cost function, with linear constraints. However, the large amount of binary variables makes the problem complexity NP-hard, as solved by classic mathematical programming techniques (e.g. branch and bound). On the other hand, it is worthwhile to observe that in typical instances of the problem just few TEN nodes are linked together. In addition, the application is at the planning level, so with no strict requirements on its computation. So, the optimal solution can be found in reasonable and feasible time for small problems as the one proposed here in the case study.

3.5 Heuristic Approach for TTDP on TEN

There is some research in the literature in which the heuristic approach to solve a TTDP problem is studied to improve tourists' travel experiences. Recommendations and personalized routes are planned for tourists considering aesthetic fatigue and variable sightseeing value [91].

To offer a tailored tourist route, in [92] a random simulation-based hybrid heuristic algorithm (RS-H2A) is proposed to design a personalized one-day route in a time-dependent stochastic environment.

In [93], PoIs that match tourist preferences are selected, taking into account a multitude of parameters and constraints while respecting the time available for sightseeing in a daily basis and integrating public transportation to travel between PoIs. The heuristic in this study takes into account time dependency in calculating travel times between POIs and make no assumption on periodic service schedules.

Apart from transportation, the planned route for tourists can include accommodation for urban tourists for several days. A two-level heuristic approach is proposed in [94], which embeds genetic algorithm, variable neighborhood search, and differential evolution algorithm into the structure of memetic algorithm.

To evaluate the proposed optimal model, a heuristic approach to solve a TTDP has been introduced.

3.5.1 Heuristic Algorithm

The heuristic algorithm aims at defining, for each group of tourists, the best path to visit the planned touristic locations respecting the planned visiting time and favouring the tour on the nodes at minimum ECC.

The algorithm processes each group serially. Let LG the list of the GTs according to decreasing $\widehat{TD}_g$. The first g in LG, the group which has the maximum value of total duration of the planned visits, is the first which accesses on the TEN Z. The motivation that is at the basis of this heuristic is that longer stays are more difficult to be assigned to satisfy the objective. In this respect, the algorithm can be brought back to the well-known first-fit decreasing algorithm used in bin packing problems [95].

The first group g consecutively visits the locations c_i according to the decrescent value of $\hat{t}_{g,c_i}$.

The following groups, extracting consecutively from LG explore the TEN Z visiting the location which has the lower value of $STOCK_{c,t}$.

Algorithm

Input: TEN $Z = (N^T, A^T)$, w_g, $Start_g$, d_{m,c_i,t_i,c_j,t_j}, ECC_c, CAP_m, $\hat{t}_{g,c}$, $\widehat{TD}_g$;

Output: determine the path for each g in Z at minimum cost

Step 0. *Initialization*

Let LG the list of the GTs according to decrescent $\widehat{TD}_g$.

Set the first group in LG as current group g.

For each node in N^T, set the occupancy $STOCK_{c,t} \quad \forall t, \forall c$

For each arc in A^T, set the transport service capacity $yp_{m,c_i,c_j,t_i,t_j} = CAP_m, \forall t, \forall c, \forall m$

$t_{curr} = 1$

Step 1. *Process the first group* g *in* LG

-Let LN_g the list of the nodes $c_i \in N$, to be visited according to the decrescent value of $\hat{t}_{g,c_i}$ for the current group g.

-Let n_{curr} the first node in LN_g

Substep 1.1. Check initial time of the visit

If $t_{curr} < Start_g$

$t_{curr} = t_{curr} + 1$

Else

Substep 1.2. Visit the node

WHILE $LN_g = \emptyset$

WHILE $t_{g,n_{curr}} < \hat{t}_{g,n_{curr}}$

Update the visiting time

$t_{g,n_{curr}} = t_{g,n_{curr}} + (O_{t_{curr}} - O_{t_{curr-1}})$

Update the occupancy of the current node

$STOCK_{n_{curr},t_{curr}} = \frac{(STOCK_{n_{curr},t_{curr}} + w_g)}{ECC_{n_{curr}}}$

$t_{curr} = t_{curr} + 1$

END

$LN_g = LN_g - \{n_{curr}\}$

Substep 1.3. Move in the next node.

Extract next node c_j from LN_g

IF $d_{m,\mathrm{n_{curr}},\mathrm{t_{curr}},c_j,\mathrm{t_{curr+1}}} == 0\ \forall m \epsilon M,$

/* any service transport exists*/

$t_{curr} = t_{curr} + 1$

Update the visiting time

$t_{g,n_{curr}} = t_{g,n_{curr}} + (O_{t_{curr}+1} - O_{t_{curr}})$

Update the occupancy of the current node

$STOCK_{n_{curr},t_{curr}} = \frac{(STOCK_{n_{curr},t_{curr}} + w_g)}{ECC_{n_{curr}}}$

ELSE

Among the service transports available from the n_{curr} at t_{curr} to the node $c_j \in LN_g$, at t_{curr+1}

IF $yp_{m,n_{curr},c_j,t_{curr},t_{curr}+1} + w_g < CAP_m$

/*the number of persons in the group do not exceed the vehicle capacity*/

Update the occupancy of the current node

$STOCK_{n_{curr},t_{curr}} = \frac{(STOCK_{n_{curr},t_{curr}} + w_g)}{ECC_{n_{curr}}}$Update

Update the occupancy of the used mean of transport

$$yp_{m,n_{curr},c_j,t_{curr},t_{curr}+1} = yp_{m,n_{curr},c_j,t_{curr},t_{curr}+1} + w_g$$

END

Go to Substep 1.2

$LG = LG - \{g\}$

Step 2. *Process the next groups* in *LG*

Let the current group *g* the next group extracting from *LG*

While $LG = \emptyset$

Substep 2.1. Check initial time of the visit

$t_{curr} = 1$

$n_{curr} = 1$

IF $t_{curr} < Start_g$

$t_{curr} = t_{curr} + 1$

ELSE

Substep 2.2. Determine the next node to be visited

WHILE $LN_g = \emptyset$

$n_{curr}, t_{curr} = \boldsymbol{NextNode\ (t_{curr}, n_{curr}, d_{m,n_{curr},t_{curr},c_j,t_{curr+1}}, LN_g)}$

Substep 2.3 Visit the node

IF $t_{g,n_{curr}} < \hat{t}_{g,n_{curr}}$

Update the visiting time

$t_{g,n_{curr}} = t_{g,n_{curr}} + (O_{t_{curr}+1} - O_{t_{curr}})$

Update the occupancy of the current node

$STOCK_{n_{curr},t_{curr}} = \frac{(STOCK_{n_{curr},t_{curr}} + w_g)}{ECC_{n_{curr}}}$

$t_{curr} = t_{curr} + 1$

$LN_g = LN_g - \{n_{curr}\}$

ELSE

Go to *Substep 2.2*

END

$LG = LG - \{g\}$

Go to step 2

END WHILE

Procedure 1 : $\boldsymbol{NextNode\ (t_{curr}, n_{curr}, d_{m,n_{curr},t_{curr},c_j,t_{curr+1}}, LN_g)}$

Output: next node to be visited at $\mathrm{t_{curr}}$+1

/If any service transport exists from the current node to another node $\in LN_g$, between $\mathrm{t_{curr}}$ and $\mathrm{t_{curr}} + 1$, the comparison between the square deviation of the visiting time have to be applied in the previous and next time intervals at the current node/

IF $d_{m,\mathrm{n_{curr}},\mathrm{t_{curr}},c_j,\mathrm{t_{curr+1}}} == 0\ \forall m \epsilon\ M,$

Then

IF $\left(t_{g,n_{curr}}^{tcurr-1} - \hat{t}_{g,n_{curr}}\right)^2 > \left(t_{g,n_{curr}}^{tcurr+1} - \hat{t}_{g,n_{curr}}\right)^2$

$\mathrm{t_{curr}} = \mathrm{t_{curr}} + 1$

Update the visiting time

$t_{g,n_{curr}} = t_{g,n_{curr}} + (O_{t_{curr+1}} - O_{t_{curr}})$

Update the occupancy of the current node

$$STOCK_{n_{curr},t_{curr+1}} = \frac{(STOCK_{n_{curr},t_{curr}+1} + w_g)}{ECC_{n_{curr}}}$$

Else

Update the visiting time

$t_{g,n_{curr}} = t_{g,n_{curr}} - (O_{t_{curr}} - O_{t_{curr-1}})$

Update the occupancy of the current node

$$STOCK_{n_{curr},t_{curr}} = \frac{\left(STOCK_{n_{curr},t_{curr}} - w_g\right)}{ECC_{n_{curr}}}$$

$\mathrm{t_{curr}} = \mathrm{t_{curr}} - 1$

ELSE

Among the service transports available from the n_{curr} at t_{curr} to the node $c_j \in LN_g$, at t_{curr+1}

If $yp_{m,n_{curr},c_j,t_{curr},t_{curr}+1} + w_g < CAP_m$

Let the next node to be visited the c_j with the minimum $STOCK_{n_{curr},t_{curr}+1}$

Update the capacity of transport service

$yp_{m,n_{curr},c_j,t_{curr},t_{curr}+1} = yp_{m,n_{curr},c_j,t_{curr},t_{curr}+1} + w_g$

End

RETURN next node ($\boldsymbol{n_{curr} = c_j}$**,** $\boldsymbol{t_{curr}}$**)**

3.5.2 Heuristic Algorithm test

To explain the application of the proposed heuristic approach, the following example has been introduced. Given three GTs and three locations to be visited by a TEN Z which include two means of transport services.

The table below, Table 1, contains the data related to the GTs, the number of tourists which each group consists of, the starting time of the tours, and the planned duration of the visits at each location.

GT	w_g	$Start_g$
GT1	15	1
GT2	10	1
GT3	11	2

$\hat{t}_{g,c}$	c_1	c_2	c_3	**Total duration of the planned tours** $\widehat{TD}_g$ **[min]**
GT1	12	15	6	33
GT2	12	11	14	37
GT3	10	16	6	32

	c_1	c_2	c_3
ECC	35	30	40

Table 1. GT Data for the Heuristic Test

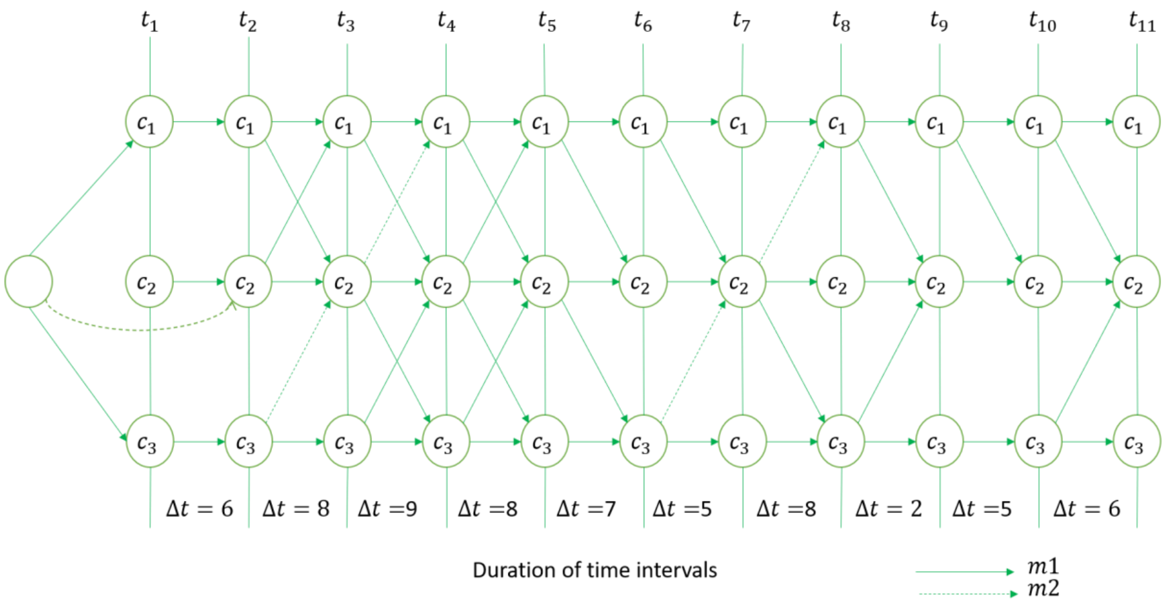


Figure 2. Proposed TEN to test heuristic approach

Let LG the following list of groups.

$\boldsymbol{LG}$	$\widehat{\boldsymbol{TD}}_{\boldsymbol{g}}$
GT2	37
GT1	33
GT3	32

For the heuristic approach, the following notations are introduced:

- let $ht_{g,c}^{t_i}$ the visiting duration at the node c, at the time instant t_i for the touristic group g;
- let $ht_{g,c}$ the total visiting duration at the node c for the touristic group g generating by the heuristic approach.

For the first group GT2, the sequence of nodes to be visited is c_3, c_1, c_2. It starts its tour in the network at time t_1 at node c_3. The group GT2 remains at the current node until t_3 with a visiting time $t_{2,c_3} = 14$. At time t_3, GT2 leaves node c_3 and moves in the next node covering the available arc in the network. Verifying that the number of persons of the group does not exceed the capacity of the available means of transport, at time t_5, GT2 reaches the node c_1. It remains at the node c_1 until time t_7 with a visiting time $t_{2,1} = 12$. Unfortunately, at the current node, no transport service is available to reach other nodes.

The GT2 may move horizontally in the network, in the next or in the previous time instants for the current node, respectively at node c_{1,t_6} or c_{1,t_8}. To evaluate the best solution, the divergence between the visiting times in the two options is compared with the planned one.

$$\left(ht_{2,1}^{t_6} - \hat{t}_{2,1}\right)^2 = (7 - 12)^2 = 25$$

$$\left(ht_{2,1}^{t_8} - \hat{t}_{2,1}\right)^2 = (20 - 12)^2 = 64$$

To minimize the divergence in respect to planned visiting time, the GT comes back at the node c_{1,t_6}. At this node, the GT2 can move toward node c which is visited until time t_{10}.

The next group in LG is GT1 which may start its tour at the first-time interval. The nodes which may be reached by the origin of the network are c_1 or c_3. At the current time instant, the value $STOCK_{c_1,t_1} < STOCK_{c_3,t_1}$ so the GT1 starts its tour at the node c_1 covering the path which has the lower impact on the location occupancy. GT1 stays at the current node until t_3 and then it moves on to the next node. Just the node c_2 is connected by an arc which capability allows the transit. The node c_{2,t_4} becomes the next node to be visited. GT1 stays at the node c_2 until t_6 reaching its desired visiting time $t_{1,2} = \hat{t}_{1,2} = 15$. At node c_2, for the current time interval, no transport service is available. Also, in this case, the divergence between the visiting time and planned one are compared for the previous and next time instant.

$$\left(ht_{1,2}^{t_5} - \hat{t}_{1,2}\right)^2 = (8 - 15)^2 = 49$$
$$\left(ht_{1,2}^{t_7} - \hat{t}_{1,2}\right)^2 = (20 - 15)^2 = 25$$

In this case, the GT1 stays at the current node until t_7 then it moves in the last node to be visited c_3.

Finally, the GT3 has been processed. Its tour may be starting at time t_2 when only $STOCK_{c_2,t_2}$ is equal to zero. Thus, GT3 reaches firstly the node c_2 by the mean of transport $m2$ and visits the node for 17 units of time. At the instant t_4, the service transport is available to reach both nodes c_1 and c_3 and it results $STOCK_{c_3,t_5} < STOCK_{c_1,t_5}$. The node c_3 has been visited by GT3 for 7 units of time. Finally, the current group reaches and visits the node c_1 transiting on the node c_2.

In the following figure, Figure 3, the paths of the three GTs are displayed.

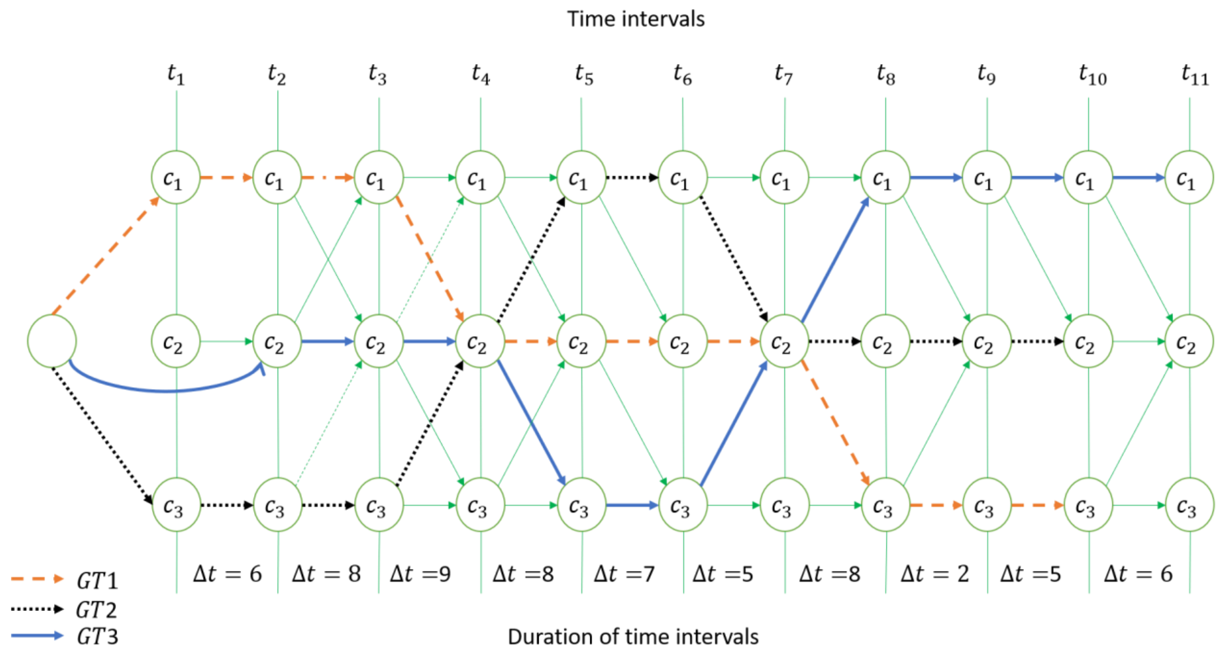


Figure 3. Proposed paths resulting from the heuristic approach.

In the following tables, we can see the occupancy of the locations in the test (Table 2) and the total duration of the tours (Table 3).

$STOCK_{c,t}$	c_1	c_2	c_3
t_1	42,90%	0,00%	25,00%
t_2	42,90%	36,70%	25,00%
t_3	42,90%	36,70%	25,00%
t_4	0,00%	86,70%	0,00%
t_5	28,60%	50,00%	27,50%
t_6	28,60%	50,00%	27,50%
t_7	0,00%	83,30%	0,00%
t_8	31,40%	33,30%	37,50%
t_9	31,40%	33,30%	37,50%
t_{10}	31,40%	33,30%	37,50%
t_{11}	31,40%	0,00%	0,00%

Table 2. Occupancy of the locations in the heuristic test

$t^h_{g,c}$	c_1	c_2	c_3	**Total duration of the generated tours [min]**	$\frac{\sum_c ht_{g,c}}{\sum_c \hat{t}_{g,c}} 100$
G1	7	15	14	36	97%
G2	14	20	7	41	124%
G3	13	17	7	37	116%

Table 3. Total duration $ht_{g,c}$ of the tours generated by the heuristic test

3.6 Case study

The proposed models have been tested on a real case study, which focused on the management of the massive touristic arrivals in the Cinque Terre National Park (
Figure 4), in Liguria region, in Italy. Cinque Terre National Park consists of five attractive locations namely Monterosso, Vernazza, Corniglia, Manarola and Riomaggiore. These locations are connected by transport services, train or ferry boat, which consecutively visit them starting the trips from the locations at the outermost of the area: Monterosso or Riomaggiore.

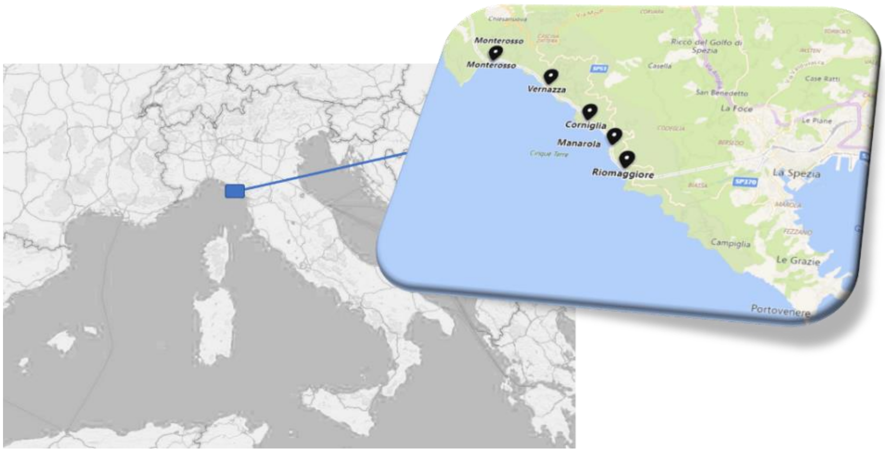


Figure 4. Cinque Terre topography

Cinque Terre, recognized in 1997 by the UNESCO Mankind’s World Heritage, is today a National Park and Protected Marine Area with the aim of protecting this great cultural heritage and natural environment. During the last decade, the number of tourists visiting the Cinque Terre area has rapidly increased, verging unsustainable, especially during the summer months.

Recently, Cinque Terre is becoming the target of the tour operators which organize quick getaway of large groups of tourists coming from the cruise ships that stop in La Spezia or Genoa.

Similarly, touristic journeys are organized to arrive in Cinque Terre from other adjacent locations in the neighbouring regions. In each day, masses of tourists transfer into the city from the rail stations or the local port and walk down the main streets of these small villages where only few hundreds of inhabitants live.

Cinque Terre cannot sustain this large crowd of tourists; thus, the five municipalities are organizing some smart measures to limit the number of persons arriving, thus protecting those environmental fragile zones.

The first step to implement an STD may be to identify optimal strategies to manage the tourist massive arrival. The proposed TEN based TTDP model aims at defining the optimal tour planning for GTs which have planned a short stay to visit Cinque Terre in a day respecting the ECC of locations and maximizing the satisfaction of tourists who can enjoy their visits.

According to the topography of the area, the network has five nodes identified by the five attractive locations (Monterosso, Vernazza, Corniglia, Manarola, and Riomaggiore).

In 2018, it has been estimated that in the next years Cinque Terre will host more than 2 million tourists. As an example, Riomaggiore registered the presence of 92 tourists per inhabitants in 2018 [96].

3.6.1 ECC definition for the locations in Cinque Terre

To apply the proposed methodology and to compute ECC, a Geographic Information Systems analysis has been a carry out to quantify the areas of the main POIs in the selected municipalities. The areas used to test the proposed methodologies only consist of the sites which are considered at risk and which suffer from significant overcrowd. From vector maps provided by Regione Liguria [97], the touristic areas of each municipality have been computed.

The value of the A_u is set to 5 m2 for tourist [90]. The values of R_f corresponds to the daily number of visits, considering that the touristic arrivals are usually planning by travel agencies in a range from 09:00 am to 05:00 pm. The average time of duration for visit has been assessed in 3 hours, thus the parameter is $R_f = {}^{8}/_{3} = 2{,}66$.

Location	Touristic Area of the PoIs in each municipality				
	Area [m]	Area/Au	PCC per day	RCC per day	ECC per day
Monterosso	5451	1090,20	2907,20	2907,20	2035,04
Vernazza	5118	1023,60	2729,60	2729,60	1910,72
Corniglia	5154	1030,80	2748,80	2748,80	1924,16
Manarola	4456	891,20	2376,53	2376,53	1663,57
Riomaggiore	4636	927,20	2472,53	2472,53	1730,77

Table 4. ECC computation

The correction factors in the proposed case study have been set to 1 if external and meteorological conditions do not affect significantly the PCC values. On the contrary, due to the problematic management of the territories and the negative aspects related to the complex geographical conformation of the area and its accesses, mc is considered equal to 0,7. Table 4 resumes the data associated with the parameters used to compute ECC by Equation 6.

3.6.2 Case study input data

The case study considers managing the TTDP for 8 different GTs in a time horizon of 6 hours starting from 9 am. The GTs can reach the locations of Cinque Terre by two kinds of transport services, by train or by boat.

The trains stop in each of the five locations which are visited consecutively. In the same way, also boat services are available, but they do not stop at the location of Corniglia. Boat service from Monterosso to Riomaggiore is about 45 minutes long. The train services last about 18-20 minutes to visit the five locations. The timetables for the transport services are available on the Cinque Terre website.

GT	w_g	$Start_g$
GT1	40	10:00
GT2	30	9:00

GT3	80	9:00
GT4	40	10:00
GT5	100	11:00
GT6	60	11:00
GT7	35	10:00
GT8	52	9:00

Table 5. GT Data of the First Case Study

The TEN is extended for 130 time-intervals and it contains more than 1500 arcs.

The capacity associated to the transport resources, train and boat, has been set to 1000 and 350 travellers respectively.

$\hat{t}_{g,c}$	**Monterosso**	**Vernazza**	**Corniglia**	**Manarola**	**Riomaggiore**	**Total duration of the planned tours $\widehat{TD}_g$ [min]**
GT1	55	40	40	50	0	185
GT2	40	40	45	45	60	230
GT3	55	45	50	55	55	260
GT4	55	40	50	0	0	145
GT5	55	30	0	45	0	130
GT6	0	50	0	45	50	145
GT7	0	0	0	60	55	115
GT8	30	45	35	45	45	200

Table 6. Planned duration of the visit for each GT

The number of tourists of each group (w_g) and the starting time ($Start_g$) of visiting the first municipality are a priori known for each GT. See Table 5.

The planned duration of the visits $\widehat{TD}_g = \sum_c \hat{t}_{g,c} \quad \forall g \in G$ for each GT in each node are shown in Table 6.

3.7 Results

This section reports the results obtained applying the model and the heuristic approach to the proposed case study.

The proposed optimal TEN based TTDP model has been implemented by CPLEX software. The results provide optimal TTDP for the selected GTs to reach their destinations. The resulted paths in TEN represent the optimal tour for each GTs by the minimization of the square divergence between the planned and the optimal visiting duration of each GT minimizing the maximum number of tourists as well in each municipality for time interval.

Arriving and departure time	Monterosso	Vernazza	Corniglia	Manarola	Riomaggiore
GT1	10.10-11.05	11.09-11.57	12.01-12.38	12.42-13.32	
GT2	9.23-10.10	10.14-11.09	11.19-12.01	12.03-12.54	12.57-13.57
GT3	9.22-10.10	10.14-11.09	11.19-12.01	12.03-12.54	12.57-13.57
GT4	10.10-11.05	11.09-11.57	12.01-12.50		
GT5	12.41 - 13.39	12.06-12.36		11.06-11.49	
GT6		11.09-11.57		12.03-12.42	12.45-13.35
GT7				12.29-13.27	11.33-12.26
GT8	13.20 - 13.48	12.14-13.03	11.39-12.09	11.06-11.36	10.14-11.03

Table 7. Arriving and departure time of each GT for the TEN based TTDP model

Table 7 shows the arrival and departure time for the optimal tour of each GT in each municipality.

It is possible to observe that the model respects the planning in terms of the visited locations: the GTs visit the expected destinations in respect to the planned starting time.

$t_{g,c}$	Monterosso	Vernazza	Corniglia	Manarola	Riomaggiore	Optimal duration of the visits TD_g [min]	$\frac{\sum_c t_{g,c}}{\sum_c \hat{t}_{g,c}} 100$
GT1	55	48	37	50	0	190	103%
GT2	47	55	42	51	60	255	111%
GT3	48	55	42	51	60	256	98%
GT4	55	48	49	0	0	152	105%
GT5	58	30	0	43	0	131	101%
GT6	0	48	0	39	50	137	94%
GT7	0	0	0	58	53	111	97%
GT8	28	49	30	30	49	186	93%

Table 8. Optimal Duration of the visits for each GT

Table 8 shows the optimal duration of the visits of each GT computed as $TD_g = \sum_c t_{g,c}$. By the obtained results, the comparison between the planned and optimal duration of the visits reveals that the GT3, GT6, GT7, and GT8 stay in the nodes a total time lightly inferior to the planned ones, and the divergence between durations, however, is at maximum 7% of the total.

The GT1, GT2, GT4, and GT5, on the other hand, spend more time in respect to the planned ones. In any case, the divergence in time is assessed to 11% which represents, in the case of GT2, 25 minutes.

Regarding the transport modes, due to the more frequent services, the train is the most common resource used by the GTs.

The following tables (Table 9 and Table 10) show the results obtain, on the contrary, from the heuristic approach application.

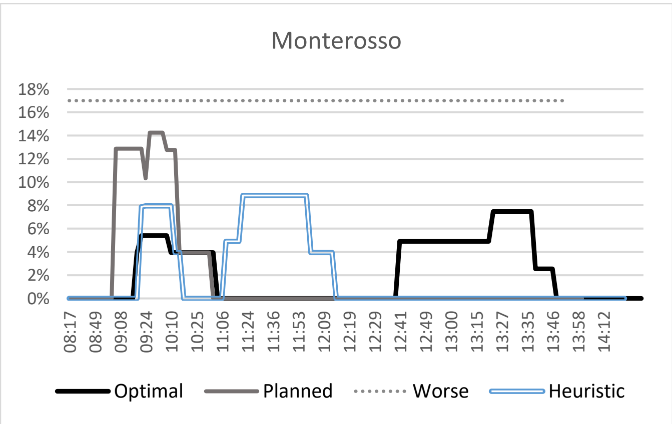
Arriving and departure time	Monterosso	Vernazza	Corniglia	Manarola	Riomaggiore
GT1	11.19-12.14	12.28-13.09	13.20-14.00	14.24-15.14	
GT2	09.23-10.10	10.14-11.03	11.19-12.05	12.24-13.09	13.27-14.27
GT3	9.22-11.05	11.09-11.57	12.01-13.20	13.24-14.24	14.27-15.24
GT4	11.19-12.14	12.28-13.09	13.20-14.12		
GT5	11.06-11.57	12.06-12.54		13.50-14.35	
GT6		14.54-15.44		12.06-12.54	11.06-11.57
GT7				12.29-13.30	11.19-12.14
GT8	09.23-10.10	10.14-11.03	11.19-11.57	12.03-12.48	12.57-13.42

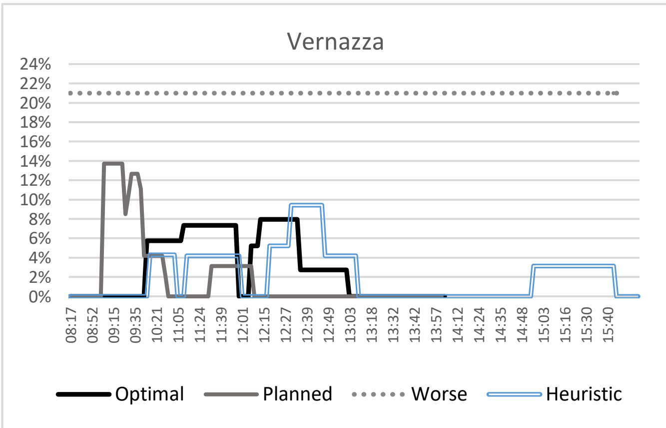
Table 9. Arriving and departure time of each GT by the Heuristic Approach

$ht_{g,c}$	**Monterosso**	**Vernazza**	**Corniglia**	**Manarola**	**Riomaggiore**	**Optimal duration of the visits TD_g [min]**	$\frac{\sum_c ht_{g,c}}{\sum_c \hat{t}_{g,c}} 100$
GT1	55	41	40	50		186	101%
GT2	47	49	46	45	60	247	107%
GT3	103	48	79	60	57	347	133%
GT4	55	41	40			136	94%
GT5	51	48		45		144	111%
GT6		50		48	51	149	103%
GT7				61	55	116	101%
GT8	47	49	38	45	45	224	112%

Table 10. Duration of the visits for each GT by the Heuristic Approach

In Figure 5, the black line shows the percentages of ECC occupation for each municipality during the time horizon for the optimal tours generating by the TEN based TTDP model.





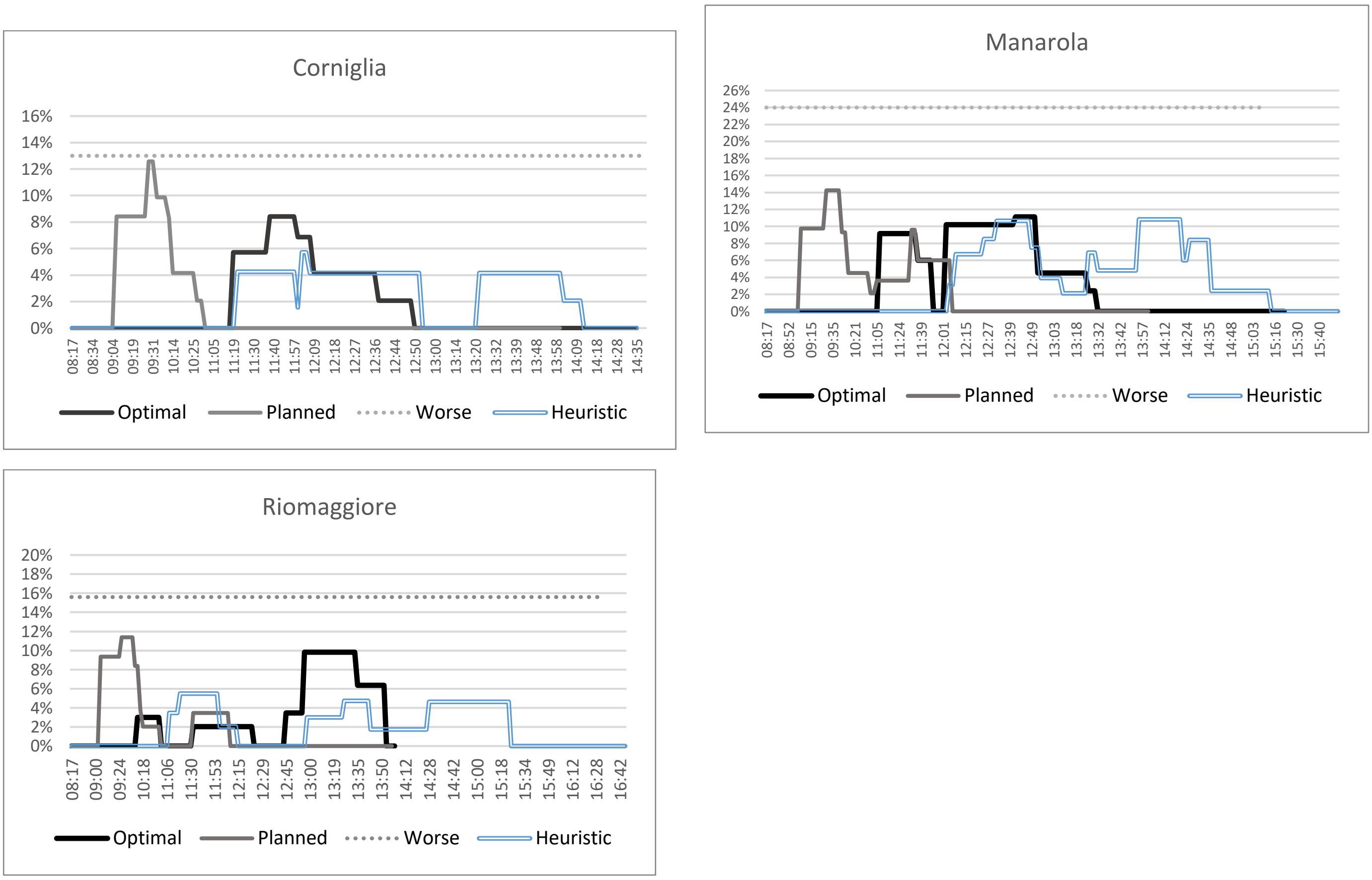


Figure 5. Occupancy of ECC in each municipality for the different solving approaches

In the optimal solutions, the most visited location, in the same time interval, is Manarola, with 12% of occupancy. This is due to the geographical conformation of the case study area which forces to visit the destination consecutively.

The grey line defines the occupancy of EEC for each location according to the planned tours. The tours start according to the GTs time arrivals and to their related duration. The planned scheduling of tours starts at 9.00 a.m and it stops 3 hours and 40 minutes later at maximum.

The dotted grey line represents the worst case. It is assumed that the GTs' start their tour contemporarily and the straight line represents the maximum percentage of occupancy in each location considering the contemporary presence of the 8 GTs in each location. The optimal percentage of occupancy obtained by applying the model is always less than the values found for the planned ones.

The double blue lines represent the solutions generating by the heuristic approach application. It is evident that also the heuristic approach aims at minimizing the impact of the massive touristic arrival, anyway when the peaks of occupancy are lower in respect to the optimal solutions, the total visiting times of the eight groups have significant increase. In the case of Riomaggiore municipality, the ECC occupancy in the heuristic solution is 2% lower than the optimal solution but the total duration of the visits gets worse of the 12%.

The heuristic algorithm provides paths that exceed the planned total visiting time.

The main important issue to be highlighted related to the optimal TEN based TTDP model is represented by the shifting of the tours for the GTs which have been postponed with respect to their planned arrival times without affecting the total duration of the visits in the selected locations. In the proposed optimal scheduling, the tours are planned in an extended time horizon in respect to the actual case. The GT8, which must visit all the five locations, as the GT2 and GT3, starts its tour leaving from the last node Riomaggiore, carrying out the tour from node 5 to 1. In this way, the small delay is due to the longer transit to reach the first visited location. However, this shifting deals with the minimization of the maximum occupancy of ECC in the destinations on the overall time horizon. Also, the heuristic approach proposes to start the visits of the GT6 and GT7 starting at node 5 toward node 1 to affect the same municipalities at the same time intervals.

Chapter 4. Train scheduling and rescheduling problem. Regional trains

4.1 Introduction

In recent years, the difficulty to offer a good quality service for passengers of European railway lines has increased. The rail transport users do not increase compared to other modes of transport but the delays and the unreliability of the timetable for arrival and departure times perceived by the passengers produce dissatisfaction in service.

Usually, passengers' demand on the network drives the rail operators' decision on the line planning to define the routes and the frequency of the trains.

In this chapter, the problem of scheduling and rescheduling are studied according to recent results obtained in [39].

In the proposed microscopic train scheduling and rescheduling models, integration of the optimization processes between trains and passenger flows is included. In the first model (TS1), the train scheduling problem has been solved to define the optimal timetable for a set of trains with the objective to minimize the travel time of passengers to reach their destination, outlining the related sequence of nodes and arcs of the network to be covered by each group of passengers.

Subsequently, a train rescheduling model (TR2) is applied on an optimal timetable (i.e., generated by TS1), which became infeasible due to unpredicted failures or disturbances introduced on the network. In this second approach, the objective is to restore the service quality by reducing the delays for trains and passengers.

The main contribution of this chapter is to implement railway scheduling and rescheduling problems by linear programming formulations introducing in the second approach the innovative concept to prioritize the train that can access the block section in case of conflicts. The possibility to associate a "priority value" for a selected set of trains has been inserted in the model. A train with higher priority can overcome other trains when it transits on interconnection to reduce its delay and to reach faster its destination.

4.2 Model formulation

In this section, the proposed scheduling and rescheduling models are introduced.

4.2.1 Description of the SOS network

A rail transportation network can be considered as several nodes linked to one another by a set of arcs. Anyway, besides the infrastructure network, the model consists also of elements that transit on the railway that are trains and passengers, and their relative journey information. Figure 6 displays the different components of the network.

– The Group of Passengers (GP), $W = \{1 \dots W\}$. For each GP, the origin ($Start^w$) and destination (End^w) nodes, and the related departure time (πw) at the origin node are a priori known. In addition, each GP has been considered as an indivisible group of persons.

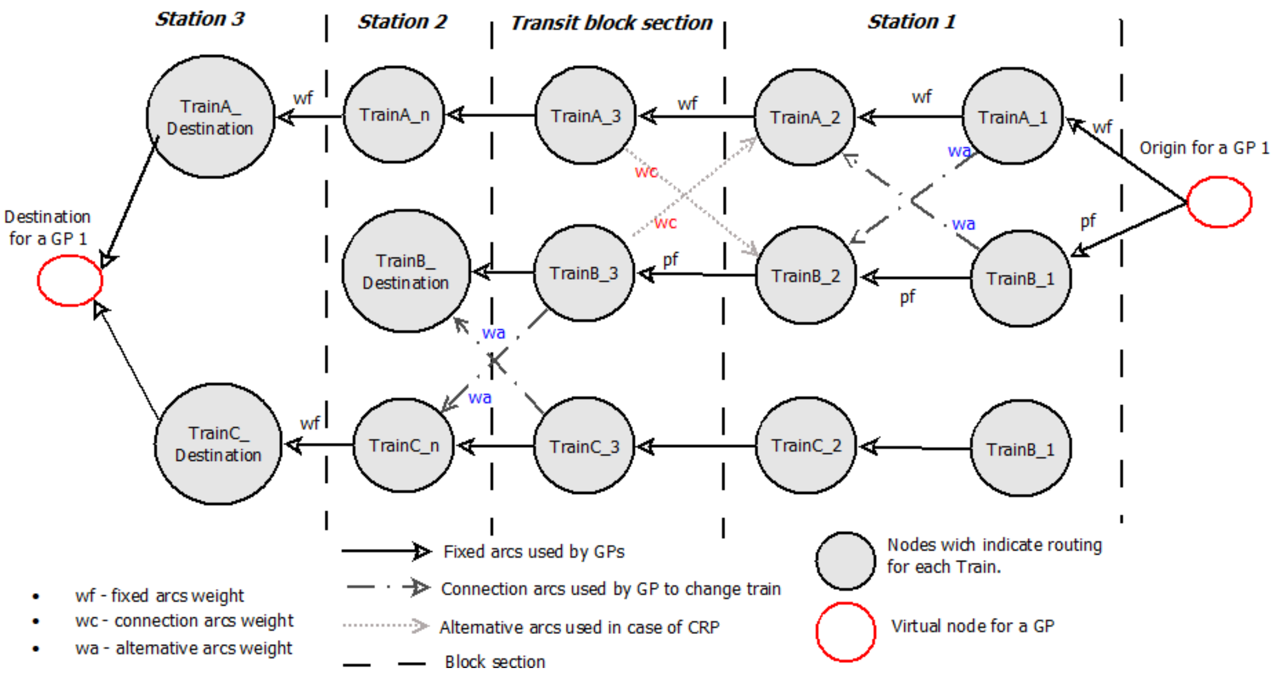


Figure 6. Main components of the scheduling problem

- Set of Nodes, $K = \{1 \dots K\}$. Each node belongs to a specific train and it represents a logistic operation in a certain section of the network. A couple of nodes connected by an arc might represent either existing stations or siding area where the train allows stopping on the railway network or transiting block sections. Each node has a related weight hi, which represents the starting time of a logistic operation at the node *i-th* $\in K$ (train arrival, or train departure if the node represents a station, or running time if the node represents a block section). Contextually, this weight value represents, at the same time, also the conclusion time of the logistic operation at the previous nodes of the train path.

- Set of arc$s$, $M = \{1 \dots M\}$. The arc represents links among nodes. The arcs can be classified as fixed arcs, connection arcs, or alternative arcs.

  - The fixed arc (FA), $F = \{1 \dots F\}$. It links a couple of nodes. The train can move from one node to another by transit on FA. A sequence of nodes and FAs represents the train routing and the sequence of logistic operation on the rail network.

  - The connection arc (CA), $C = \{1 \dots C\}$. It connects nodes that represent rail stations. It allows transferring the GP from a train to another during its trip in order to minimize the transit time toward its destination.

  - Couples of alternative arcs (AA), $AA = \{1 \dots A\}$. They exist to join couples of nodes that belong to two consecutive block sections. Each couple of AAs can assume alternatively different status: activated or deactivated. The AA is activated in case of CRP. If two or more trains arrive at the same block section, the activation of one AA provides one train with surpassing the others to enter into the next section.

In the proposed model, $M = \{F\} \cup \{C\} \cup \{A\}$. A specific weight is associated with each arc. For FAs, the weight means traversing or dwell time, for ACs represents transferring time for passengers while, for AAs, the weight might be considered as a difference in time between two trains in conflict on the origin nodes.

- The Virtual Nodes (VN). The virtual nodes do not represent any physical place, but they indicate only a connection to the virtual origin or destination of the GPs. Each GP is provided with two VNs connected to the nodes associated with the trains, which can be used respectively to start and finish their journey. The routing of those trains starts and stop, respectively, in the same station $Start^w$ and End^w of the GP.

4.2.2 Scheduling TS1 model

The first proposed train scheduling model (TS1) has the objective to minimize the time spent by the GPs on the rail network and reduce passengers' discomfort. It defines the optimal path through nodes and arcs for each GP from the assigned origin to the destination node.

The GP which starts their trip at the same origin node and arrives at the same destination node might use different trains in order to minimize the duration of their trip. It is assumed that trains have sufficient capacity to accommodate the assigned GPs.

Notation

$W = \{1 \dots W\}$	Sets of PGs
$K = \{1 \dots K\}$	Set of nodes
$F = \{(i,j) \dots\}$	Set of FAs
$A = \{(i,j),(k,l),\dots\}$	Set of AAs
$C = \{(i,j) \dots\}$	Set of CAs

Parameters

$Start^w$	The origin node for GP $w, w \in W$;
End^w	Destination node for GP $w, w \in W$;
wf_m	Weight on FAs, $m \in F$;
wc_m	Weight on CAs, $m \in C$;
wa_m	Weight on AAs, $m \in A$;
o_{im}	Binary parameter which assumes value 1 if node *i-th* is the origin of arc m, $m \in M$;
d_{im}	Binary parameter equal to 1 if node *i-th* is the destination of arc m, $m \in M$;
n_w	The number of passengers for GP $w, w \in W$;
π_w	Arrival time at origin node of GP $w, w \in W$;
z_{rm}	Binary parameter which indicates the presence of CRP for the couple of arcs *(r,m)* with $r, m \in A$

Decisional Variables

h_i	Starting time of a logistic operation at the node i, $i \in K$;
T_w	Arrival time of GP w at destination station, $w \in W$;

x_{rm}	Binary decision variable associated to the CRP solution: variable assumes value 1 if arc $m(r, m \in A)$ is selected to be covered to solve the conflict; o otherwise
q_f^w	Binary decision variable equal to 1 if arc f, $f \in F \cup C$; 0 otherwise

The objective function is the minimization of the time spent by all the GPs in the rail network.

$min \sum_{w=1}^{W} n_w \,(T_w - \pi_w)$		*Equation 20*
$h_j \geq h_i + (o_{if} d_{if} w f_f) - M \cdot (1 - o_{if} d_{if})$	$i, j \in K$ c	*Equation 21*
$h_i \geq h_j + (o_{jm} d_{im} a_m) - M \cdot (1 - o_{jm} d_{im} z_{rm}) - M \cdot (1 - o_{jm} d_{im} z_{rm} x_{rm})$	$i, j \in K$ $m, r \in A, m \neq r$	*Equation 22*
$h_k \geq h_j + (o_{jr} d_{kr} a_r) - M \cdot (1 - o_{jr} d_{kr} z_{rm}) - M \cdot (1 - o_{jr} d_{kr} z_{rm} x_{rm})$	$i, j, l \in K$ $m, r \in A, m \neq r$	*Equation 23*
$\sum_{i=1}^{K} \sum_{s=1}^{F \cup C} o_{start^w,s} d_{is} q_s^w = 1$	$w \in W$	*Equation 24*
$\sum_{i=1}^{K} \sum_{s=1}^{F \cup C} o_{i,s} d_{end^w,s} q_s^w = 1$	$w \in W$	*Equation 25*
$\sum_{r=1}^{F \cup C} d_{ir} q_r^w = \sum_{m=1}^{F \cup C} o_{im} q_m^w$	$i \in K,$ $i \neq Start^w$ $i \neq End^w$ $w \in W$	*Equation 26*
$h_j \geq \pi_w - M(1 - o_{start^w,s} d_{is} q_s^w)$	$i \in K$ $s \in F$ $w \in W$	*Equation 27*

$h_j \geq h_i + \left(o_{is} d_{js} w c_s\right) - M \cdot \left(1 - o_{is} d_{js}\right) - M \cdot \left(1 - o_{is} d_{js} q_s^w\right)$	$i, j \in K$ $s \in C$ $w \in W$	*Equation 28*
$T_w \geq h_i - M\left(1 - o_{i,s} d_{end^w,s} q_s^w\right)$	$i \in K$ $s \in F$ $w \in W$	*Equation 29*
$h_i \geq 0$	$i \in K$	*Equation 30*
$x_{rm}, q_r^w \in \{0,1\}$		*Equation 31*

In order to implement a linear programming formulation of the proposed TS1 problem, the constraints are linearized by introducing binary variables and Big-M method. Binary parameters o_{if} and d_{if} are used to assure that nodes *i-th* and *j-th* are connected by the same FA *f-th*. Thus, Equation 21 means that the arrival time of a train at node *j-th* has to be greater than the sum of the departure time on the previous node *i-th* and the traversing time to cover the arc which links the nodes.

By Equation 22 and Equation 23, the model tackles the CRP deciding which AC has to be activated to solve the conflict among trains.

Equation 24, Equation 25, and Equation 26 manage GPs' flows on the rail network. The binary parameter $o_{start^w,s}$ for GP *w-th* assumes value 1 if the VN associated to the origin of the path is the origin of arc s, with $s \in F \cup C$. Similarly, $d_{end^w,s}$ assumes value 1 if VN associated to the destination of the GP *w-th* is the destination of arc s, with $s \in F \cup C$.

Equation 24 and Equation 25 assure that the path of each GP starts at the origin and finishes at the destination predefined stations. Equation 26 represents the GPs flow conservation at the nodes.

Equation 27 focuses on passengers' transfer. The trains available to load GPs at the origin station must leave the node after the GPs arrival time. Finally, Equation 28 guarantees the feasibility of GP' transfer through the CAs: the departure time of the leaving train has to be greater than the arrival time of the GP' coming train.

Equation 29 defines the computation of the arrival time of the GP to the destination station.

Finally, Equation 30 and Equation 31 constrained the optimization variable values as positive and binary.

4.2.3 Rescheduling TR2 model

The TR2 model provides, based on the predefined optimal schedule (i.e., obtained by the TS1 model application), a new timetable adapted to manage the disturbances which affect the network. The TR2 model consists of the same notations and variables used in the TS1 model. Anyway, to implement the TR2 model, new parameters have been added to the TS1 model.

The $priority_i$ values indicate the priority level of a train at a node *i-th*, $i \in K$.

The following decisional variables are introduced.

- The variables $hTR2_i$ represent the optimal starting time of a logistic operation at the node *i-th*, $i \in K$ generated by the TR2 model.
- The variables $wfTR2_s$ are the new weight values associated to FAs, $f = \{1 \dots F\}$computed by the TR2 model.
- $delay_i$ indicates the delay time of a train at node *i-th*, $i \in K$.
- $advance_i$ indicates the advance time of a train at node *i-th*, $i \in K$.

In addition, the objective function has to be modified and new constraints have been added are described below.

$min \sum_{w=1}^{W} n_w \,(T_w - \pi_w) + \sum_{i=1}^{K} priority(i) \cdot delay(i) + \sum_{i=1}^{K} advance(i)$		Equation 32
$wfTR2_s \geq wf_s$	$s \in F$	Equation 33
$hTR2_i \geq h_i$	$i \in K$	Equation 34
$delay_i > hTR2_i - h_i$	$i \in K$	Equation 35
$advance_i > h_i - hTR2_i$	$i \in K$	Equation 36
$hTR2_i \geq 0$	$i \in K$	Equation 37

The TR2 model consists of the new objective (Equation 32) and it is subject to Equation 20 – Equation 31 and Equation 33 – Equation 37.

Anyway, in this second model, the variable h_i for the node *i-th*, $i \in K$ is assumed to be known and present the optimal starting time of a logistic operation at the node *i-th*, generated by solving previously a scheduling problem.

The objective of the TR2 model is to minimize the total time spent by passengers in the system, giving importance to the train with the highest priority and allowing the train in a delay to improve its timing performance, respecting the maximum speed limits for each of the trains.

Equation 33 imposes that the weight of FAs must be greater or equal to the predefined weights used in the TS1 model.

Equation 34 defines that the starting operational time on node *i-th* might be greater than or equal to the optimal predefined ones obtained by the scheduling model.

Equation 35 computes the values of delay at each node imposing it to be greater than the difference between the current optimal operational time and the predefined ones. In accordance, Equation 36 describes the advanced train time at each node as greater than the difference between the predefined operational time and the optimal ones. Equation 37 constraints the optimization variable values to be positive.

4.3 Case study

The presented use case focuses on a real case study located on the railway network in Genoa, Regional Capital of Liguria Region, in Italy.

The considered railway network consists of eight stations, as shown in
Figure 7. According to the topography of the chosen location, five stations (stations on the horizontal ax in the
Figure 7) are located on the Liguria coast, while three stations (stations in vertical in the
Figure 7) represent rail connection with the hinterland. Genova Piazza Principe Station represents the main important station in Genoa and in Liguria Region and it consists of significant daily traffic.

The train can move along horizontal and vertical guidelines.

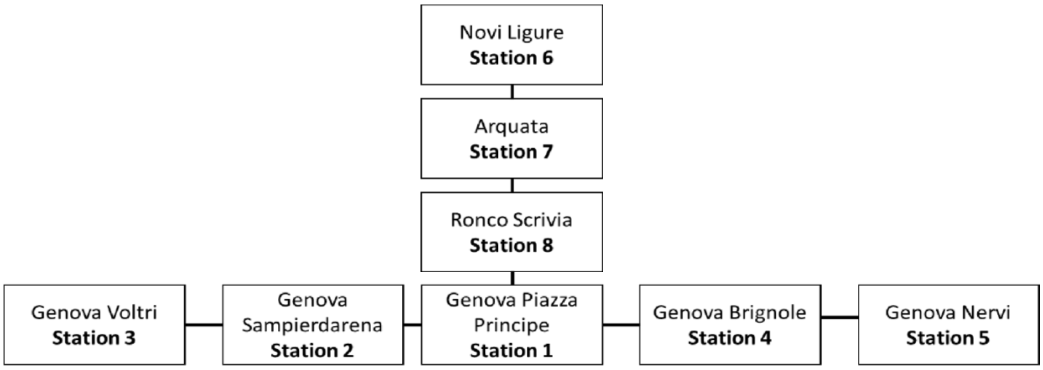


Figure 7. Genoa Network

The case study considers scheduling and rescheduling of 4 different trains. The timetable data of the selected trains have been provided by Ansaldo STS Group, the Italian company which manages railway signaling system on the main part of Italian railway network. Table 11 describes the characteristics of the trains in the case study.

	Train 1	**Train 2**	**Train 3**	**Train 4**
Origin station	Station 3	Station 5	Station 1	Station 6
Destination Station	Station 5	Station 3	Station 3	Station 3
Intermediate Station	Station 2 – 1 – 4	Station 4 – 1 – 2	Station 2	Station 7 – 8 – 1 – 2
Category	Regional train	Regional train	Intercity train	Regional train

Table 11. Characteristics of the trains

Train 1 and 2 represent high-traffic flow passenger trains with frequent stops on the railway. They run on the same railway sections but in opposite directions.

Train 1 has its origin at Genova Voltri station and destination in Genova Nervi station stopping in all intermediate stations.

On the contrary, the second train starts its trip from Genova Nervi and stops at Genova Voltri station, stopping likewise at all intermediate stations.

Train 3 leaves from Genova Piazza Principe Station with destination at Genova Voltri transiting through Sampierdarena station without stopping. It is classified as a high-speed train.

Finally, train 4 departs from Novi Ligure station and stops at Arquata, Ronco Scrivia, and Genova Piazza Principe stations then it turns toward its destination Genova Voltri stopping also at Sampierdarena station.

Figure 8 shows a simplified diagram of the proposed alternative graph, which represents the railway network and the train paths.

The case study manages the trip of 6 GPs. The number of passengers, the origin station of GP' journey, the arrival time at the origin station and, finally, the destination station is a priori known for each GP (Table 12).

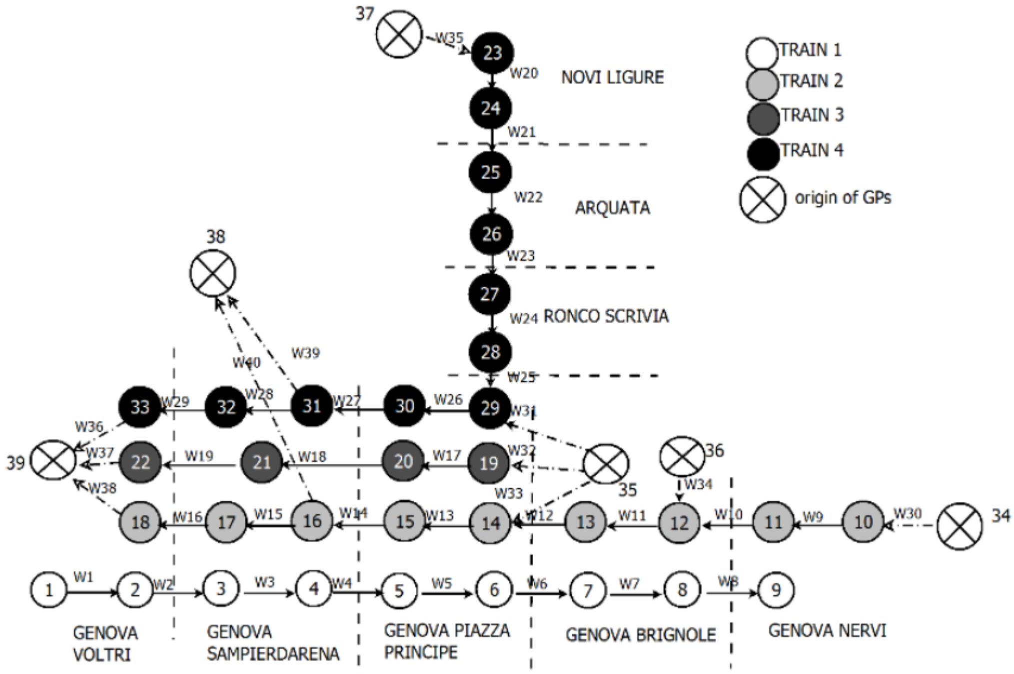


Figure 8. Network schem

	Origin station	Destination station	n_w	π_w
GP1	Station 1	Station 3	1000	10.95
GP2	Station 1	Station 3	10	10.95
GP3	Station 5	Station 3	1000	10.60
GP4	Station 4	Station 2	100	10.88
GP5	Station 6	Station 2	50	10.15
GP6	Station 6	Station 3	200	10.15

Table 12. GP Data

Five different couples' origin-destination (OD) is associated to the GP. The first and second GPs leave from Genova Piazza Principe Station and have a destination in Genova Voltri. The first PG consists of 1000 passengers and the second one only of 10 passengers. They run of the same route but in opposite directions.

The third GP has Genova Nervi as origin station, and it aims at reaching Genova Voltri with a total number of 1000 passengers.

The fourth GP leaves from Genova Brignole and stops at Genova Sampierdarena with 100 passengers.

GPs 5 and 6 have the same origin station, Novi Ligure. GPs 5 consists of 50 passengers while GPs 6 has a total of 200 passengers. GPs 5 has to reach Genova Sampierdarena while the GPs 6 has Genova Voltri as destination.

4.4 Results

This section reports the results obtained applying TS1 and TR2 models on the proposed case study.

The Lingo software has been used to implement the models. The results provide the optimal scheduling for the selected trains and routing of GPs to reach their destinations. The routing is represented by a sequence of nodes and arcs to be covered which in turn represent the sequence of trains and rail sections to be used to complete the journeys. The resulted path represents the optimal tour for each GPs in terms of minimum length of time spent on the railway network.

4.4.1 TS1 Model application

The proposed TS1 associates a departure train to each GP in order to reach its destination as soon as possible. Table 13 and Table 14 contain the proposed timetable for trains and GPs.

	Station	$\boldsymbol{h_i}$	**Station**	$\boldsymbol{h_i}$	**Station**	$\boldsymbol{h_i}$	**Station**	$\boldsymbol{h_i}$
	Train 1		**Train 2**		**Train 3**		**Train 4**	
Departure time		10.92		10.60		10.95		10.15
Intermediate station time	Station 2	11.25	Station 4	10.88	Station 2	11.07	Station 7	10.37

	Station 1	11.45	Station 1	11.03			Station 8	10.53
							Station 1	10.93
	Station 4	11.58	Station 2	11.22			Station 2	11.37
Arrival time		11.88		11.66		11.22		12.06

Table 13. Optimal Timetable for trains

GP ID	Scheduled Train	T_w	Travel time in TR2
GP1	Train 3	11.22	0.27
GP2	Train 3	11.22	0.27
GP3	Train 2	11.66	1.06
GP4	Train 2	11.22	0.34
GP5	Train 4	11.37	1.22
GP6	Train 4	12.06	1.91

Table 14. Optimal GPs routing

In the figures below, Figure 9 and Figure 10, the allocation of each GP to the different trains is displayed.

Train 3 allocates two GPs with 1010 passengers among the Station 1 and 2. Train 2 allocates 1100 passengers among the Station 2 and 4 and finally Train 4 only 250 passengers. In the proposed TS1, according to the objective function, trains with more passengers receive priority over other trains.

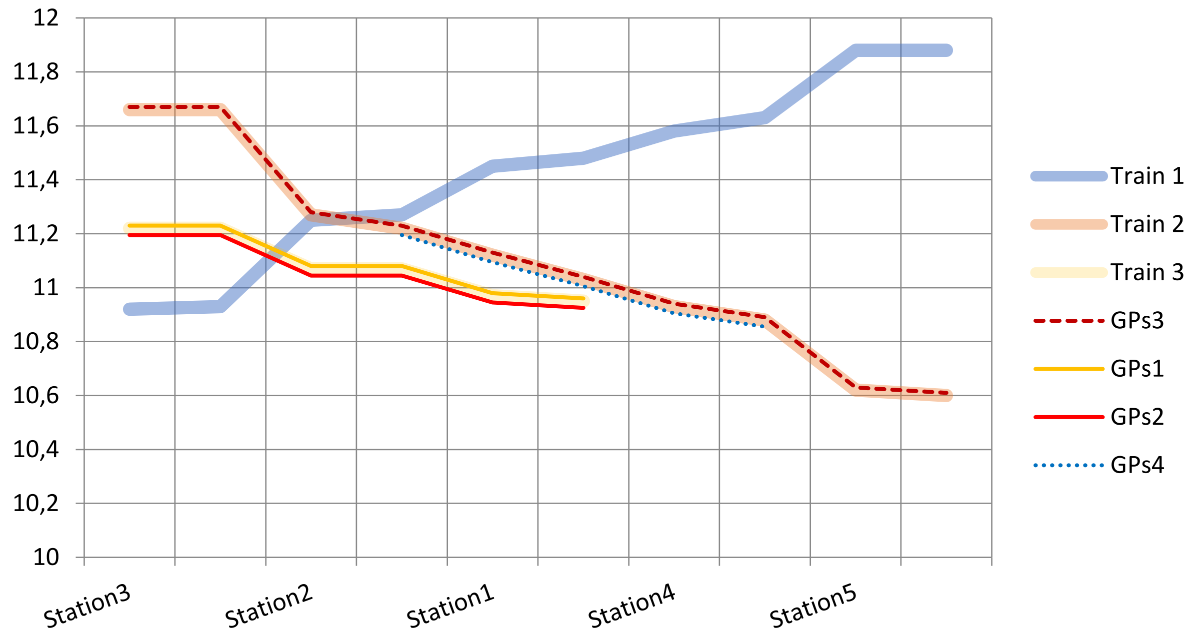


Figure 9. GP 1, 2, 3 and 4 paths

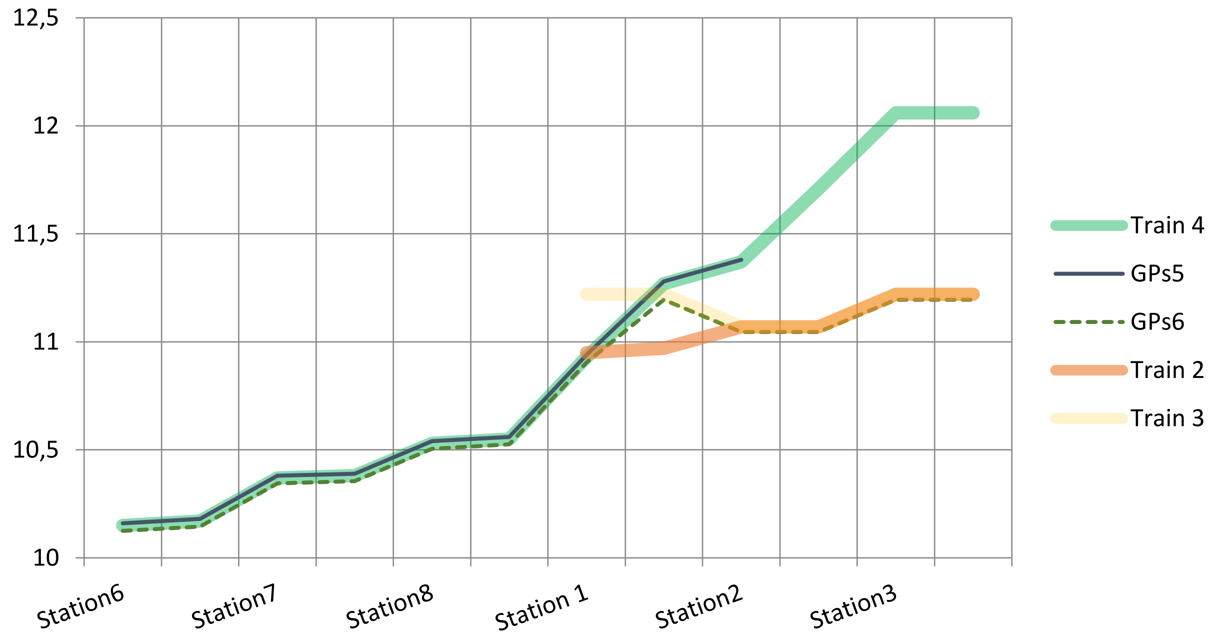


Figure 10. GP 5 and 6 paths

Train 4 accommodates GP 5 and 6. The first GP stops its trip at station 2 while the second one stops at station 3.

4.4.2 Rescheduling TR2 Model application

The optimal data for the train timetable and GPs arrival times obtained by solving the scheduling ST1 model are the input of the TR2 rescheduling model. In order to evaluate the model's performance, a disturbance has been added to the network causing a delay on a random node. In detail, the disturbance consists of increasing the time to start the logistic operation in a specific node. In this way, a delay is created in the path of the train that includes that node.

To validate the model performance, a delay has been added at node 19, which belongs to the path of the high priority Train 3. The departure time at Station 1 for Train 3 has been postponed for 35 units of time ($h_{19} = 11.30$ in TR2 instead of departing at 10.95 for TS1). The disturbance propagates in the railway network causing delays for the other trains. This new scenario imposes GPs to change their routing in order to minimize their trip duration.

Also, priority values have been associated to the trains. Only four nodes (node 19, 20, 21, 22) that belong to the path of Train 3 have the highest priorities and it allows the selected train to have right of way on the alternative arcs in case of conflicts with other trains.

From the results, it is possible to verify that model fosters Train 3 with high priority (despite the delay) and it activates the alternative arcs to penalize the other train.

Table 15 contains the new optimal timetable of each GPs after disturbances. Figure 11 and Figure 12 show the optimal GPs path.

GP ID	**Departure train**	**Arrival train**	$\boldsymbol{\pi_w}$	$\boldsymbol{T_w}$ **for TS1**	$\boldsymbol{T_w}$ **for TR2**	**Travel time for TR2**
GP 1	Train3	Train3	10.95	11.22	11.54	0.59
GP 2	Train3	Train3	10.95	11.22	11.54	0.59
GP 3	Train2	***Train3***	***10.60***	***11.66***	***11.54***	***0.94***
GP 4	Train2	Train2	10.88	11.22	11.22	0.34
GP 5	Train4	***Train2***	***10.15***	***11.37***	***11.22***	***1.07***
GP 6	Train 4	***Train3***	***10.15***	***12.06***	***11.54***	***1.39***

Table 15. Optimal Passengers Routing with disturbances

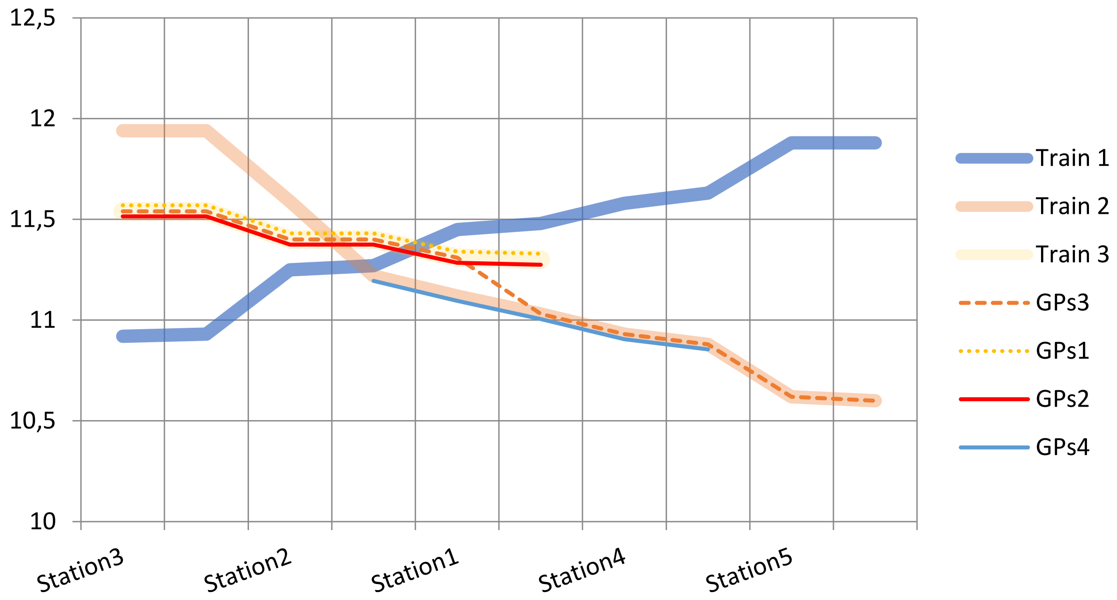


Figure 11. GP 1, 2, 3 and 4 paths

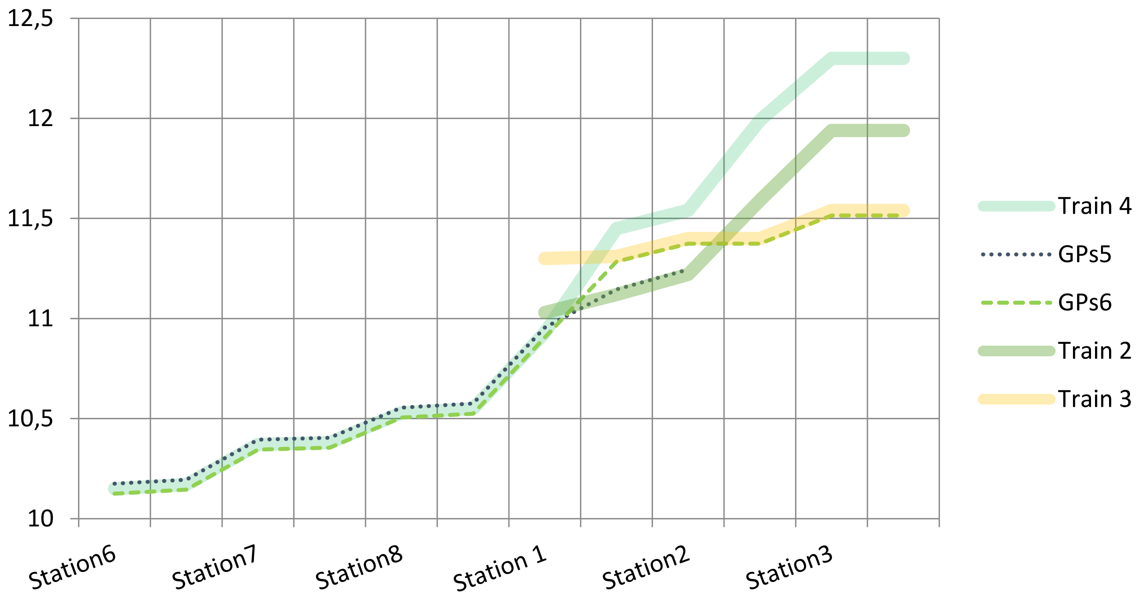


Figure 12. GP 5 and 6 paths

It is important to note that, by applying the rescheduling model, GP 3, 5 and 6 change train during their tours in order to reach their destination faster.

The rescheduling model, which introduces priority values for trains, avoids the propagation of the disturbance on the network. Train 3, which starts with a delay, regains some minutes at the arrival destination station. Also, tours of Trains 2 and 4 are affected by the disturbances but the delay is mitigated at the arrival. Modification of the train rerouting in respect to train scheduling results appears underlined and in bolt in Table 16.

<table>
<tr><th></th><th>Station</th><th>h_i</th><th>Station</th><th>h_i</th><th>Station</th><th>h_i</th><th>Station</th><th>h_i</th></tr>
<tr><th></th><th colspan="2">Train 1</th><th colspan="2">Train 2</th><th colspan="2">Train 3</th><th colspan="2">Train 4</th></tr>
<tr><td>Departure time</td><td></td><td>10.92</td><td></td><td>10.60</td><td></td><td>11.30</td><td></td><td>10.15</td></tr>
<tr><td rowspan="4">Intermediate station time</td><td>Station 2</td><td>11.25</td><td>Station 4</td><td>10.88</td><td rowspan="4">Station 2</td><td rowspan="4">11.40</td><td>Station 7</td><td>10.37</td></tr>
<tr><td rowspan="2">Station 1</td><td rowspan="2">11.45</td><td rowspan="2">Station 1</td><td rowspan="2">11.03</td><td>Station 8</td><td>10.53</td></tr>
<tr><td>Station 1</td><td>10.93</td></tr>
<tr><td>Station 4</td><td>11.58</td><td>Station 2</td><td>11.22</td><td>Station 2</td><td>11.54</td></tr>
<tr><td>Arrival time</td><td></td><td>11.88</td><td></td><td>11.94</td><td></td><td>11.54</td><td></td><td>12.30</td></tr>
</table>

Table 16. Optimal timetable after disturbances

Anyway, the performances related to the travel times for GPs improve in the rescheduling approach by the optimal rerouting.

The comparison among travel times for GPs in the scheduling and rescheduling model application confirms that, by rescheduling, the GP 3, 5, and 6 save time to reach their destination. Respectively, they save 12, 15, and 52 units of time, while any delay does not affect the tour of GP 4.

Chapter 5. Train scheduling and rescheduling problem. High-speed train

5.1 Introduction

In respect to the past literature, in this chapter, dedicated to high-speed trains, constraints about customers' demand and maximum passengers' capacity of trains are considered. Unlike regional trains, high-speed ones are a limited carrying capacity and passengers have an assigned seat. This option allows knowing the number of passengers allocated to each train.

There are some new researches about train scheduling on high-speed trains. In [98], the authors study the double-track train scheduling problem for planning applications with multiple objectives, focusing on a high-speed passenger rail line.

In [99], the authors use some linearization techniques to identify the operation modes and the timetable trains, by integrating the time window selection of regular maintenances on high-speed railways.

The study [100] considers a high-speed rail corridor that requires high fidelity scheduling of train speed for many trains with both tight power supply and temporal capacity constraints.

The research developed in the article [101] study a high-speed rail corridor in order to generate a new timetable for both of the additional trains and the existing trains, minimizing the total travel time of the additional trains and the adjustment on the existing trains at the same time.

In [102], the authors propose a meta-model simulation-based optimization approach for minimizing the passenger wait time under random disturbances.

The main contribution of this chapter is dedicated to the scheduling and rescheduling models for high-speed trains giving importance to the carrying capacity of trains and their occupation, to the priority level of the trains, and to the minimization of passengers' travel time.

This chapter is divided into three sections. The first part describes the scheduling (SM) and rescheduling model (RM) for high-speed trains.

In the second section, these models, SM and RM, are applied to a real case study, using the Northern Italian high-speed train network as the railway network.

Finally, in the last section, are presented the results obtained when applying the scheduling (SM) and rescheduling model (RM) to the real case study.

5.2 Model formulation

In this section, the description of the network and the raised scheduling and rescheduling models are proposed.

5.2.1 Network description

The rail network is implemented as a system of systems consisting of a set of nodes connected by arcs on which trains may travel. The problem is formalized according to the following main elements:

- The Passengers Group (PG), $G = \{1 \dots G\}$. It is an indivisible group of people that starts the travel at $start_g$ node and finish their tour at end_g node. The departure time of the tour for each PG is denoted by the parameter dep_time_g.
- Set of Nodes, $N = \{1 \dots N\}$. The nodes of the network represent logistic operations in the different network sections for each train. Thus, each node has a starting time t_i for the specific logistic operation at node i. The logistic operations consist of the train's arrival or departure time if the node represents a station or running time if the node represents a block section. The nodes are connected through arcs allowing PG to travel from one node to another until they reach their destinations.
    - The Virtual Nodes (VN) are non-physical nodes whose function is to connect the virtual origin and destination of PG to the other nodes of the network. Each PG has an associated origin ($start_g$) and destination node (end_g). Both are virtual nodes.
- Set of arcs, $R = \{1 \dots R\}$. Each arc has an associated weight that represents the travel time to be covered.

There are three types of arcs:

- Fixed Arcs (FA), $F = \{1 \dots F\}$. This type of arc connects the nodes that belong to the same train. The train covers these arcs and the weight kf_r represents the travel time from one node to another. The sequence of visited nodes and covered FAs represents the train tour on the network.
- Connection Arcs (CA), $C = \{1 \dots C\}$. Those arcs connect the nodes which represent stations, and they are associated to the different train tours. Through these arcs, the PG can change the train at the stations.

- Alternative Arcs (AA), $A = \{1 \ldots A\}$. This type of arcs does not allow PG to travel on. They are associated to a couple of nodes that belong to the same block section. They can assume two status: activated (when a CRP arises in a block section) or deactivated (when there is not a conflict). In case of CRP, one of these arcs will be activated allowing one train to surpass the other one.

5.2.2 Scheduling Model (SM)

The proposed scheduling model SM is introduced with the objective to minimize the travel time of PGs guaranteeing them the greatest possible satisfaction.

Each train has a maximum carrying capacity of passengers. The proposed scheduling model depends on the number of passengers which compose each PG, to their origin and destination stations, and to the starting time of the tours. According to the available FAs exiting from the VNs, the PG is allocated to the starting node. If two or more PG start from the same origin station, they can take different trains to reach the destination.

Notation

$G = \{1 \ldots G\}$	Set of PG
$N = \{1 \ldots N\}$	Set of Nodes
$F = \{1 \ldots F\}$	Set of Fixed Arcs
$C = \{1 \ldots C\}$	Set of Connection Arcs
$A = \{1 \ldots A\}$	Set of Alternative Arcs

Parameters

$start_g$	Origin node for the tour PG, $g \in G$
end_g	End node for PG, $g \in G$
kf_r	Weight for FA, $r \in R$
kc_r	Weight for CA, $r \in R$
ka_r	Weight for AA, $r \in R$
$o_{i,r}$	If i is the source node of arc r, the parameter

	assumes value 1, 0 otherwise. $i \in N, r \in R$
$d_{i,r}$	If i is the destination node of arc r, the parameter assumes value 1, 0 otherwise. $i \in N, r \in R$
np_g	Number of passengers for PG, $g \in G$
dep_time_g	Departure time for PG, $g \in G$
$y_{m,r}$	Binary parameter which assumes value 1 if m and r are a couple of AA. $m, r \in A$
$cmax_i$	Indicates the maximum passenger capacity that train can assume on node $i \in N$

Decisional Variables

t_i	Starting time of a logistic operation at the node $i \in N$
at_g	Arrival time at destination station for the PG, $g \in G$
$z_{m,r}$	Binary variable that indicates the presence of a CRP. It assumes value 1 if arc r is selected to solve the conflict. $m, r \in A$
q_f^g	Binary variable that assumes value 1 if arc f belongs to the tour of the PG g. $f \in F \cup C, g \in G$

The objective function (Equation 38) minimizes the travel time of the PGs weighted for the number of persons in which the group consists.

$$min \sum_{g=1}^{G} np_g\left(at_g - dep\_time_g\right) + \sum_{i=1}^{N} t_i$$	*Equation 38*
$$t_j \geq t_i + \left(o_{i,f} d_{i,f} k f_f\right) - M\left(1 - \left(o_{i,f} d_{i,f}\right)\right) \quad i, j \in N \quad f \in F$$	*Equation 39*

$t_i \geq t_j + \left(o_{j,m}d_{i,m}ka_m\right) - M\left(1 - \left(o_{j,m}d_{i,m}z_{r,m}\right)\right) - M\left(1 - \left(o_{j,m}d_{i,m}z_{r,m}y_{r,m}\right)\right)$		
	$i, j \in N$ $m, r \in A, m \neq r$	*Equation 40*

$t_k \geq t_j + \left(o_{j,r}d_{k,r}ka_r\right) - M\left(1 - \left(o_{j,r}d_{k,r}z_{r,m}\right)\right) - M\left(o_{j,r}d_{k,r}z_{r,m}y_{r,m}\right)$		
	$k, j \in N$ $m, r \in A, m \neq r$	*Equation 41*
$\sum_{i=1}^{N}\sum_{u=1}^{F\cup C} o_{start_g,u}d_{i,u}q_u^g = 1$	$g \in G$	*Equation 42*
$\sum_{i=1}^{N}\sum_{u=1}^{F\cup C} o_{i,u}d_{end_g,u}q_u^g = 1$	$g \in G$	*Equation 43*
$\sum_{u=1}^{F\cup C} d_{i,r}q_u^g = \sum_{m=1}^{F\cup C} o_{i,m}q_m^q$	$i \in N, g \in G,$ $i \neq start_g,$ $i \neq end_g$	*Equation 44*
$t_i \geq dep\_time_g - M\left(\left(1 - o_{start_g,c}\right)d_{i,c}q_c^g\right)$		
	$i \in N, g \in G, c \in C$	*Equation 45*
$t_j \geq t_i + \left(o_{i,c}d_{j,c}kc_c\right) - M\left(1 - \left(o_{i,c}d_{i,c}\right)\right) - M\left(1 - \left(o_{i,c}d_{j,c}q_c^g\right)\right)$		
	$i, j \in N, c$ $\in C, g \in G$	*Equation 46*
$at_g \geq h_i - M\left(1 - \left(o_{i,u}d_{end_g,u}q_u^g\right)\right)$		
	$i \in N, g \in G, u \in F \cup C$	*Equation 47*
$\sum_{g=1}^{G} o_{i,u}d_{i,u}q_u^g np_g \leq cmax_i$	$u \in F \cup C$ $i \in N$	*Equation 48*
$t_i \geq 0$	$i \in N$	*Equation 49*
$y_{m,r}, q_r^g \in \{0,1\}$	$m, r \in F \cup C$ $m \neq r$ $g \in G$	*Equation 50*

By Equation 39, it is assumed, for each arc, that the time at destination node j might be greater or equal to the starting time at origin node i plus the traversing time. In Equation 40 and Equation 41, it is decided which alternative arc A has to be activated in case of CRP. Equation 42, Equation 43, and Equation 44 are used to manage the flow of PGs. Each PG has to leave the planned station (Equation 42), it has to finish its trip at the destination station (Equation 43) and all PGs entering the origin node of an arc have to reach the associated destination node (Equation 44). Equation 45 ensures that, for connection arcs, the train might leave the station only after the arrival of the PG at the current node. Equation 46 ensures that the PGs that might travel through the connection arcs arrive at the station before the next train leaves. Equation 47 defines the arrival time of each PG at the destination station. Equation 48 does not allow to exceed the maximum capacity of the train. Finally, Equation 49 and Equation 50 define the optimization variables as positives and binaries.

5.2.3 Rescheduling Model (RM)

The rescheduling model has to be applied consecutively to the SM. Based on the SM optimal timetable for trains, the rescheduling model RM generates a modified timetable adapted to reduce the disturbances on the network. It includes new parameters and variables that are listed below.

kfR_f: this variable indicates the new weight of fixed arcs $f, f \in F$;

tR_i: decisional variable that indicates the starting time of a logistic operation on node i on the RM model, where $i \in N$.

dly_i: the decisional variable indicates the delay time of a train at the node $i, i \in N$.

adv_i: indicates, in case of delay, the time that the train saved at the node i to optimize its trip. $i \in N$.

p_i: input value that indicates the priority level at node i, $i \in N$.

It is assumed that the value of t_i is a priori known. It indicates the optimal starting time of a logistic operation in the node i computed as result of the SM model.

As mentioned, new variables have been added to the RM model. Therefore, the objective function has been adapted to adjust the train schedules in case of disturbances and to reduce the time to restore the rail system.

$$min \sum_{g=1}^{G} np_g(at_g - dep\_time_g) + \sum_{i=1}^{N} p_i dly_i + \sum_{i=1}^{N} adv_i \qquad \text{Equation 51}$$

$$dly_i \geq tR_i - t_i \qquad i \in N \qquad \text{Equation 52}$$

$$adv_i \geq t_i - tR_i \qquad i \in N \qquad \text{Equation 53}$$

$$kfR_f \geq kf_f \qquad f \in F \qquad \text{Equation 54}$$

$$tR_i \geq t_i \qquad i \in N \qquad \text{Equation 55}$$

$$tR_i \geq 0 \qquad i \in N \qquad \text{Equation 56}$$

The main objective (Equation 51) is to minimize the time travel time of the PGs and to reduce the delay or the advance time caused by the disturbances, ensuring the recovery of the network. To minimize the delay, the priority level of the train is considered. The number of passengers on the train gives the priority level: the train which carries more passengers is scheduled with the highest priority.

The constraints of the rescheduling model RM consist of the scheduling model SM by Equation 39 - Equation 50 and of the new equations Equation 52 - Equation 56.

Equation 52 indicates that the delay, at each node, has to be greater than or equal to the difference between the starting time of a logistic operation in the RM and the scheduled one generated in the SM. By Equation 53, it is assumed that the time advance at each node is greater than or equal to the difference between the scheduled starting time of a logistic operation and the new one generated by the rescheduling approach. Equation 54 defines the weight of each arc in RM as greater than the fixed weight on SM model. Equation 55 defines the starting operational time as greater than or equal to the predefined scheduled one. Finally, Equation 56 defines the variables domain.

5.3 Case study

This section presents a real case study focused on the northern Italy stations. High-speed trains connect the cities with a limited passenger capacity. There are two types of train: freccia and intercity. The first one is considered faster with respect to the second one, but intercity has greater capacity compared to freccia trains.

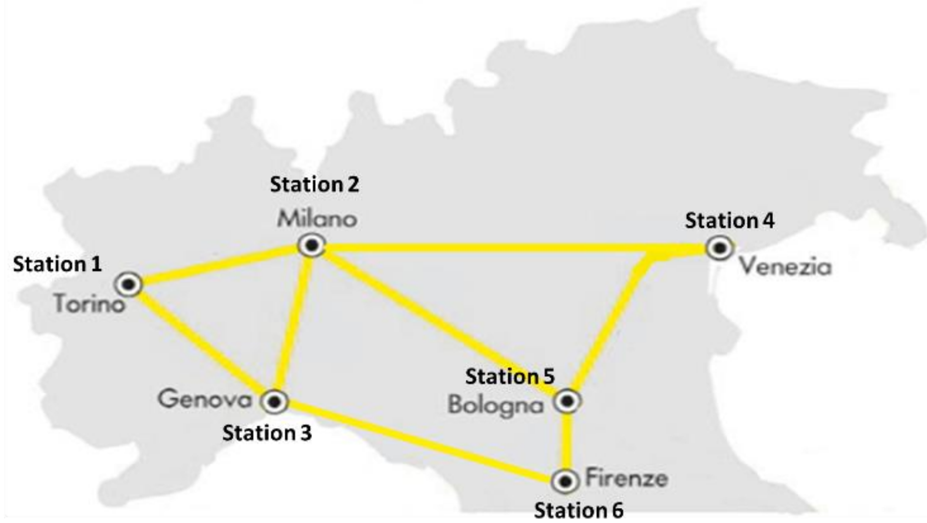


Figure 13. Northern Italy Network

Figure 13 represents the main stations in Northern Italy network. Station 1 represents the city of Turin with a direct link to Milan (Station 2) and Genoa (Station 3). Milan, station 2, is directly connected to Venice (Station 4) and Station 5, represented by the city of Bologna. Finally, Station 6, Florence, is linked to Bologna, Station 5.

The case study is based on scheduling and rescheduling of 9 trains considered the tours of 9 PGs. Figure 14 is shown each train path. All trains are considered freccia except Train 3 and Train 8 that are classified as intercity trains.

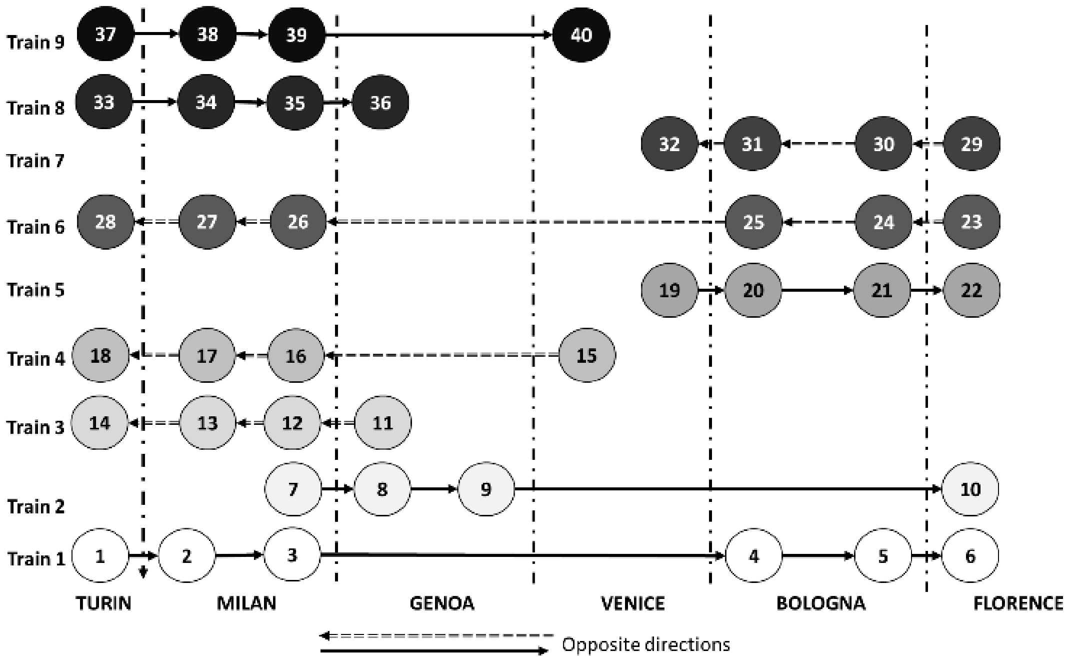


Figure 14. Trains' path

The main data of the 9 trains for the case study and the passenger capacity of each train is given by Trenitalia website [103], the main Italian company for rail transport. The departure times of the trains, the timetables, the traversing time, and platforms information have been explored to extract the 9 trains, used for the case study application, that started their journey in a time horizon of 4 hours in the morning (from 08:00 to 12:00). Table 17 shows the characteristics of trains of this case study.

	Origin station	Destination station	Intermediate stations	Maximum capacity
Train 1	Station 1	Station 6	Station 2, 5	492
Train 2	Station 2	Station 6	Station 3	492
Train 3	Station 3	Station 1	Station 2	600
Train 4	Station 4	Station 1	Station 2	492
Train 5	Station 4	Station 6	Station 5	492
Train 6	Station 6	Station 1	Station 5, 2	492
Train 7	Station 6	Station 4	Station 5	492
Train 8	Station 1	Station 3	Station 2	600
Train 9	Station 1	Station 4	Station 2	492

Table 17. Train Characteristics

Train 1 and Train 6 carry out the same tour but in opposite directions. They are both freccia with a capacity of 492 passengers. The origin station of Train 1 is Turin and the destination station is Florence. The intermediate stations are Milan and Bologna. The same path is for Train 6 but the origin and destination stations are Florence and Turin respectively.

Train 2 has the origin station in Milan, stops at Genoa station, and destination in Florence. This freccia train has a capacity of 492 passengers.

Train 3 and Train 8 are the same train but in opposite directions. The origin station of the first one is Genoa, stopping at Milan station and destination at Turin station. Train 8 is an intercity train, the passenger's capacity is 600.

Train 4 and Train 9 are another couple of trains with opposite directions. In this case, the path includes Venice station, Turin station with a stop in Milan. Train 9 travels the same stations as Train 4 but in reverse order: Turin, Milan and finally Venice.

Train 5 and Train 7 stop at the same stations.

PG	$start_g$	end_g	np_g	dep_time_g
1	STATION 3	STATION 6	230	8:00
2	STATION 1	STATION 6	400	8:00
3	STATION 6	STATION 3	200	8:00
4	STATION 4	STATION 3	100	7:00
5	STATION 5	STATION 3	200	8:00
6	STATION 4	STATION 1	90	7:00
7	STATION 2	STATION 6	100	8:00
8	STATION 6	STATION 4	100	8:00
9	STATION 4	STATION 6	250	7:00

Table 18. PG Data

Table 18 represents the PGs data. In detail, in the table appear the departure station, the arrival station, the number of passengers for each group, and the departure time (given in hours and minutes) for each of the nine PGs.

5.4 Results

In this section, the results obtained applying the scheduling SM and rescheduling models RM are introduced. The model has been implemented by Cplex software. The SM model generated the optimal timetable for trains and the optimal PG paths. The RM model modifies the optimal timetable generated by the SM considering the introduction of potential disturbances on the network.

5.4.1 SM Model Application

The main objective of the scheduling model is to find the optimal path of the PGs to reach their destination as soon as possible. Each train has a limited passenger capacity, and it limits the optimal PGs path.

Table 19 and

Table 20 show the scheduling results. In Figure 15, the used capacity of each train at each station is displayed.

Train	Departure time	Time at intermediate stations		Arrival time
1	8:00	9:03-9:13	10:23-10:25	10:57
2	8:00	9:46-9:49		11:15
3	12:34	14:16-14:18		16:04
4	8:00	10:00-10:50		11:50
5	8:00	9:50-9:52		10:25
6	8:06	8:39-8:41	9:51-10:50	11:50
7	8:33	9:03-9:51		11:41
8	9:03	10:49-10:51		12:33
9	11:51	12:51-13:01		15:01

Table 19. Optimal Timetable for Trains

PG	Departure train	Arrival train	Departure time	Arrival time	Travel time
1	Train 2	Train 2	9:49	11:15	1:25
2	Train 1	Train 1	8:00	10:57	2:57
3	Train 6	Train 8	8:00	12:33	4:33
4	Train 4	Train 8	8:00	12:33	4:33
5	Train 6	Train 8	8:34	12:33	3:58
6	Train 4	Train 6	8:00	11:50	3:50
7	Train 2	Train 2	8:00	11:15	3:15
8	Train 7	Train 7	8:33	11:41	3:08
9	Train 5	Train 5	8:00	10:25	2:25

Table 20. Optimal PG Path

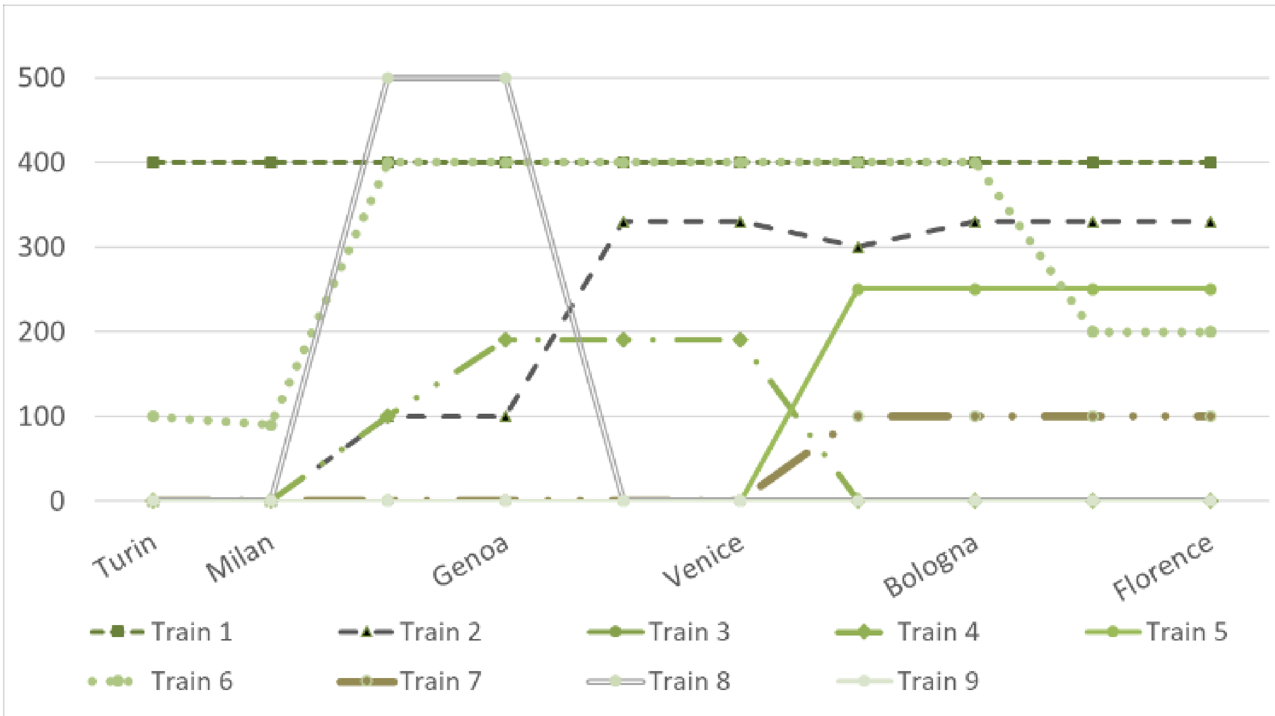


Figure 15. Occupancy of each train

From the results, it is interesting to notice that some PGs have to use different trains due to the capacity limit. It is the case, for example, of PG2 and PG7. Without exceeding capacity, both PGs could take the same train (Train 1). However, the sum of the number of passengers in both groups is greater than the capacity of Train 1. That is why the PG7 takes Train 2 to reach its destination with a delay of 11 min. According to the objective function, the PG2, which counts 400 passengers, has been favored to use the shorter path by Train 1 instead of PG 7 which consists of 100 passengers. In Figure 16, the allocation of the PGs to the different used trains and their timetables appears.

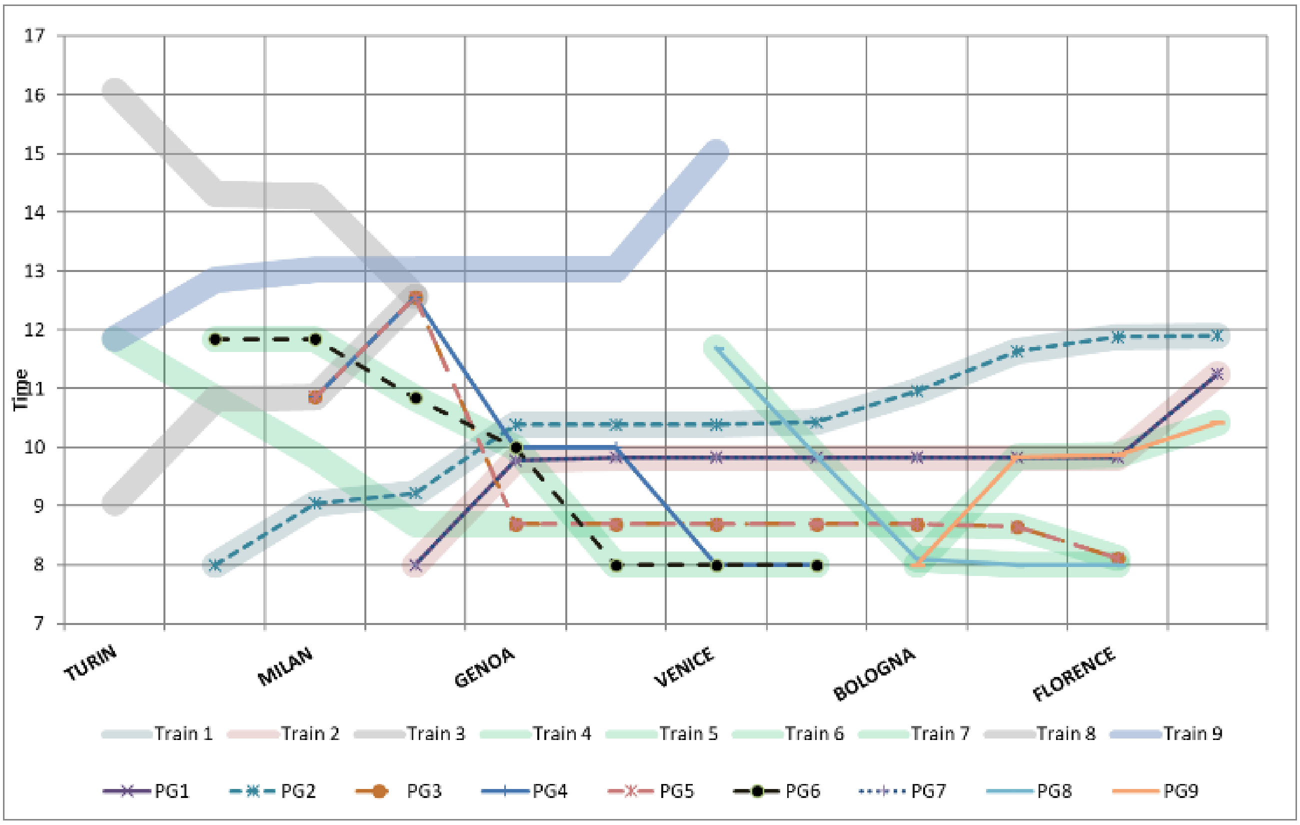


Figure 16. Allocation of the PGs to the different trains by the SM

In addition, it can be appreciated the changes of train for some PGs. For example, PG3 leaves Florence (Station 6) to reach Genoa (Station 3) but there is not a direct path. The group correctly change trains to arrive at the destination station, by Station 6, Station 5, Station 2 and Station 1.

5.4.2 RM Model Application

Before applying the RM model, a disturbance in the network has been applied. This disturbance is represented as a delay in one or more important nodes. In this case, two main delays have been introduced: 16 minutes of delay at node 35, (services available at 11:40 in respect to 11:24) which belongs to Train 8, and 20 minutes at node 25 (services available at 9:50 in respect to 9:30) which belongs to Train 6 (see Figure 14). Table 21 and Table 22 display the optimal timetable for the trains and PGs' paths after disturbances. In Figure 17, the allocation of the PGs to the different trains and their timetables appear as a result of the rescheduling model application.

In order to evaluate the performance of the proposed RM model, the schedules assessment in the RM and in SM are presented.

In Table 21 and Table 22, the RM results which differ from the previously scheduled ones in the SM are highlighted by bold characters.

Train	**Departure time**	**Time at intermediate stations**		**Arrival time**
1	8:00	9:03-9:13	10:23-10:25	10:57
2	8:00	9:46-9:49		11:15
3	**13:06**	**14:48-14:51**		**16:36**
4	8:00	10:00-10:50		11:50
5	8:00	9:50-9:52		10:25
6	**8:00**	**8:32-9.30**	**10:40**-10:50	11:50
7	8:33	9:03-9:51		11:41
8	9:03	10:49-**11:24**		**13:06**
9	11:51	12:51-13:01		15:01

Table 21. Optimal Timetable after disturbances with RM

PG	**Departure train**	**Arrival train**	**Departure time**	**Arrival time**	**Travel time**
1	Train 2	Train 2	9:49	11:15	1:25
2	Train 1	Train 1	8:00	10:57	2:57
3	Train 6	Train 8	8:00	**13:06**	**5:06**
4	Train 4	Train 8	8:00	**13:06**	**5:06**
5	Train 6	Train 8	**9:30**	**13:06**	<u>*3:36*</u>
6	Train 4	<u>Train 4</u>	8:00	11:50	3:50
7	Train 2	Train 2	8:00	11:15	3:15
8	<u>Train 6</u>	Train 7	**8:00**	11:41	**3:41**
9	Train 5	Train 5	8:00	10:25	2:25

Table 22. Optimal PG Path after disturbances with RM

Train 3 leaves 40 minutes later than the optimal scheduled timetable. However, it arrives at its destination only 32 minutes later. This means that the train has recovered 8 minutes from the expected delay thanks to RM application.

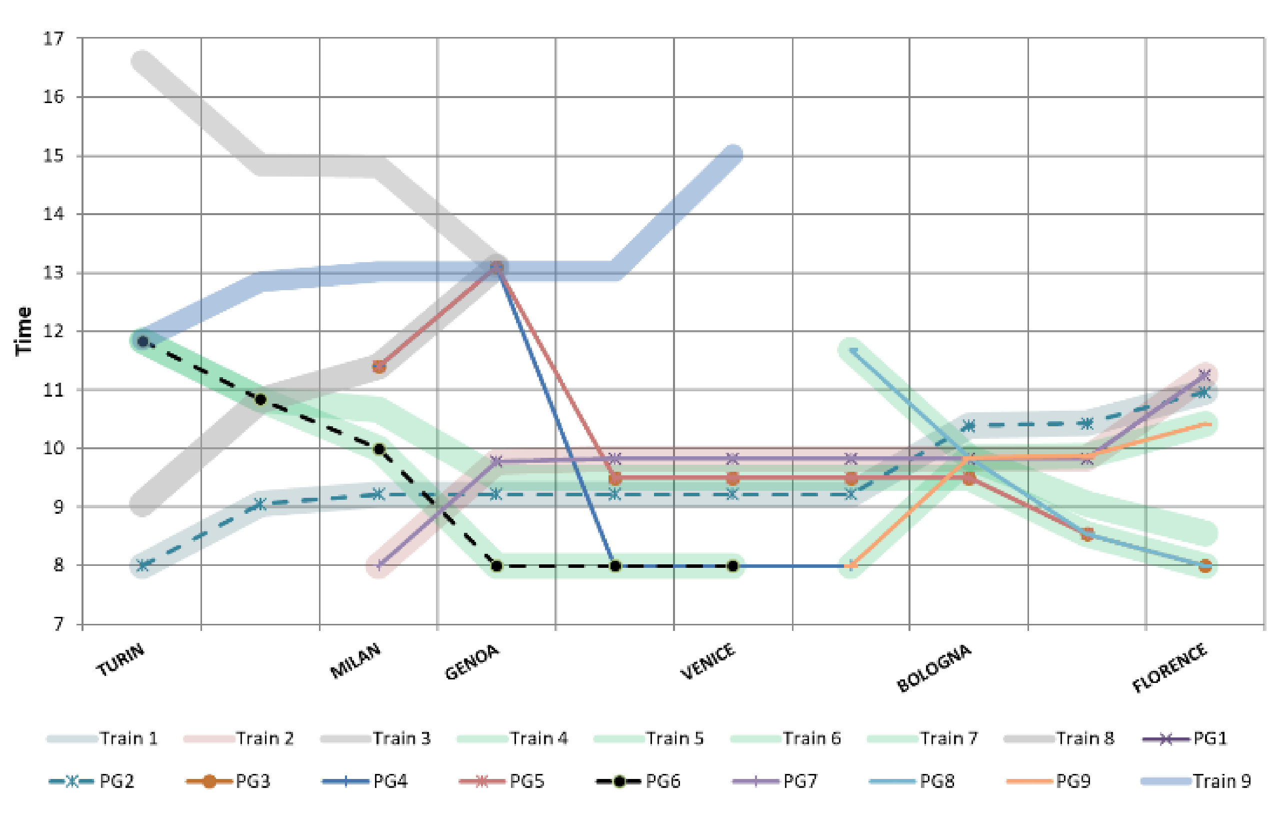


Figure 17. Allocation of the PGs to the different trains by the RM

Besides, it is interesting to observe that the delay of Train 8 affects PG3 and PG4 but not PG5. Despite the delay, Train 8 just represents the best option for these three PG to arrive at Station 3. This happens because the three groups, that have the same destination station (Station 3-Genoa), exceed the maximum capacity of the alternative freccia Train 2 which transit at Genoa station. Anyway, by RM application, the travel time of PG 5 decreases significantly saving 22 minutes. Further, PG6 arrives with a different train and PG8 leaves the origin station by a different train. On the other hand, Train 3 increases its arrival time at the destination station. It is meaningful for model efficiency because Train 3 is not used by the PGs. In the proposed approach, in fact, trains that transit empty are penalized in the network to favor crowded trains.

PG	Scheduled travel time	Rescheduled travel time	Real travel time
1	**1:25**	1:25	1:25
2	**2:57**	**2:57**	3:04
3	**4:33**	5:06	4:41
4	**4:33**	**5:06**	5:17
5	3:58	3:36	2:49
6	**3:50**	**3:50**	5:05
7	**3:15**	**3:15**	3:15
8	3:08	3:41	1:53
9	**2:25**	**2:25**	2:33

Table 23. Scheduled, Rescheduled and Real Travel Time

Finally, Table 23 compares the total travel time for passengers among the SM model, RM model, and the real travel time for freccia and intercity trains in Northern Italy according to the real scheduling coming by the railway service operator website [103]. It can be observed, marked in bold, that by the SM model, in most cases, the PGs arrive faster at their destination station. In particular, the PG 6 reaches the arrival station saving 25% of the time. Also, in case of disturbances, the RM model provides good results, as for the PG 2, 4, 6, and 9.

Chapter 6. Min-Max Approach for High-Speed Train Scheduling and Rescheduling Models

6.1 Introduction

This chapter can be positioned in the context of robustness proposing two approaches for the optimal scheduling and rescheduling problem evaluating both robustness and resilience, using a min-max approach.

The railway network might be considered immutable for a long time, so decision-makers can increase train scheduling performance by evaluating improvements in the assignment of route alternatives for trains or by identifying potential resource conflicts. Those latter conflicts on the network represent one of the main issues in the rescheduling problem and they depend substantially on network topology, track layout, rail units, and communication among rail network components.

Firstly, a train scheduling problem is solved to find the optimal TS to minimize passengers' discomfort in terms of the traveling time. Besides, the proposed approach implements the ability to solve the CRP.

The second part of this chapter deals to present a rescheduling problem, which proposed a min-max approach to minimize the maximum delay in the scheduling tasks in case of occurrence of disturbances on the network according to safety and operation restrictions.

The chapter is organized as follows. Section 2 presents the microscopic min-max criteria train scheduling model (MTSM) and train rescheduling model (MTRM). In Section 3 the proposed approaches are applied to a real case study which considers the high-speed line infrastructure in the Norther Italy and in the section 4 the results are discussed. Finally, Section 4 also contains the performance evaluation of the proposed MTRM against a rescheduling model formalized as a mathematical programming problem.

6.2 Model description

6.2.1 Network description

The scheduling and rescheduling problems are implemented through a network modeled as a graph, which consists of a set of nodes and a set of arcs. In this approach, the nodes represent the events associated to each train (arrivals, departures) and the arcs the different operational tasks among nodes whose weights define the execution time.

In the graph, each row in the horizontal direction represents the path of each train while the vertical columns are associated to the track sections of the railway network. Another characteristic of the model is related to the passengers' groups with cover the network according to their corresponding information about the trips.

- The Passengers Group (PG), $W = \{1 \dots W\}$ represents an indivisible group of passengers that travels from one station to another, with the aim of reaching its destination. Each group PG is characterized by data about its journey: the origin station (α_w), destination station (β_w), the number of passengers of the group (π_w) and the arrival time at the origin station (dt_w).
- Set of nodes, $N = \{1 \dots N\}$. Each node represents a logistic operation in a network section. Each train is represented by a specific group of nodes that in the graph appear horizontally. Two consecutive nodes in each row of the graph may represent a station in which the train stops and departs or the movement of the train from one station to the next one. Each node is characterized by a parameter (l_i) which represents the starting time of a logistic operation related to the associated train. To implement the model, for each PG, two Virtual Nodes (VNs) have been added. The VNs do not represent a true station but just the virtual origin and destination stations of the PG. The PG departs and arrives, respectively, at the virtual origin node (α_w) and to the virtual destination node (β_w), which are connected to the nodes of the network associated to the available trains. The VNs connect passengers to the stations and not directly to the trains. VNs provide the PG with the possibility to choose the train and the route that best fits the needs of the group in terms of departure time.
- Set of arcs, $S = \{1 \dots S\}$. Each directed arc joins two nodes and, depending on the type, allows the train to travel through the network. Three types of arcs exist: fixed arcs, connection arcs, and alternative arcs.
  - Fixed Arcs (FF), $F = \{1 \dots F\}$. These horizonal arcs link the nodes from the departure station to the last planned station designing the path of each train. Each arc represents, with the respective nodes, a stop area, or a siding area. The travel time to cover the

arc s, $s\in$ F, is indicated by the parameter pf_s, which also regulates the speed of the train. PG can travel on these arcs. The origin and destination virtual nodes are also connected to the network through fixed arcs, but in this case, the weight of the arc is zero.

- Connection Arcs (CC), $C = \{1 \dots C\}$. These arcs connect nodes that represent the train's stop/departure at railway stations in order to allow PG to change the train if necessary. These arcs are included in track sections. The parameters of the connection arcs (pc_s) are related to the time spent by PG to change train at the related station.

- Couples of Alternative Arcs (AA), $\boldsymbol{A} = \{\mathbf{1} \dots \boldsymbol{A}\}$. They join nodes that belong to different trains and to two consecutive block sections (red dashed line in the Figure 1). They are used to solve possible conflicts when two or more trains need to enter the same block section at the same time. In case of CRP, one of the two alternative arcs may be activated to allow one train to enter the block section preceding the other one. The weight $\boldsymbol{pa_s}$ indicates the time that the trains need waiting the permission to proceed on the arc $\boldsymbol{s}$, $\boldsymbol{s}\in$ C, in case of conflict. PGs cannot travel through these arcs.

6.2.2 Min-Max Approach Train Scheduling Model (MTSM)

The proposed train scheduling model (MTSM) computes an optimal train timetable based on passengers' demand. It defines the TS according to PG's requirements, considering a min-max approach. The problem minimizes the completion time for PGs paths, and it skips the economic cost of the journeys. In the following, the notation, parameters, and variables of the model are listed.

Notation

$W = \{1 \dots W\}$	Set of PG
$N = \{1 \dots N\}$	Set of Nodes
$S = \{1 \dots S\}$	Set of Arcs
$F = \{1 \dots F\}$	Set of Fixed Arcs
$C = \{1 \dots C\}$	Set of Connection Arcs
$A = \{1 \dots A\}$	Set of Alternative Arcs

Parameters

α_w	Origin node for the path PG, $w \in W$
β_w	End node for PG, $w \in W$
pf_s	Weight for FA, $s \in S$
pc_s	Weight for CA, $s \in S$
pa_s	Weight for AA, $s \in S$
$orig_{i,s}$	Binary variable, if i is the source node of arc s, the parameter assumes value 1, 0 otherwise. $i \in N, s \in S$
$dest_{i,s}$	Binary variable, if i is the destination node of arc s, the parameter assumes value 1, 0 otherwise. $i \in N, s \in S$
π_w	Number of passengers for PG, $w \in W$
dt_w	Departure time for PG, $w \in W$
$o_{m,r}$	Binary parameter which assumes value 1 if m and r are a couple of alternative arcs, $m, r \in A$
cap_i	Indicates the maximum passenger capacity that train can assume at the node $i \in N$
M	Big value in respect to the value of the variables of the problem

Decisional Variables

l_i	Starting time of a logistic operation at the node $i \in N$
at_w	Arrival time at destination station for the PG, $w \in W$
$y_{m,s}$	Binary variable that indicates the presence of a CRP between two nodes associated to arcs m and s. It assumes value 1 if arc s is selected to solve the CRP and it assumes value 0 if the arc m is selected to solve the CRP. $m, s \in A$
q_f^w	Binary variable that assumes value 1 if arc f belongs to the path of the PGg. $f \in F \cup C, w \in W$
K_{SM}	PG's paths completion time index in the scheduling model
K_{RM}	PG's paths completion time index in the rescheduling model

Model definition

The MTSM is formalized by min-max criteria associated to a minimization problem with a linear objective. The min–max version consists of finding a solution having the best-worst case value in the traveling time of the considered set of PGs.

$$\min\ K_{SM} + \gamma_s \sum_{i=1}^{N} l_i \qquad \text{Equation 57}$$

The objective function (Equation 57) has two terms. The first one minimizes K_{SM} which represents the maximum value of the completion time of the PGs' paths to reach the destination weighted by the number of passengers of each PG and implemented by Equation 58. The second term is the sum of the overall time to compute the logistic operations in the rail network. The parameter γ_s weights the second term of the objective function.

$$\pi_w(at_w - dt_w) < K_{SM} \qquad w \in W \qquad \text{Equation 58}$$

Constraints (2) allow the implementation of the min-max approach.

$$\begin{aligned} l_j \geq l_i + \left(orig_{i,f} dest_{jf} pf_f\right) & \qquad i,j \in N \\ - M\left(1 - \left(orig_{i,f} dest_{j,f}\right)\right) & \qquad f \in F \qquad \text{Equation 59} \end{aligned}$$

Equation 59 ensures that, for two consecutive nodes, the starting time of a logistic operation at the node j$\in N$ has to start after the completion of the preceding operation. So l_j has to be greater than the starting time at node i and the travel time from node i to j, if the nodes i and j represent, respectively, the origin and the destination of the arc $f \in F$. This means that the arrival time of a train to the destination node of an arc has to be greater than the sum of the starting time at the origin node and the travelling time on the same arc in respect to the speed limits.

$$l_i \geq l_j + (orig_{j,m} dest_{i,m} pa_m) - M\left(1 - (orig_{j,m} dest_{i,m} o_{r,m})\right) - M\left(1 - (orig_{j,m} dest_{i,m} y_{r,m} o_{r,m})\right) \quad i,j \in N \quad m,r \in A, \quad m \neq r$$

Equation 60

$$l_k \geq l_h + (orig_{h,r} dest_{k,r} pa_r) - M\left(1 - (orig_{h,r} dest_{k,r} o_{r,m})\right) - M(orig_{h,r} dest_{k,r} y_{r,m} o_{r,m}) \quad k,h \in N \quad m,r \in A, m \neq r$$

Equation 61

According to the alternative graph construction as in [67], by Equation 60 and Equation 61, the model decides to activate one of the alternative arcs r or m in case of CRP ($o_{r,m} = 1$) among a couple of conflict operations at nodes i and k for one which belong to two different trains. Assuming that, the alternative arc m connects nodes j and i and arc r connect nodes h and k, if $o_{r,m} = 0$, the starting times of the logistic operations at the nodes are not constrained. By the big M approach and the binary variables associated to the matrices node-arc related to the alternative arcs, Equation 60 formalize the possibility to activate the arc m in order to allow the train, whose the node j-th belongs to, accessing firstly the disputed rail section. If $y_{r,m} = 1$ and contemporary $o_{r,m} = 1$, arc m is activated, so the operation at node j-th is scheduled before the operation at i-th whose starting time l_i has been postponed and it can start only after the starting time of the previous operation l_j added to the alternative arc cost pa_m, which represents a delay in the execution.

Complementary to Equation 60 is Equation 61 which allows activating arc r in case of CRP ($y_{r,m} = 0$) giving precedence to l_h.

$$\sum_{i=1}^{N} \sum_{u=1}^{F \cup C} orig_{\alpha_w,u} dest_{i,u} q_u^w = 1 \quad w \in W$$

Equation 62

Equation 62 ensures that the PGw starts its travel at the predefined station α_w.

$$\sum_{i=1}^{N}\sum_{u=1}^{F\cup C} orig_{i,u} dest_{\beta_w,u} q_u^w = 1 \qquad w \in W \qquad \text{Equation 63}$$

Equation 63 control that the PGw finishes the travel at predefined destination station β_w.

$$\sum_{u=1}^{F\cup C} dest_{i,u} q_u^w = \sum_{m=1}^{F\cup C} orig_{i,m} q_m^w \qquad i \in N, w \in W, \quad i \neq \alpha_w, \quad i \neq \beta_w \qquad \text{Equation 64}$$

Equation 64 guarantees PGs flow conservation at node i.

$$l_i \geq dt_w - M\left(\left(1 - orig_{\alpha_w,c}\right) dest_{i,c} q_c^w\right) \qquad i \in N \quad w \in W \quad c \in C \qquad \text{Equation 65}$$

Equation 65 ensures that the train on which PG can just depart after the arrival of the selected PG at the origin station.

$$\begin{aligned} l_j \geq l_i &+ \left(orig_{i,c} dest_{j,c} pc_c\right) \\ &- M\left(1 - \left(orig_{i,c} dest_{j,c}\right)\right) \\ &- M\left(1 - \left(orig_{i,c} dest_{j,c} q_c^w\right)\right) \end{aligned} \qquad i,j \in N \quad c \in C \quad w \in W \qquad \text{Equation 66}$$

By Equation 66, the model guarantees that PG may change train in case of transfer. A train cannot leave until the PG has reached the station at node $j - th$.

$$at_w \geq l_i - M\left(1 - \left(orig_{i,u} dest_{\beta_w,u} q_u^w\right)\right) \qquad i \in N \quad u \in F \cup C \quad w \in W \qquad \text{Equation 67}$$

Equation 67 computes the PGs arrival time at_w at the respective destination stations.

$$l_i \geq 0$$

$$i, j \in N$$

$$\sum_{w=1}^{W} orig_{i,u} dest_{j,u} q_u^w \pi_w \leq cap_i \qquad u \in F \cup C$$

Equation 68

Equation 68 assure that the number of passengers traveling on the train does not exceed the maximum allowed capacity at node i.

$$y_{r,m}, o_{m,r}, q_r^w \in \{0,1\} \qquad m, r \in F \cup C,$$

$$m \neq r$$

$$w \in W$$

$$orig_{i,c} dest_{i,c} \in \{0,1\} \qquad i \in N$$

$$l_i \geq 0 \qquad c \in \mathrm{S}$$

Equation 69

Finally, Equation 69 defines the optimization variables as positive and binary.

6.2.3 Min-Max Approach Train Rescheduling Model (MTRM)

Based on the MTSM results, the MTRM provides the new timetable adapted to the presence of possible disturbances on the railway network. The MTRM has been formalized assuming the same notation and using the same parameters of the MTSM. However, TRM takes, as input variables, the optimal value associated to the decision variables in output to the MTSM related to the starting time of the logistic operations l_i $i \in N$.

In the proposed model, the disturbances are represented by delays that occur on one or more nodes of the network. In this case, for the nodes affected by perturbations, a new value of the starting time is assumed to be worsened in respect to the optimal value coming from TSM application.

To apply the MTRM, the following new decision variables must be added.

- pfR_f: the new weight of fixed arcs concerning the traversing time.
- lR_i: new logistic operational time at node $i - th$.

- d_i: delay time of the logistic operational at node $i-th$ with respect to the optimal timetable obtained by applying MTSM.

- a_i: the advanced time of the logistic operational at node $i-th$ with respect to the optimal timetable obtained by applying MTSM.

Besides, a new parameter θ_i has been introduced in the model to represent the priority of the train at node $i-th$. The priority level decides which train has more importance to access firstly the track block when a CRP appears. Higher priority is given, more resilience is associated to the train.

The MTRM consists of the new objective (Equation 70) and a new set of constraints (Equation 71 and Equation 72 – Equation 76) but also it is subject to the Equation 59 – Equation 69 coming from MTSM.

The new objective and the new constraints for the MTRM are introduced below.

$$\min Obj1 + \gamma_{r2}\, Obj2 + \gamma_{r3} Obj3 + \gamma_{r4} Obj4 \qquad \text{Equation 70}$$

where

$$Obj1 = K_{RM}$$

$$Obj2 = \sum_{w=1}^{W} \pi_w (at_w - dt_w)$$

$$Obj3 = \sum_{i=1}^{N} \theta_i . d_i$$

$$Obj4 = \sum_{i=1}^{N} a_i$$

In the objective (Equation 70), the first component, $Obj1$, implements the min-max approach minimizing the maximum delay for each PG as computed in the constraint (Equation 71). The $Obj2$ minimizes the overall completion time of the PGs' travels compensating the drawbacks of the PGs' performances in terms of travel time. The $Obj3$ minimizes the delay time for the trains with higher priority. Finally, also the advance time for the overall logistic operations is minimized in $Obj4$.

The parameters $\gamma_{r2}, \gamma_{r3}, \gamma_{r4}$ weighting the different components in the objective function.

$$\pi_w(at_w - dt_w) \leq K_{RM} \qquad w \in W \qquad \text{Equation 71}$$

Equation 71 implement the min-max decision making which implies minimizing the worst scenario with respect to the set of PGs' paths in which higher is the difference between the arrival and the destination time. Those values are weighted anyway also by the number of persons for PG.

$$d_i \geq lR_i - l_i \qquad i \in N \qquad \text{Equation 72}$$

Equation 72 computes the delay time of the logistic operations at each node of the network. It must be greater than or equal to the difference between the starting time of the logistic operation decided in the MTRM solution and the optimal one coming from the previous scheduling phase MTSM. The presence of the third addendum $Obj3$ in the objective function guarantees that d_i will be as small as possible.

$$a_i \geq l_i - lR_i \qquad i \in N \qquad \text{Equation 73}$$

By Equation 73, the model guarantees that the advance time of the logistic operation at node i must be greater than or equal to the difference between the starting time generated in the MTSM and the new one generated by the MTRM.

$$pfR_f \geq pf_f \qquad f \in F \qquad \text{Equation 74}$$

Equation 74 defines the new weight of fixed arcs as greater than or equal to the predefined one in the MTSM.

$$lR_i \geq l_i \qquad i \in N \qquad \text{Equation 75}$$

By Equation 75, the new time of the logistic operation must be greater than or equal to the optimal logistic operational time in the MTSM. If $d_i = 0$, Equation 75 is equal to Equation 72.

$$lR_i \geq 0 \qquad i \in N \qquad \text{Equation 76}$$

Finally, Equation 76 defines the variables domain.

6.3 Case study

This section presents the case study based on a real application located on the railway network in Italy. Trenitalia is the main important rail company in Italy. The selected network consists of the railway infrastructures which connect the 6 main cities in Northern Italy by 10 high-speed train services. Two types of train have been considered: “freccia” and “intercity”. Freccia is the high-speed train of Trenitalia, it can travel on all European high-speed networks and it can reach a max speed of 400km/h. It has a maximum passenger capacity lower than intercity trains. Intercity trains connect major and minor cities in Italy to meet the different mobility clients’ requirements of medium to long distances. Figure 18 represents the map of the network in North Italy, with the main stations in the leading cities.

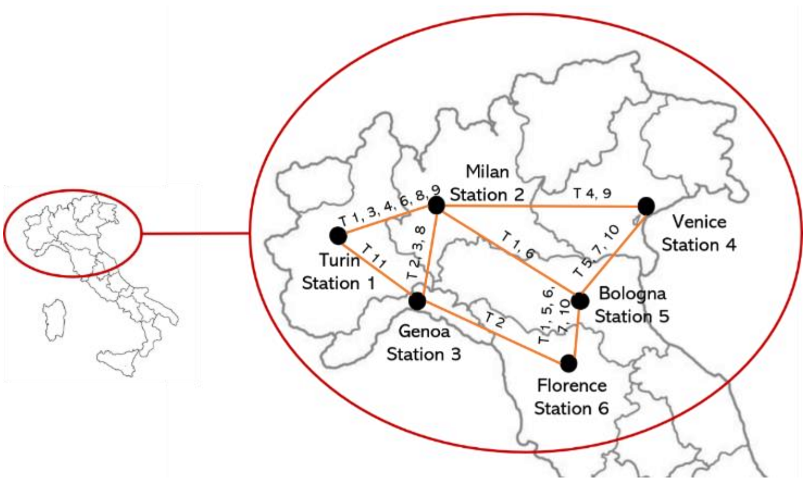


Figure 18. Northern Italy Trenitalia network. Tx on the links represent the considered train lines.

As Figure 18 shows, Station 1 (Turin) is linked to Station 2 (Milan) through trains 1, 3, 4, 6, 8, and 9; Station 1 is also liked to Station 3 (Genoa) by train 11. Station 2 (Milan) is linked to Station 3 (Genoa) through trains 2, 3, and 8, to Station 4 (Venice) through trains 4 and 9, and to Station 5 (Bologna) through trains 1 and 6. Station 3 (Genoa) is also linked to Station 6 (Florence) through train 2. Finally, Station 5 (Bologna) is also linked to Station 4 (Venice) through trains 5, 7, 10, and to Station 6 (Florence) through trains 1, 5, 6, 7, and 10. Figure 19 shows the railway network scheme with each train stop and siding area. In the graph, each line represents a different train; the nodes represent the logistic operation related to the selected train while the vertical sections represent the track blocks associated to the stations of the network. Turin and Venice stations may be the only origin or destination for the PGs' paths while the other station also includes origin, stop, or siding area.

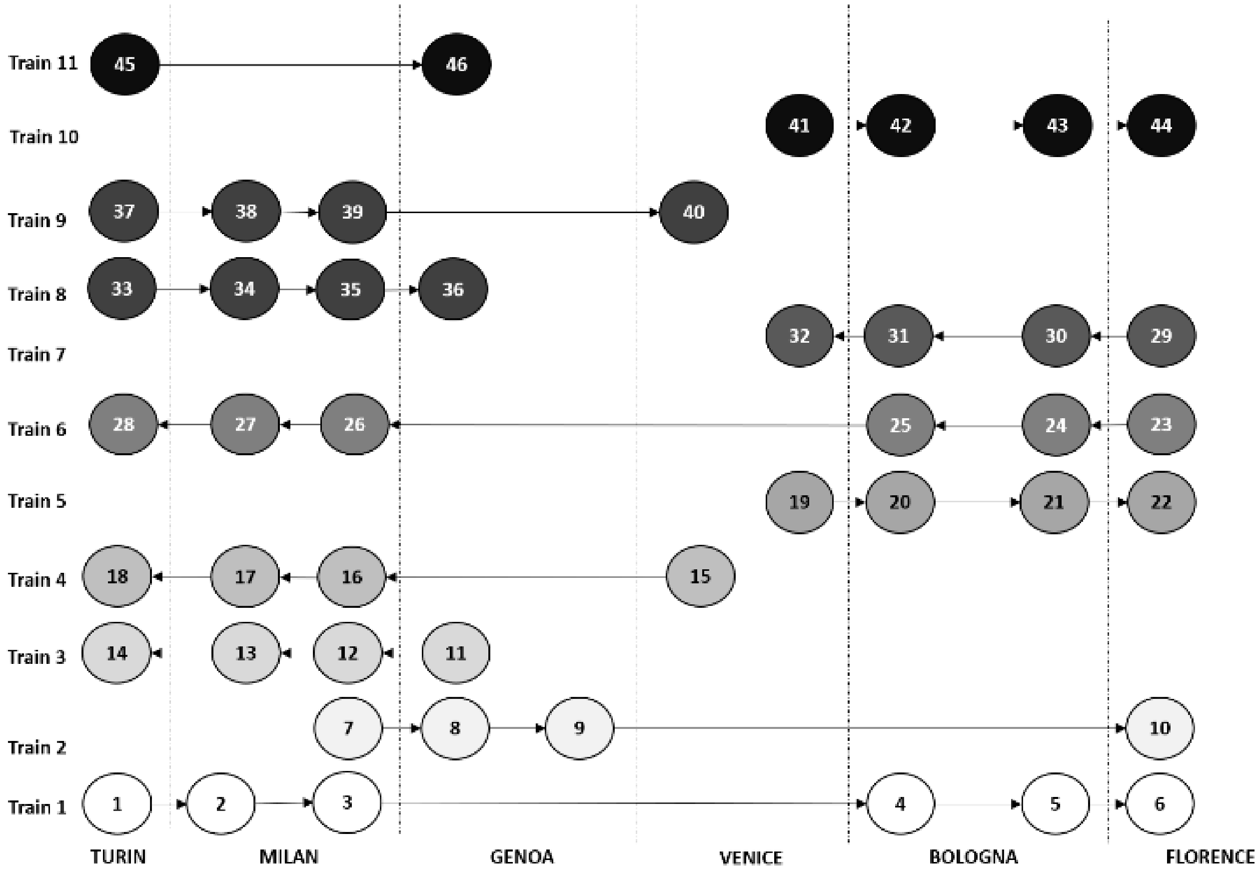


Figure 19. Network scheme

For better readability of the network scheme in Figure 19, some examples are presented. The nodes 1 to 6 belong to Train 1 which departs from Turin and stops at Milan and Bologna, with Florence as the destination. Node 2 represents the train arrival in Milan station while node 3 its departure to the Bologna station. It is a freccia train with a capacity of 492 passengers. Nodes 23 to 28 belong to Train 6, a freccia train, traveling from Florence to Turin, with stops in Bologna and Milan. Train 8 departs from Turin with node 33, stops at Milan station (nodes 33 and 34), and finishes the path at Genoa station at node 36. It is an intercity train with a maximum capacity of 600 passengers.

Table 24 summarizes the train's path features with the origin, destination, and intermediate stations, type of train, and maximum passenger capacity.

	Origin Station	*Intermediate Stations*	*Destination Station*	*Type of Train*	*Maximum passenger's capacity*
T1	Station1	Station2 Station5	Station6	*Freccia*	492
T2	Station2	Station3	Station6	*Freccia*	492
T3	Station3	Station2	Station1	Intercity	600
T4	Station4	Station2	Station1	*Freccia*	492
T5	Station4	Station5	Station6	*Freccia*	492
T6	Station6	Station5 Station2	Station1	*Freccia*	492
T7	Station6	Station5	Station4	*Freccia*	492
T8	Station1	Station2	Station3	Intercity	600
T9	Station1	Station2	Station4	*Freccia*	492
T10	Station4	Station5	Station6	Intercity	600
T11	Station1	-	Station3	Intercity	600

Table 24. Train data

The proposed case study has to manage the paths of 9 PGs with a different starting time, origin, and destination stations for the paths. The PGs data, a priori known, appears in

Table 25.

	Origin station	*Destination station*	π_w	dt_w
PG 1	Station3 Genoa	Station6 Florence	230	8:00
PG 2	Station1 Turin	Station6 Florence	200	8:00
PG 3	Station1 Turin	Station3 Genoa	200	8:00
PG 4	Station4 Venice	Station3 Genoa	100	7:00
PG 5	Station5 Bologna	Station3 Genoa	200	8:00

PG 6	Station4 Venice	Station1 Turin	90	7:00
PG 7	Station2 Milan	Station6 Florence	100	8:00
PG 8	Station6 Florence	Station4 Venice	100	8:00
PG 9	Station4 Venice	Station6 Florence	250	7:00

Table 25. PGs Data

6.4 Results

This section presents the results obtained with the application of the MTSM and MTRM. The models have been implemented in Cplex. Once the optimal train schedule results from the MTSM, set disturbances (delays) that affect the network has been applied. Finally, the MTRM model generates the optimal timetabling adapted to manage the applied perturbations in order to minimize the secondary delays and the failure propagation.

6.4.1 MTSM Model Application

Each PG intended to reach the destination station in the shortest possible time according to the operational constraints related to the network. The following Table 26 and Table 27 present, respectively, the optimal routes for trains and PGs.

	Departure time (l_i)	***Time at intermediate stations***		***Arrival time (l_i)***
T1	9:46	10:49-11:00	12:10-12:12	12:43
T2	8:00	9:46-10:00		11:25
T3	12:00	13:42-13:44		15:30
T4	8:00	10:00-10:50		11:50
T5	8:00	9:50-9:52		10:25
T6	8:30	9:03-9:05	10:15-11:51	12:51
T7	8:00	8:30-9:51		11:41
T8	8:00	9:46-10:17		11:59

T9	8:00	9:00-10:00	12:00
T10	11:42	13:31-13:33	14:30
T11	8:00	-	9:58

Table 26. Train timetable by MTSM

	Train departure station	***Train arrival station***	***Departure time***	***Arrival time*** (at_w)	***Travel time***	***Completion time*** $(at_w - dt_w)$
PG1	T2	T2	10:00	11:25	1:25	3:25
PG2	T11	T2	8:00	11:25	3:25	3:25
PG3	T11	T11	8:00	9:58	1:58	2:58
PG4	T4	T8	8:00	11:59	3:59	4:59
PG5	T6	T8	9:05	11:59	2:54	3:59
PG6	T4	T3	8:00	15:30	7:30	8:30
PG7	T1	T10	11:00	14:30	3:30	6:30
PG8	T7	T7	8:00	11:41	3:41	3:41
PG9	T5	T5	8:00	10:25	2:25	3:25

Table 27. PG's Optimal Paths

Four PGs used a direct route to reach their destination while other PGs needed to change, at least one time, the train. In Table 27 it is possible to observe the travel time of each PG (time of the trip) and the related completion time which starts at the PG's arrival at the virtual starting node and the arrival time at the destination.

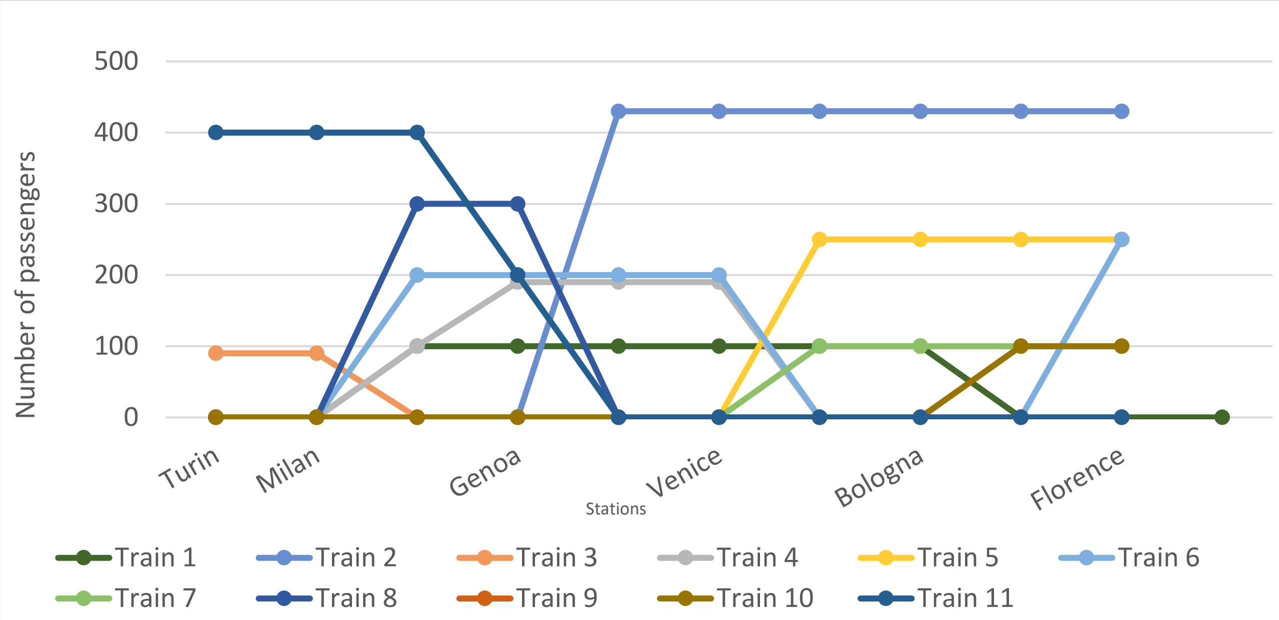


Figure 20. Train occupancy

In the proposed solution, trains 2, 11, and 8 are mostly used by PGs while train 9 travels empty, as we can see in Figure 20.

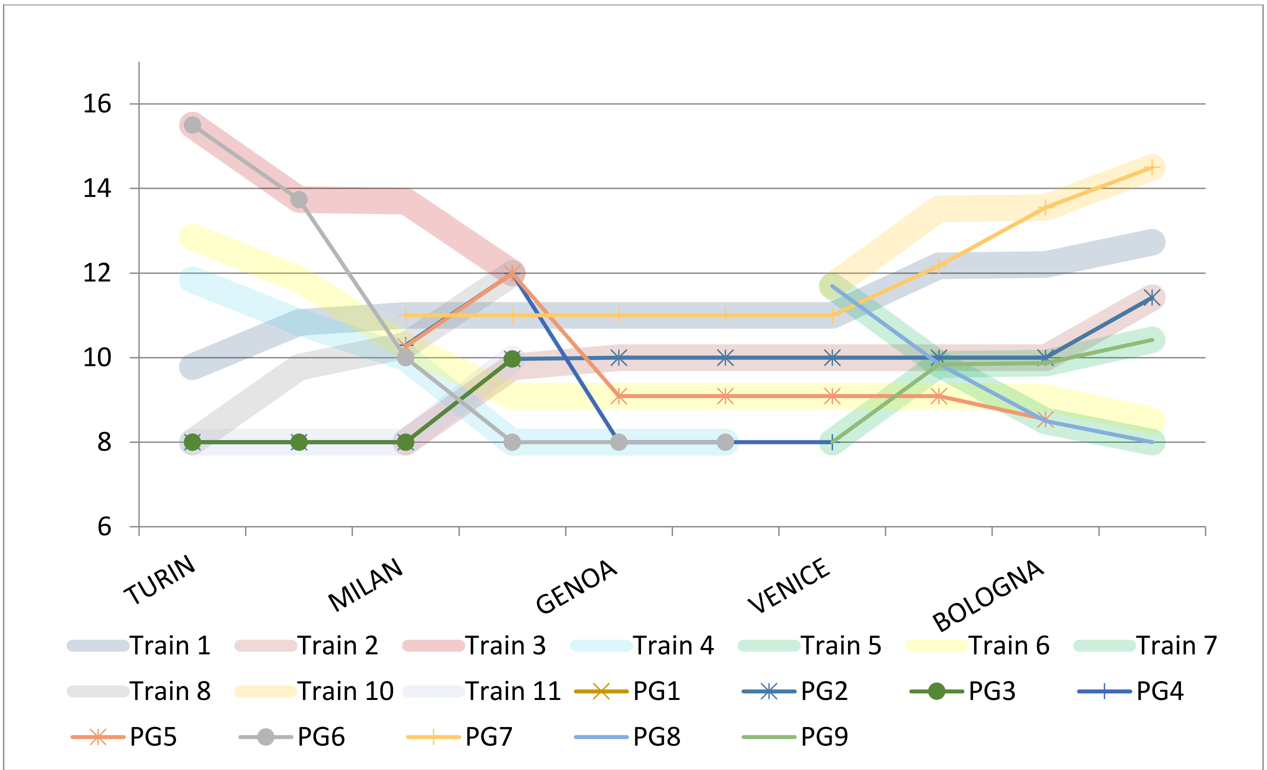


Figure 21. MTSM results and PGs' allocation to trains

Figure 21 shows the route of each PG through the different available trains and the stations where the train changing takes place. As an example, PG6 departs from Venice with Train 4 and, at Station 2 (Milan), it changes from Train 4 to Train 3 to reach Turin at 15:30. The PG9 remains on Train 5, from the beginning (Venice) to the end of its travel (Florence). By this approach, PG's paths completion time index is $K_{SM} = 854{,}2$.

According to the presented MTSM results, the MTRM is then applied to recover the delays generated by the operational disturbances on some nodes.

6.4.2 MTRM Model Application

To evaluate the MTRM performances, the disturbances have been added to the nodes which belong to the paths of the mainly used trains. A delay of half an hour on the departure time has been forced for train 2 and train 8 at nodes 7 and node 33 of the network in figure 3, so let's l_7 = 8.30 and l_{33} = 8.30.

The MTRM results appear in Table 28.

	Departure time	***Time at intermediate stations***		***Arrival time***
T1	**10.16**	**11:19-11:30**	**12:40-12:42**	**13:13**
T2	**8:30**	**10:16-10:19**		**11:45**
T3	12:00	13:42-13:45		15:30
T4	8:00	10:00-**11:20**		**12:20**
T5	8:00	9:50-9:52		10:25
T6	8:30	9:03-9:05	10:15-**12:21**	**13:21**
T7	8:00	8:30-9:51		11:41
T8	**8:30**	**10:16-10:18**		**12:00**
T9	8:00	9:00-10:00		12:00
T10	11:42	13:31-13:33		14:30
T11	8:00	-		9:58

Table 28. Train Timetable by MTRM after disturbances application

In Table 28 we can see that the input disturbances on the path of Train 2 and 8 also affect the timetable of Train 1, 4, and 6, generating delays in some or all the stations where the trains stop. In the case of Train 1, the disturbance causes the delay already at the beginning of the trip. Instead, in Train 4 and 6, the delay only occurs in the last two stations.

	Train departure station	***Train arrival station***	***Departure time***	***Arrival time*** (at_w)	***Travel time***	***Completion time*** $(at_w - dt_w)$
PG1	T2	T2	**10:19**	**11:45**	**1:26 (+0:01)**	**3:45 (+0:25)**
PG2	T11	T2	8:00	**11:45**	**3:45 (+0:20)**	**3:45 (+0:25)**
PG3	T11	T11	8:00	9:58	1:58	2:58
PG4	T4	T8	8:00	**12:00**	**4:00 (+0:01)**	**5:00 (+0:01)**
PG5	T6	T8	9:05	**12:00**	**2:55 (+0:01)**	**4:00 (+0:01)**
PG6	T4	**T4**	8:00	**12:20**	**4:20 (-3:10)**	**5:20 (-3:10)**
PG7	T1	**T1**	**11:30**	**13:13**	**1:47 (-1:43)**	**5:13 (-0:43)**
PG8	T7	T7	8:00	11:41	3:41	3:41
PG9	T5	T5	8:00	10:25	2:25	3:25

Table 29. PGs' paths in MTRM after disturbances (in bold the difference in time in respect to the MTSM in Table 27)

Table 29 shows how the new timetable affects the passengers' journeys.

The input disturbances at the node l_7 affect the paths of PG1 and PG2, which reach the destination with a delay of 25 minutes with respect to the MTSM. PG3, PG8, and PG9 do not perceive any consequences on their trips.

On the other hand, PG 7 obtains the advantage to compute its path one hour and 43 minutes in advance. Mainly benefits are produced for PG6. The reason is related to the priority variables associated to the trains. The PG6, in fact, starts its travel on Train 4, which is a freccia train, whose nodes are classified as a higher priority. In the MTSM, the PG6 changes the train at an intermediate station, while in the MTRM, it continues its trip through Train 4 without any changes. This provides the PG6 with arriving at the destination 3 hours and 10 minutes in advance. The reason may be reconducted to the objective function: in the scheduling model, MTSM, the objectives minimize the maximum completion time of the PGs weighted for the number of PG's passengers. Unfortunately, PG counts the smaller number of passengers, $\pi_6 = 90$, so it may leave Train 4 and complete its path by Train 3.

On the contrary, in the rescheduling model MTRM, Train 4 holds the nodes at a higher priority, so this path has precedence on Train 3 which is classified as intercity, with lower priority. This means that PG6 can proceed on the same train and reach its destination in advance. It is verified by a CRP detection between Train 3 and 4 to enter the block section at Station 1 (Turin) coming from Station 2 (Milan). Between the pair of alternative arcs, AA1, which connects node 14 of Train 3 to node 17 of the Train 4, and AA2, which connects node 18 of Train4 and node 13 of Train 3, only the arc AA2 is activated.

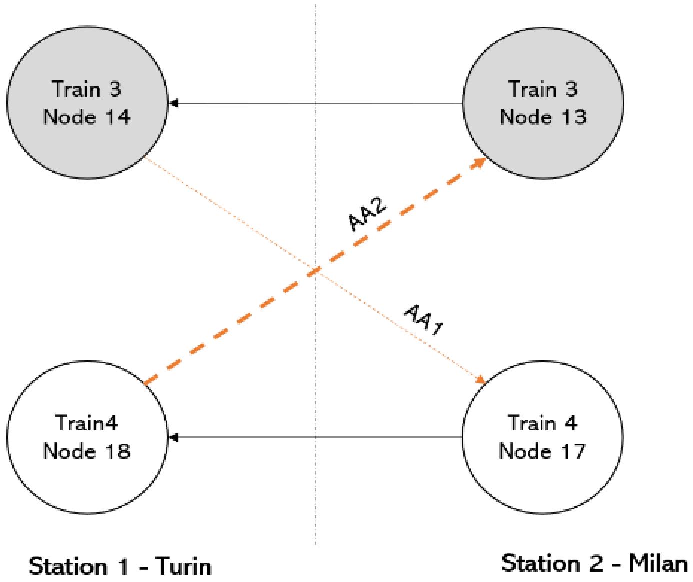


Figure 22. CRP between Train 3 and Train 4 in the case study

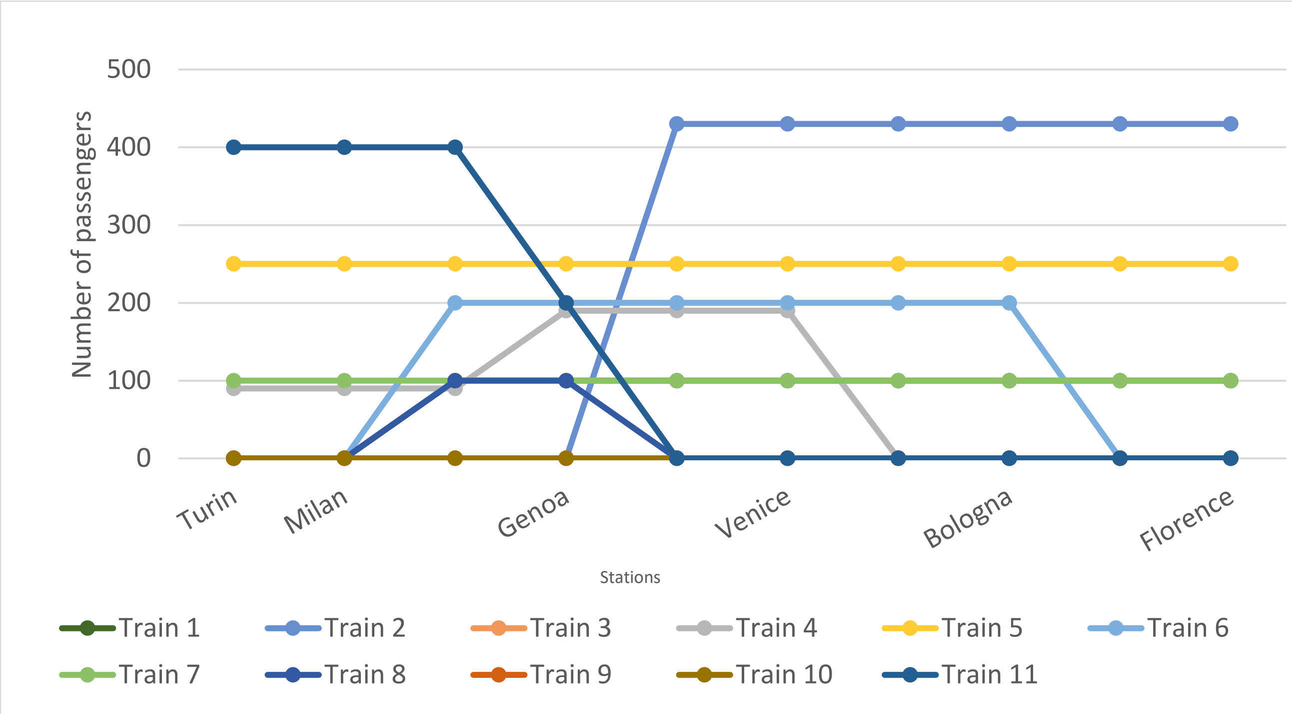


Figure 23. Occupancy of each train

This means that priority is given to Train 4 while the access of Train 3 is delayed, as shown in Figure 22. The starting time of operation at node 13, l_{13} may start only after the completion of l_{18} plus the alternative arc AA2 cost. The MTRM approach produces the PG's paths completion time index $K_{RM} = 862{,}5$.

Figure 23 shows train capacities. Throughs Figure 23 and Figure 24, which represent PGs allocation on the train paths, also highlight the PGs 6 and 7 do not change trains concerning the MTSM.

6.4.3 MTRM VS Rescheduling Model

To evaluate the MTRM performances, a rescheduling model based on a traditional minimization problem has been implemented.

The objective function in the rescheduling model (RM) is replaced and formalized considering only the last three objectives in Equation 70 omitting the min-max criteria. The new objective in the RM (Equation 77) is the following, where $\vartheta_1, \vartheta_2, \vartheta_3$ are weighting parameters.

$$\min \quad \vartheta_1 \sum_{w=1}^{W} \pi_w (at_w - dt_w) + \vartheta_2 \sum_{i=1}^{N} \theta_i . d_i + \vartheta_3 \sum_{i=1}^{N} a_i \qquad \text{Equation 77}$$

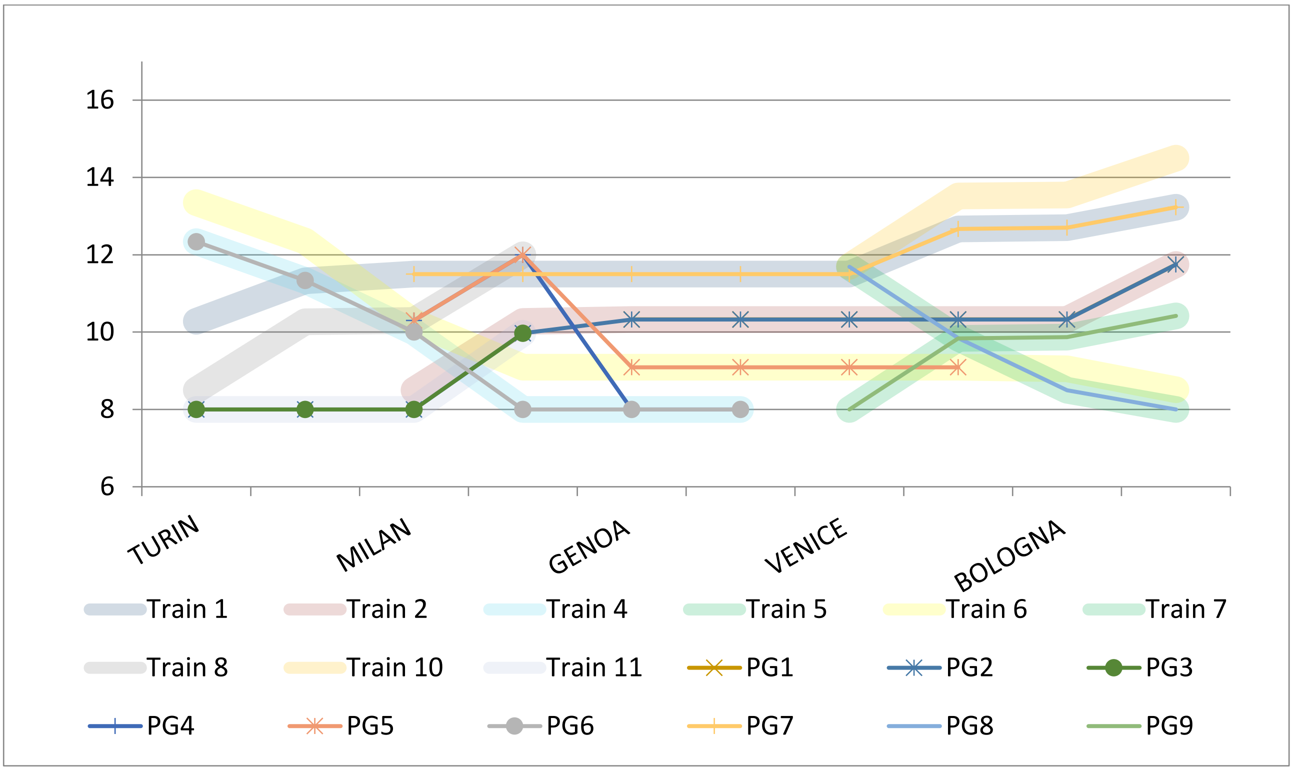


Figure 24. MTRM results and PGs' allocation to trains

	Departure time	*Time at intermediate stations*	*Arrival time*
T1	**10.16**	**11:19-11:30 12:40-12:42**	**13:13**
T2	**8:30**	**10:16-10:19**	**11:45**
T3	12:00	13:42-13:45	15:30
T4	8:00	10:00-**11:20**	**12:20**
T5	8:00	9:50-9:52	10:25
T6	8:30	9:03-9:05 10:15-**12:21**	**13:21**
T7	8:00	8:30-9:51	11:41
T8	**8:30**	**10:16-10:18**	**12:00**
T9	8:00	9:00-10:00	12:00
T10	11:42	13:31-13:33	14:30
T11	8:00	-	9:58

Table 30. Train timetable by RM after disturbances application

	Train departure station	*Train arrival station*	*Departure time*	*Arrival time* (at_w)	*Travel time*	*Completion time* $(at_w - dt_w)$
PG1	T2	T2	**10:19**	**11:45**	**1:26 (+0:01)**	**3:45 (+0:25)**
PG2	**T1**	**T1**	**10:16**	**13:13**	**2:57 (-0:28)**	**3:45 (+0:25)**
PG3	T11	T11	8:00	9:58	1:58	2:58
PG4	T4	T8	8:00	12:00	4:00 (+0:01)	**5:00 (+0:01)**
PG5	T6	T8	9:05	12:00	2:55 (+0:01)	**4:00 (+0:01)**
PG6	T4	T4	8:00	12:20	4:20 (-2:50)	**5:20 (-3:10)**
PG7	T1	T10	**11:30**	14:30	**3:00 (-0:30)**	6:30
PG8	T7	T7	8:00	11:41	3:41	3:41
PG9	**T10**	**T10**	**11:42**	**14:30**	**2:48 (+0:23)**	**7:30 (+4:05)**

Table 31. Optimal PGs' paths in RM after disturbances (in bold the difference in respect to the MTSM in Table 26)

The RM is subject to Equation 59 – Equation 69 by MTSM and to Equation 70 – Equation 76 by MTRM. Equation 58 and Equation 71 which implement the min-max approaches are skipped.

The results of the RM application appear in Table 30 and
Table 31.

Table 30 shows that the timetable in the RM approach, applying the same disturbances, reflects the MTRM results.

On the other hand, Table 31 shows that the new optimal PGs' paths present variances with respect to the MTRM application.

	$\boldsymbol{\pi_w(at_w - dt_w)}$, $\boldsymbol{w \in W}$		
	MTSM	**RM**	**MTRM**
PG1	785,8	862,5	**862,5 ($\boldsymbol{K_{RM}}$)**
PG2	683,3	750,0	750,0
PG3	393,3	593,3	593,3
PG4	498,3	500,0	500,0
PG5	796,7	800,0	800,0
PG6	765,0	480,0	480,0
PG7	450,0	650,0	521,7
PG8	368,3	368,3	368,3
PG9	**854,2 ($\boldsymbol{K_{SM}}$)**	**1875,0**	854,2

Table 32. PGs' paths completion time indices (in bold the maximum value for each approach)

	Travel time of the PGs		***Completion time of the PGs*** $\boldsymbol{\pi_w(at_w - dt_w)}$	
	Average value	**Maximum value**	**Average value**	**Maximum value**
MTSM	03:14	07:30	04:12	08:30
RM	03:00	04:20	04:42	07:30
MTRM	02:54	04:20	04:07	05:20

Table 33. Performance Comparison

Now, PG2 and PG9 use different trains to carry out their tours. While the completion time of PG2 is just the same, PG9 suffers a delay both in travel and in completion time. This latter presents a delay of four hours and five minutes in respect to the MTRM approach. This result demonstrates as the min-max approach fits the maximum disturbance dejection. In the RM results, in fact, the larger time completion is generated for the PG9 which, due to the great number of passengers, generates the worse objective function value associate to the term $\boldsymbol{\pi_w(at_w - dt_w)}$ among the set of PGs (see Table 32).

The concept of min-max criteria should provide the best solution in the worst case minimizing the main impact of perturbations on the system.

In the proposed case study, the MTRM minimizes the maximum values of delay in the time schedule, associated to the PG9, reducing to more than the halved objective function, and providing feasible solutions for the other PGs. However, from Table 33, it is evident that MTRM approach dominated the solutions of the other models in terms of average and maximum value both for travel time and completion time for the selected set of PGs.

Chapter 7. Discussion and future development

7.1 Conclusions

The first part of this study, Chapter 3, shows a mixed-integer optimization model for a TEN-based TTDP for short stays in mass tourist destinations.

The performance of the proposed optimal model has been compared with the solution generated by an innovative heuristic approach. The case study focuses on a particular sensible and precious touristic area located in Liguria Region, in Italy.

The main purpose of the research in this area is to present methodologies useful to local administrators who need to reduce the negative impact of mass tourism in their territories. The objective is not to deny access to the locations but to manage the touristic arrivals in respect to the living conditions of the residents as well as the experience of tourists who visit the places, paying particular attention to limiting the crowding of the municipalities.

The models proved to be particularly effective for the case study developed. The management of touristic arrivals in the selected locations minimize the ECC occupation in respect to the planned timetable of the GTs' tours.

The second part of this study, developed in three chapters, contains the development of a scheduling and rescheduling model that controls the railway traffic in real-time, minimizing the travel time for passengers and solving potential conflicts among trains on the specific interconnection of the railway network. The railway systems represent a set of many sub-systems with complex connections.

The research simplifies the optimization problem by generating the alternative graph of the railway network and then, formulates the scheduling and rescheduling problems with linear programming models. Among the trains in conflict, on the same block section, the train with greater occupancy has the priority to cover the best path and to reach its destination faster, applying the resolution of the problem presented as CRP.

When a disturbance enters the network, delays appear on the railroad, which can lead to dissatisfaction in the network user. In this case, the rescheduling model is applied to restore the network in the shortest time. In the results obtained, there are some trains that recover part of the delay and arrive at the destination station ahead of schedule, respecting the speed limits.

Chapter 4 aims at developing two models, which assess strategies for trains and passengers acting on railway sub-systems behavior such as train speed, passengers behavior, or failures on the network. In detail, the TR2 model allows the trains to reach the maximal speed on the rail section to reduce the delay if a disturbance has been detected on the network. At the same time, the optimization problem aims also at minimizing the travel times of passengers to reach their destination by changing their routing.

Chapters 5 and 6 focus on the development of the scheduling and rescheduling model in high-speed trains. The objective remains the same, to minimize the travel time of the passengers. Unlike regional trains, in this case the train's capacity is limited. In addition, the real case study focuses on two types of trains with different priority ("freccia" and intercity, giving the highest priority and importance to category "freccia" trains). Analysing the results obtained when applying the models presented in Chapter 5, the efficiency of the approach to the problem presented is confirmed.

Furthermore, in Chapter 6, introducing some disturbances, the min-max approach for the rescheduling model highlights that perturbation may be reduced in respect to the simple minimization of the objective function. The introduction of the concept of priority of trains at high-speed profile guarantees more resilience for the secondary delay propagation favouring the passengers' requirement to reach their destination with a minimum travel time. The comparison between the min-max algorithm and the minimization model proves the efficiency of the proposed approaches. The PG's paths completion time index appears significantly inferior in the min-max approach which means that the maximum value of the secondary delay on the network has been reduced improving the real-time traffic management.

7.2 Future research

For a future development of the project, there are some open issues to be investigated.

The first issue is related to the complexity of the problem presented in Chapter 3, that is directly linked to the dimension of the Time Expanded Network. Future research of this theme should be dedicated to testing the model increasing the number of groups of tourists and the number of available transport services. For this purpose, an ad-hoc algorithm should be implemented to generate automatically the TEN associating touristic demand and their parameters.

The same happens with the train scheduling and rescheduling models. The complexity of the problem depends on the network dimension. In the proposed case studies, the models are shown to be consistent for limited instances of the problems. Anyway, special attention must be dedicated to computation time for more complex applications.

A future line of investigation could be dedicated to test the model increasing the number of trains stations, the number of trains and the Group of Passengers'. Also, for this purpose, an ad hoc software should be implemented to automatically generate the alternative graph, that allows to solve the Conflict Resolution Problem.

Besides, also features related to passengers can be further explored. In the proposed approach, the PGs are considered indivisible, anyway, it possible to consider different solutions for passengers according to resource availability.

In the study of railway networks, also a heuristic algorithm may be explored to solve larger instances of the problem, since the different case studies presented focus on relatively small networks.

On the other hand, in the study of mass tourism, it could be improved the quality of the heuristic method reconducting the algorithm to a variation of the classic assignment problem in order to increase the performance.

Future research should anyway consider the integration in the model of train scheduling and rescheduling, the speed profile of trains and dwell time for the logistic operations, or other strategic goals of the decision-makers as the ticket costs for passengers or crew management and economic profits for railway managers. Also, in the case of mass tourism, it could be considered the ticket prices of the different means of transport, for example.

Bibliography

[1] D. Streimikiene, B. Svagzdiene, E. Jasinskas and A. Simanavicius, “Sustainable tourism development and competitiveness: The systematic literature review,” *Sustainable Development,* vol. 29, no. 1, pp. 259-271, 2020.

[2] C. Zhu, J. Q. Hu and F. Wang, “On the tour planning problem.,” *Annals of Operations Research,* vol. 192, pp. 67-86, 2012.

[3] G. H. Brundtland, “Our Common Future,” World Commission on Environment and Development, 1987.

[4] L. Dwyer and D. Edwards, “Understanding the Sustainable Development of Tourism,” in *Sustainable tourism planning,* Goodfellow Publishers Ltd, 2010, pp. 20-44.

[5] C. Padin, “A sustainable torusim planning model: components and relationships.,” *European Business Review,* vol. 24, no. 6, pp. 510-518, 2012.

[6] S. Gössling and D. Scott, “Scenario planning for sustainable tourism: an introduction.,” *Journal of Sustainable Tourism,* vol. 20, no. 6, pp. 773-778, 2012.

[7] B. Bramwell and A. Sharman, “Approaches to sustainable tourism planning and community participation,” in *Tourism and Sustainable Community Development,* London, Routledge, 2000, p. 19.

[8] A. Scuttari, M. Della Lucia and U. Martini, “Integrated planning for sustainable tourism and mobility. A tourism traffic analysis in Italy's South Tyrol Region.,” *Journal of Sustainable Tourism,* vol. 21, no. 4, pp. 614-637, 2012.

[9] E. W. Manning and T. D. Dougherty, “Planning Sustainable Tourism Destinations,” *Tourism Recreation Research,* vol. 25, no. 2, pp. 3-14, 2014.

[10] I. Maltese, V. Gatta and E. Marucci, “Active Travel in Sustainable Urban Mobility Plans. An Italian overview.,” *Research in Transportation Business & Management,* 2021.

[11] J. Dallen, “Sustainable Transport, Market Segmentation and Tourism: The Looe Valley Branch Line Railway, Cornwall, UK.,” *Journal of Sustainable Tourism,* vol. 15, no. 2, pp. 180-199, 2009.

[12] L. Steg and R. Gifford, “Sustainable transportation and quality of life.,” *Journal of Transport Geography,* vol. 13, no. 1, pp. 59-69, 2005.

[13] F. Xiong, L. Z. Yang, J. Luo and Y. L. He, “Research on Green Railway System of Sustainable Development,” *Journal of Railway Engineering Society,* vol. 5, 2007.

[14] R. F. Abenoza, O. Cats and Y. O. Susilo, “Travel satisfaction with public transport: Determinants, user classes, regional disparities and their evolution,” *Transportation Research Part A: Policy and Practice,* vol. 95, pp. 64-84, 2017.

[15] M. Mrníková, M. Poliak, P. Šimurková, S. Hernandez and N. Reuter, “How Important is the Integration of Public Passenger Transport.,” *LOGI – Scientific Journal on Transport and Logistics,* vol. 8, no. 2, pp. 59-68, 2017.

[16] T. Dean and S. Kambhampati, “Planning and Scheduling,” in *Computer Science Handbook,* CRC Press, 2004, pp. 23-67.

[17] X. Zhou and M. Zhong, “Bicriteria train scheduling for high-speed passenger railroad planning applicactions.,” *European Journal of Operational Research,* vol. 167, no. 3, pp. 752-771, 2005.

[18] S. Maas, M. Bugeja and M. Attard, “Sustainable Tourism Mobility in Malta: Encouraging a Shift in Tourist Travel Behavior Through an Innovative Smartphone App for Trip Planning.,” *Sustainable Transport and Tourism Destinations (Transport and Sustainability),* vol. 13, pp. 79-95, 2021.

[19] C. L. Ho, P. S. Li, Y. C. Wang, P. Y. Chou, Y. L. Pan and S. T. Chen, “Constructing a Customized Travel Scheduling Recommendation Service Based on Personal Preference and Special Requirements.,” *ICST,* vol. 354, pp. 414-425, 2021.

[20] K. Sylejmani, J. Dorn and N. Musliu, “Planning the trip itinerary for tourist groups.,” *Information Technology & Tourism,* vol. 3, no. 17, pp. 275-314, 2017.

[21] D. Gavalas, C. Konstantopoulos, K. Mastakas and G. Pantziou, “A survey on algorithmic approaches for solving tourist trip design problems.,” *Journal of Heuristics,* vol. 3, no. 20, pp. 291-328, 2014.

[22] K. Lim, J. Chan, C. Leckie and S. Karunasekera, “Personalized trip recommendation for tourists based on user interests, points of interest visit durations and visit recency.,” *Knowledge and Information Systems,* vol. 54, pp. 375-406, 2018.

[23] A. Expósito, S. Mancini, J. Brito and J. A. Moreno, “A fuzzy GRASP for the tourist trip design with clustered POIs.,” *Expert Systems with Applications,* vol. 127, pp. 210-227, 2019.

[24] A. Gunawan, H. C. Lau and P. Vansteenwegen, “Orienteering problem: A survey of recent variants, solution approaches and applications.,” *European Journal of Operational Research,* vol. 2, no. 255, pp. 315-332, 2016.

[25] M. Fieschetti, J. J. Salazar-González and P. Toth, “The Generalized Traveling Salesman and Orienteering Problems. In: Gutin G., Punnen A.P. (eds) The Traveling Salesman Problem and Its Variations.,” *Combinatorial Optimization,* vol. 12, pp. 609-662, 2007.

[26] W. Zheng and Z. Liao, “Using a heuristic approach to design personalized tour routes for heterogeneous tourist groups,” *Tourism Management,* vol. 72, pp. 313-325, 2019.

[27] K. Sylejmani, J. Dorn and N. Musliu, “Planning the trip itinerary for tourist groups.,” *Information Thecnology & Tourism,* vol. 17, pp. 275-314, 2017.

[28] J. F. Bérubé, J. Y. Potvin and J. Vaucher, “Time-dependent shortest paths through a fixed sequence of nodes: application to a travel planning problem.,” *Computers and Operations research,* vol. 33, no. 6, pp. 1838-1856, 2006.

[29] C. Zhu, J. Q. Hu, F. Wang, Y. Xu and R. Cao, “On the tour planning problem.,” *Annals of Operations Research,* vol. 192, no. 1, pp. 67-86, 2012.

[30] X. Kong, M. Li, T. T. K. Tang, L. Moreira-Matias and F. Xia, “Shared Subway Shuttle Bus Route Planning Based on Transport Data Analytics.,” *IEEE Transactions on Automation Science and Engineering,* vol. 15, no. 4, pp. 1507-1520, 2018.

[31] R. A. Abbaspour and F. Samadzadegan, “Time-dependent personal tour planning and scheduling in metropolises.,” *Expert Systems with Applications,* vol. 38, no. 10, pp. 12439-12452, 2011.

[32] M. Shakibayifar, E. Hassannayebi, Mirzahossein, H., F. Taghikhah and A. Jafarpur, “An intelligent simulation platform for train traffic control under disturbance.,” *International Journal of Modelling and Simulation.,* no. 39, pp. 135-156, 2019.

[33] C. Scheffer, “Train scheduling: Hardness and algorithms.,” *Proc. Int. Workshop Algorithms Comput. Cham, Switzerland: Springer.,* pp. 342-347, 2020.

[34] D. S. W. Lai and J. M. Y. Leung, “Real-time rescheduling and disruption management for public transit.,” *Transportmetrica B: Transport Dynamics,* no. 6, pp. 17-33, 2018.

[35] C. Meloni, M. Pranzo and M. Samà, “Risk of delay evaluation in real-time train scheduling with uncertain dwell times.,” *Transportation Research Part E: Logistics and Transportation Review,* vol. 152, 2021.

[36] S. Narayanaswami and N. Rangaraj, “Scheduling and rescheduling of railway operations: A review and expository analysis.,” *Technology Operation Management,* vol. 2, no. 2, pp. 102-122, 2011.

[37] R. M. P. Goverde, N. Bešinović, A. Binder, V. Cacchiani, E. Quaglietta, R. Roberti and P. Toth, “A three-level framwork for performance-based railway timetabling,” *Transportation Research Part C: Emerg. Technol.,* vol. 67, pp. 62-83, 2016.

[38] B. He, P. Chen, A. D'Ariano, L. Chen, H. Zhang and G. Lu, “A microscopic agent-based simulation for real-time dispatching problem of a busy railway passenger station.,” in *Proc. IEEE 23rd Int. Conf. Intell. Transp. Syst. (ITSC),* 2020.

[39] F. Corman, A. D'Ariano, A. Marra, D. Pacciarelli and M. Samà, “Integrating train scheduling and delay management in real-time railway traffic control.,” *Transportation Research Part C,* vol. 105, pp. 213-239, 2017.

[40] S. Binder, Y. Maknoon and M. Bierlaire, “The multi-objective railway timetable rescheduling problem.,” *Transportation Research Part C: Emerging Technologies,* vol. 78, pp. 78-94, 2017.

[41] C. Bersani, S. Qiu, R. Sacile, M. Sallak and W. Schön, “Rapid, robust, distributed evaluation and control of train scheduling on a single line track.,” *Control Engineering Practice,* vol. 35, pp. 12-21, 2015.

[42] J. Qi, S. Li, Y. Gao, K. Yang and P. Liu, “Joint optimization model for train scheduling and train stop planning with passengeres distribution on railway corridors.,” *Journal of the Operational Research Society,* vol. 69, pp. 556-570, 2018.

[43] C. Bersani, F. Papa, R. Sacile, M. Sallak and S. Terribile, “Towards dynamic exposure-based schedule for hazarfous material trains.,” *Journal of Rail Transport Panning and Management,* vol. 6, no. 2, pp. 116-127, 2016.

[44] Y. Wang, A. D'Ariano, J. Yin, L. Meng, T. Tango and B. Ning, “Passenger demand oriented train scheduling and rolling stock circulation planning for an urban rail transit line.,” *Transportation Research Part B: Methodological,* vol. 118, pp. 193-227, 2018.

[45] J. Lange and F. Werner, “Approaches to modeling train scheduling problems as job-shop problems with blocking constraints.,” *Journal of Scheduling,* vol. 21, no. 2, pp. 191-207, 2018.

[46] V. Cacchiani, “Models and algorithms for combinatorial optimization problems arising in railway applications.,” Doctoral Dissertation, Springer, DEIS, Univ. Bologna., Bologna, Italy, 2009.

[47] M. A. Shafia, S. J. Sadjadi, A. Jamili, R. Tavakkoli-Moghaddam and M. Pourseyed-Aghaee, “The periodicity and robustness in a single-track train scheduling problem.,” *Appl. Soft Comput.,* vol. 12, no. 1, pp. 440-452, 2012.

[48] W. Tian and E. Demeulemeester, “Railway scheduling reduces the expected project makespan over roadrunner scheduling in a multi-mode project scheduling environment.,” *Ann. Oper. Res.,* vol. 213, no. 1, pp. 271-291, 2014.

[49] A. Caprara, M. Monaci, P. Toth and P. L. Guida, “A lagrangian heuristic algorithm for a real-world train timetabling problem.,” *Discrete Appl. Math,,* vol. 154, no. 5, pp. 738-753, 2006.

[50] K. Ghoseiri, F. Szidarovszky and M. J. Asgharpour, “A multi-objective train scheduling model and solution.,” *Transportation Research Part B: Methodol.*, vol. 38, no. 10, pp. 927-952, 2004.

[51] A. D'Ariano, D. Pacciarelli and M. Pranzo, “A branch and bound algorithm for scheduling trains in a railway network.,” *Eurpean Journal of Operational Research,* vol. 183, no. 2, pp. 643-657, 2007.

[52] E. König, “A review on railway delay management.,” *Public Transp.*, vol. 12, no. 2, pp. 335-361, 2020.

[53] S. Yu, X. Han, B. Lin, Y. Gao, X. Dai and D. Cui, “Delay propagation mechanism model for high-speed train operation under arrival/departure time delay.,” in *IEEE 23rd Int. Conf. Intell. Transp. Syst.*, Sep. 2020.

[54] H. Belhomme, S. Dauzere-Peres, M. Gagnon and F. Ramond, “Using a new multi-objective concept for real-time rescheduling in dense railway systems.,” in *IEEE 23rd Int. Conf. Intell. Transp. Syst. (ITSC)*, Sep. 2020.

[55] J. Törnquist and J. A. Persson, “N-tracked railway traffic re-scheduling during disturbances.,” *Transp. Res. B: Methodol.*, vol. 41, no. 3, pp. 342-362, 2007.

[56] C. G. Walker, J. N. Snowdon and D. M. Ryan, “Simultaneous disruption recovery of a train timetable and crew roster in real-time.,” *Comput. Oper. Res.*, vol. 32, no. 8, pp. 2077-2094, 2005.

[57] V. Cacchiani, J. Qi and L. Yang, “Robust optimization models for integrated train stop planning and timetabling with passenger demand uncertainty.,” *Transp. Res. B: Methodol,* vol. 136, pp. 1-29, 2020.

[58] V. Cacchiani and P. Toth, “Nominal and robust train timetabling problems.,” *Eur. J. Oper. Res.*, vol. 219, no. 3, pp. 727-737, 2012.

[59] F. Corman, A. D'Ariano and I. A. Hansen, “Evaluating disturbance robustness of railway schedules.,” *J. Intell. Transp. Syst.*, vol. 18, no. 1, pp. 106-120, 2014.

[60] Y. Takeuchi, N. Tomii and C. Hirai, “Evaluation method of robustness for train schedules.,” *Quart. Rep. RTRI,* vol. 48, no. 4, pp. 197-201, 2007.

[61] N. Bešinović, R. M. P. Goverde, E. Quaglietta and R. Roberti, “An integrated micro-macro approach to robust railway timetabling.,” *Transp. Res. B: Methodol.,* vol. 87, pp. 14-32, 2016.

[62] R. M. P. Goverde and I. A. Hansen, “Performance indicators for railway timetables.,” in *IEEE Int. Conf. Intell. Rail Transp.,* 2013.

[63] P. Jovanović, P. Kecman, N. Bojović and D. Mandić, “Optimal allocation of buffer times to increase train schedule robustness,” *Eur. J. Oper. Res.,* vol. 256, no. 1, pp. 44-54, 2017.

[64] H. Wang and Y. Yue, “Optimizing train-platforming plans at arrival-departure tracks of high-speed railway stations.,” in *IEEE 5th Int. Conf. Intell. Transp. Eng. (ICITE),* 2020.

[65] S. Burggraeve and P. Vansteenwegen, “Robust routing and timetabling in complex railway stations.,” *Transp. Res. B: Methodol.,* vol. 101, pp. 228-244, 2017.

[66] C. Bersani, C. Guerisoli, N. Mazzino, R. Sacile and M. Sallak, “A multi-criteria methodology to evaluate the optimal location of a miltifunctional railway portal on the railway network.,” *Journal of Rail Transport Planning and Management,* vol. 5, no. 2, pp. 78-91, 2015.

[67] A. D'Ariano, M. Pranzo and I. A. Hansen, “Conflict Resolution and Train Speed Coordination for Solving Real-Time Timetable Perturbations.,” *IEEE Transactions on Intelligent Transportation Systems,* vol. 8, no. 2, pp. 208-222, 2007.

[68] A. Mascis and D. Pacciarelli, “Job shop scheduling with blocking and no-wait constraints.,” *Eurpean Journal of Operational Research,* vol. 143, no. 3, pp. 498-517, 2002.

[69] A. D'Ariano, D. Pacciarelli and M. Pranzo, “Assessment of flexible timetables in real-time traffic management of a railway bottleneck.,” *Transportation Research Part C: Emerging Technologies,* vol. 16, no. 2, pp. 232-245, 2008.

[70] C. F, A. D'Ariano, D. Pacciareli and M. Pranzo, “Evaluation of green wave policy in real-time railway traffic management.,” *Transportation Research Part C: Emerging Technologies,* vol. 17, no. 6, pp. 607-616, 2009.

[71] F. Corman, A. D'Ariano, D. Pacciarelli and M. Pranzo, “Bi-objective conflict detection and resolution in railway traffic management.,” *Transportation Research Part C: Emerging Technologies,* vol. 20, no. 1, pp. 79-94, 2012.

[72] B. Khosravi, J. A. Bennell and C. N. Potts, “Train scheduling and rescheduling in the UK with a modified shifting bottleneck procedure.,” in *12th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems. 120-131*, 2012.

[73] E. Woo, M. Uysal and M. J. Sirgy, “What Is the Nature of the Relationship Between Tourism Development and the Quality of Life of Host Communities?,” *Best Practices in Hospitality and Tourism Marketing and Management. Springer, Cham.,* pp. 43-62, 2019.

[74] “Report on the World Heritage Thematic Programmes. Decsion: 34 COM 5F. 2.,” 2010. [Online]. Available: https://whc.unesco.org/en/decisions/4240/.

[75] L. Dwyer and C. Kim, “Destination competitiveness: determinants and indicators.,” *Curret issues in tourism,* vol. 5, no. 6, pp. 369-414, 2003.

[76] M. Cucculelli and G. G, “Does sustainability enhance tourism destination competitiveness? Evidence from Italian Destinations of Excellence.,” *Journal of Cleaner Production,* vol. 111, pp. 370-382, 2016.

[77] S. Tjandra, “Dynamic network optimization with application to the evacuation problem. PhD thesis, Universität Kaiserslautern, Shaker Verlag, Aachen,” 2003.

[78] M. Skutella, An Introduction to Network Flows over Time. In: Cook W., Lovász L., Vygen J. (eds), Berlin: Research Trends in Combinatorial Optimization., 2009.

[79] M. R. Silver and O. L. De Weck, “Time-expanded decision networks: A framework for designing evolvable complex systems.,” *Systems Engineering,* vol. 10, no. 2, pp. 167-188, 2007.

[80] V. Gintner, N. Kliewer and L. Suhl, “Solving large multiple-depot multiple-vehicle-type bus scheduling problems in practice.,” *OR Spectrum,* vol. 27, no. 4, pp. 507-523, 2005.

[81] N. Shah, S. Kumar, F. Bastani and I. L. Yen, “Optimization models for assessing the peak capacity utilization of intelligent transportation systems.,” *European Journal of Operational Research.,* vol. 216, no. 1, pp. 239-251, 2012.

[82] M. P. Helme, “Reducing air traffic delay in a space-time network,” in *IEEE International Conference on Systems, Man and Cybernetics*, 1992, October.

[83] F. G. Engineer, G. L. Nemhauser and M. W. Savelsbergh, “Dynamic programming-based column generation on time-expanded networks: Application to the dial-a-flight problem.,” *Journal on Computing,* vol. 23, no. 1, pp. 105-119, 2011.

[84] L. R. Ford Jr and D. R. Fulkerson, Flows in Networks, New Jersey: Princeton University Press, 1962.

[85] L. Fleischer and M. Skutella, “Quickest flows over time.,” *SIAM Journal on Computing,* vol. 36, no. 6, pp. 1600-1630, 2007.

[86] *Guidelines for Carrying Capacity Assessment for Tourism in Mediterranean Coastal Areas Priority Actions Programme Regional Activity Centre (Split),* Turkey: UNEP/MAP/PAP, 1997.

[87] C. Corbau, G. Benedetto, P. Congiatu, U. Simeoni and D. Carboni, “Tourism analysis at Asinara Island (Italy): Carrying capacity and web evaluaions in two pocket beaches.,” *Ocean and Coastal Management,* vol. 169, pp. 27-36, 2019.

[88] D. L. Kerstetter and K. S. Bricker, Relationship Between Carrying Capacity of Small Island Tourism Destinations and Quality-of-Life. In: M. Uysal, R. Perdue, M. Sirgy (eds), Dordrecht: Handbook of Tourism and Quality-of-Life Research. International Handbooks of Quality-of-Life., 2012.

[89] D. A. Zacarias, A. T. Williams and A. Newton, “Recreation carrying capacity estimations to support beach management at Praia de Faro, Portugal.,” *Applied Geography,* vol. 31, pp. 1075-1081, 2011.

[90] R. Sridhar, E. Yuvaraj, V. sachithanandam, T. Mageswaran, R. Purvaja and R. Ramesh, “Tourism Carrying Capacity for Beaches of South Andaman Island, India.,” in *Tourism - From Empirical Research Towards Practical Application*, IntechOpen, 2016.

[91] W. Zheng, Z. Liao and J. Qin, “Using a four-step heuristic algorithm to design personalized day tour route within a tourist attraction.,” *Tourism Management,* vol. 62, pp. 335-349, 2017.

[92] Z. Liao and W. Zheng, “Using a heuristic algorithm to design a personalized day tour route in a time-dependent stochastic environment.,” *Tourism Management,* vol. 68, pp. 284-300, 2018.

[93] D. Gavalas, C. Konstantopoulos, K. Mastakas, G. Pantziou and N. Vathis, “Heuristics for the time dependent team orienteering problem: Application to tourist route planning.,” *Computers & Operations Research,* vol. 62, pp. 36-50, 2015.

[94] W. Zheng, H. Ji, C. Lin, W. Wang and B. Yu, “Using a heuristic approach to design personalized urban tourism itineraries with hotel selection.,” *Tourism Management,* vol. 76, 2020.

[95] G. Dósa and S. György, “First Fit bin packing: A tight analysis.,” *30th International Symposium on Theoretical Aspects of Computer Science,* vol. 20, pp. 538-549, 2013.

[96] ISTAT. [Online]. Available: http://www.comune.riomaggiore.sp.it/.

[97] “Regione Liguria, "geoportal",” [Online]. Available: https://geoportal.regione.liguria.it/. [Accessed 2 2019].

[98] X. Zhou and M. Zhong, “Bicriteria train scheduling for high-speed passenger railroad planning applications.,” *European Journal of Operational Research,* vol. 167, pp. 752-771, 2005.

[99] Z. Chuntian, G. Yuan, Y. Lixing, K. Uday and G. Ziyou, “Integrated optimization of train scheduling and maintenance planning on high-speed railway corridors.,” *Omega,* vol. 87, pp. 86-104, 2019.

[100] Z. Leishan, C. T. Lu, C. Junhua, T. Jinjin and Z. Xuesong, “Joint optimization of high-speed train timetables and speed profiles: a unified modeling approach using space-time-speed.,” *Transportation Research Part B,* vol. 97, pp. 157-181, 2017.

[101] G. Yuan, K. Leo, Y. Lixing and G. Ziyou, “Three-stage optimization method for the problem of scheduling additional trains on a high-speed rail corridor.,” *Omega,* vol. 80, pp. 175-191, 2018.

[102] H. Erfan, B. Morteza, J. Shafagh Alaei and K. Hamrah, “Train schedule optimization in a high-speed railway system using a hybrid simulation and meta-model approach.,” *Computers and Industrial Engineering,* vol. 138, pp. 106-110, 2019.

[103] TrenItalia, “TrenItalia,” TrenItalia, [Online]. Available: http://www.trenitalia.com. [Accessed February 2020].

[104] C. Scheffer, “Train scheduling: Hardness and algorithms.,” in *Proc. Int. Workshop Algorithms Comput.*, Switzerland, Springer, 2020, pp. 342-347.

[105] M. Dedík, L. Čechovič and J. Gašparík, “Methodical Process for Innovative Management of the Sustainable Railway Passenger Transport.,” *Transportation Research Procedia,* vol. 44, pp. 305-312, 2020.