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Railway freight node capacity evaluation: a timetable-saturation approach and its application to the Novara freight terminal

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Abstract

This paper presents a timetable-based approach to assess the capacity of a railway freight node, based on the microscopic simulation and saturation of the timetable. Saturation is done by scheduling additional saturation train paths without introducing any traffic conflict, while respecting the required technical and operational constraints, until no more paths can be added. The approach is applied to analyze the potential effects on capacity of some infrastructure improvements planned by Rete Ferroviaria Italiana (RFI) for the rail freight node of Novara, Italy. The capacity is evaluated by means of two KPIs computed on saturated timetables: the number of daily pairs of saturation freight trains and the infrastructure Occupancy Time Rate (OTR). The first KPI represents an absolute estimation of the capacity (theoretical or practical, depending on the presence of buffer times). Instead, the OTR is computed by the UIC 406R compression method and it is used to identify local bottlenecks. For the analysis, we use SASTRE, an analysis environment for railway systems developed at Politecnico di Torino, which combines a MILP formulation for the timetable saturation problem with a saturation strategy layer. The saturation strategy considers a given set of priorities between the different network areas and the train types to be used during the saturation process. The results reveal that using a microscopic model to schedule traffic flows on a complex railway node allows for a good accuracy of the timetable, but at a high computational cost.

Keywords: Railway Capacity; Train Timetable; Freight Trains; Saturation; Mixed-Integer Linear Program (MILP).

1. Introduction

The rail market liberalization has led to a steady increase of the demand for rail freight transport in recent decades. This encourages European Infrastructure Managers to improve the capacity of railway systems on freight corridors, as well as in node areas, which most likely act as the system's bottlenecks. One way to achieve this objective is to

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expand the rail infrastructure. However, given the high cost of building new infrastructures, a preliminary study is usually performed to assess the characteristics, costs and possible results of a project. This paper focuses on the capacity analysis of an Italian rail freight node in relation to some recent infrastructural improvements planned by Rete Ferroviaria Italiana (RFI).

According to (Abril et al., 2008), we define railway capacity as the maximum number of trains which can be operated on a given infrastructure within a certain time window and for a given set of operational constraints. The majority of European Infrastructure Managers (RFI included) uses techniques for railway capacity evaluation based on the analytical method of timetable compression (Goverde, et al., 2013; Pouryousef, et al., 2015), like the one proposed by the UIC leaflet 406R (UIC, 2013). Such a method can be used to calculate the capacity consumption of pre-determined timetables or to schedule trains as close as possible to each other. The latter is called timetable-saturation if the scheduling exploits all the available capacity (Delorme, et al., 2001).

A saturated timetable permits to estimate the maximum system capacity in terms of number and type of scheduled trains. Several approaches have been pursued to solve the timetable saturation problem, see e.g. the literature reviewed by Cacchiani, et al. (2016) and Coviello, et al. (2017). Although some of the approaches in the literature are suitable for large instances or for freight traffic (Cacchiani, et al., 2010), they do not take into account rail operations interactions in highly interconnected freight nodes. In these cases, additional technical and operational constraints have to be satisfied, which are not normally present in corridors or passenger nodes, and a reciprocal interdependence between alternatives routes has to be considered (Mu & Dessouky, 2011; UIC, 2013).

Our work extends a microscopic method introduced for lines to jointly manage freight nodes and lines. We integrate a general timetabling saturation algorithm with a *saturation strategy layer,* which considers priorities between the different network areas and the train types to be used during the saturation process. When saturation is performed without such priorities, some areas of the system may be saturated before others, and eventually block their access. Furthermore, without a saturation strategy, it is difficult to implement any priority between the trains to be scheduled.

In this study, capacity is evaluated by means of two KPIs, computed on saturated timetables: the number of daily pairs of saturating freight trains (a pair is composed by an arriving train and by the corresponding departing one) and the infrastructure Occupancy Time Rate (OTR). The first KPI is directly obtained from the timetable and represents an absolute estimation of the capacity (theoretical or practical, depending on the presence of buffer times). Instead, the OTR is computed by the UIC 406R compression method (UIC, 2013) and it is used to identify local bottlenecks.

For the analysis, we use SASTRE, a simulation and analysis environment for railway systems developed at Politecnico di Torino (Coviello, 2018). For the timetable saturation problem, SASTRE combines a Mixed Integer-Linear Programming (MILP) formulation, based on one recently proposed by (Pellegrini, et al., 2017), and the blocking time theory (Hansen & Pachl, 2014). The infrastructure is modelled in a microscopic way - whose fundamental element is the *track detection section* (Rodriguez, 2007) - and supports any implementation of signaling and interlocking systems. In particular, we consider the route block-sectional release system, in which the sections are released one-by-one after track-free detection, according to the passage of a train (Corman, et al., 2009).

The capacity assessment is applied to a case-study provided by the Novara freight node (Italy) for different infrastructure configurations, in order to point out the impact of planned infrastructural improvements. Two infrastructure scenarios are considered: with minimum and maximum improvements. However, the same infrastructure can be operated by different timetable patterns, resulting in a different number of train paths obtained with saturation. We thus saturate a given infrastructure scenario with different operational sub-scenarios.

The next section extensively presents the used method, describing the microscopic model of the railway system (Section 2.2), the timetable saturation algorithm and the saturation strategy layer (Section 2.3). Section 2.4 illustrates the KPIs utilized to evaluate the saturated timetables. Section 3 reports the practical case study of the freight node of Novara, with the description of the relevant scenarios. Section 4 provides a set of preliminary experimental results. Conclusions are drawn in Section 5, highlighting the achievements and open issues related to the proposed methodology as well directions for future developments and improvements.

2. Methodology

The proposed approach is implemented in SASTRE, an analysis environment for railway systems proposed by Coviello (2018), implemented through Python 3 and C++ libraries. Specifically, we use SASTRE to: (1) define a microscopic infrastructure model; (2) automatically generate (feasible) saturated timetables; (3) evaluate capacity through the calculation of two KPIs, computed on saturated timetables.

2.1. Problem definitions

A *train path* is the train time-way line in a time-distance graph, characterized by the arrival and departure times of a train in each traversed station and the corresponding route across the network. A *track detection section* (TDS) is the minimum infrastructural section that is able to detect the presence of a train. *Infrastructure utilization* is the time interval over which an infrastructure section is allocated exclusively to a specific train, and blocked for other trains (UIC, 2013). According to this definition, for each TDS it is possible to define the utilization slot of a given train path. A *headway section* is a maximal set of all adjacent track detection sections shared by a pair of trains. For each headway section, a *minimum headway time* is defined, which is the minimum time that shall separate the two train paths in order to avoid any overlap of the utilization time slots of the relevant TDSs. A *buffer time* is the minimum time span which shall always separate the utilization slots of two consecutive trains in each shared track section.

2.2. Data modeling

The rail system is modelled in a microscopic way as described in Coviello (2018) considering: the infrastructure topology discretized in TDSs; the signaling system; the active train control/protection systems; the station routes interlocking dependencies and their possible speed limitations. Trains are then defined by the following attributes: a rolling stock; a stopping pattern (i.e., the list of all locations where a train is scheduled to stop) and a set of alternative routes. We explicitly differentiate between station and network routes: the station routes are formed by the set of TDSs crossed by a train within a station area, while the network routes by those outside station areas.

Once the data has been entered, trains running are simulated with free-way signals. Speed profiles are calculated by numerically integrating the fundamental motion equation. Thus, by applying the blocking time theory (UIC, 2013; Hansen & Pachl, 2014) to the simulated run speed profiles, the utilization times of each travelled TDS are computed. The utilization of a TDS by a certain train starts when it is reserved by the signaling system and it ends when the TDS is cleared by the train and released by the signaling system. In a time-distance graph, the consecutive TDS utilization slots relevant to the same train form a so-called *utilization stairway*, used to calculate the minimum headway times allowed by the signaling system between each pair of possible consecutive trains. The minimum headway times is computed as the difference between the start of a headway section utilization by two consecutive trains.

2.3. The timetable saturation problem

The proposed saturation approach is composed by two level: (i) the timetable saturation function and (ii) the saturation strategy layer. The algorithm inside (i) is implemented by a MILP formulation based on the one proposed by Pellegrini et al. (2017). Given a base timetable and a set of saturation trains, the algorithm schedules copies of the saturation trains into the base timetable within a given time window, while respecting technical and operational constraints, until no more trains can be added without incurring into a constraint violation. With respect to Pellegrini et al. (2017) formulation, we introduce routing/scheduling flexibility for the saturating train paths (i.e., the saturating trains dwell times in stations can be modified, as well as their station routing) to maximize the total number of saturating trains in the timetable. Our mathematical formulation also considers rolling stock re-utilization constraints to model turn-around operations and shunting movements in rail terminals. Such constraints impose that a train arriving and ending in one location shall be followed by a train that begins its run from the same platform. The time span between the two linked arrival and departure is the process time within the terminal. During the process time, the TDSs relevant to the platform track are assumed as utilized. In some cases, a train passes through several terminals before the turn-around, we thus modelled it by a chain of trains linked by re-utilization constraints. The reader is referred to Coviello (2018) for a description of the timetable saturation formulation.

The saturation function itself does not apply any choice priority among the saturation trains used to saturate the timetable, their selection being guided just by the objective of maximizing the overall number of scheduled trains. For this purpose, the saturation strategy layer (ii) is designed at a higher hierarchical level. It iteratively launches the saturation function with different *saturation train instances*. An instance is a specific configuration of the saturation train's attributes defined in the strategy layer. Each call of the saturation function saturates the timetable obtained in the previous iteration with the saturation train instance received as argument. In this way, the priority of each saturation train instance is given by its position within the iterations sequence.

The train saturation's attributes implement the prioritization criterion, which can be either *functional* or *spatial*. A *functional* criterion applies when a saturation train instance represents a particular kind of rail service: in this way, e.g., it is possible to saturate a timetable according more priority to rolling highway (trains on which entire trucks are transported by rail) or intermodal trains (trains on which entire semi-trailers or containers are transported by rail) rather than conventional freight trains. A *spatial* criterion differentiates the saturation train instances according to their routing within the network, having fixed the stopping pattern. This means that by specifying a route attribute (e.g. a network route) it is possible to foster the timetable saturation with trains which use the specified route. In this study, we use spatial criteria to investigate the maximum number of trains, which can be scheduled on infrastructure sections.

When the saturation function is iteratively launched on the same timetable, with different saturation train instances, the first iterations would have more available capacity, and so more saturation train instances will likely be scheduled. To leave capacity left for the following iterations, an upper bound to the number of schedulable trains is set. The saturation strategy can also take advantage from feedbacks from previous iterations in order to modify the control parameters of the next ones. Thus, at a certain iteration, it can adapt the upper bound of the number of schedulable trains according to the amount of those already scheduled by previous iterations.

In summary, the saturation problem deals with train's routing and scheduling. In large-scale and complex instances, such a problem results NP-hard (Caprara, et al., 2002; Sama, et al., 2016), difficult to optimally solve within a reasonable calculation time. Through the saturation strategy layer, we reduce the saturation problem to smaller sub-problems, in which sub-sets of trains are considered. A further simplification is made: the saturation time window (daily horizon) is divided into sub-windows, in which saturation is sequentially performed. The MILP is solved with GUROBI 8.1, setting a time limit equals to 20 times a starting upper bound (maximum schedulable trains, in minutes) and an optimality gap limit of 2%. The solver stops when optimality or one of the two limits is reached. Because of all these simplifications, the algorithm gives sub-optimal solutions, so it may be considered heuristic.

2.4. Capacity evaluation KPIs

We compute two Key Performance Indicators (KPIs) on saturated timetables to assess capacity: the number of daily pairs of saturating freight trains and the infrastructure Occupancy Time Rate (OTR). The first KPI is directly obtained from the timetable and represents an absolute estimation of the capacity (theoretical or practical, depending on the presence of buffer times). The second KPI is computed by the compression method presented by the UIC 406R leaflet (UIC, 2013). It consists in decomposing the infrastructure into compression sections and in shifting paths as close as possible, avoiding overlaps of the utilization stairways within the same compression section. In SASTRE, the compression method is implemented with the algorithm described in (Jensen, et al., 2017).

We use the OTR to identify bottlenecks within the network, characterised by a high local capacity consumption (Goverde & Hansen, 2013). These bottlenecks likely represent a stability issue (because of the occurrence of knock-on delays) when the OTR overpasses a given threshold. The UIC 406R leaflet provides some threshold values, discriminating between full-line stretches (60% for mixed traffic over a daily period) and station/node areas. For the latter, the leaflet proposes a segmentation into platform (40% - 50% over a daily period) and switch areas (60% - 80% over a daily period). Several authors (Landex, et al., 2008; Lindner, 2011; Bešinović & Goverde, 2018) consider this segmentation as poorly effective since it neglects the mutual interactions of traffic in different infrastructure zones. Therefore, differently from the UIC 406R leaflet, we include whole station/node areas into single compression sections. When the UIC compression method is applied to a saturated timetable, the bottlenecks also indicate the spots which prevent the insertion of further saturating trains.

3. Case study

This section presents the capacity evaluation for the rail freight node of Novara (Italy), meant to analyze the effects on freight traffic of some infrastructure improvements planned by the national manager RFI. The considered area

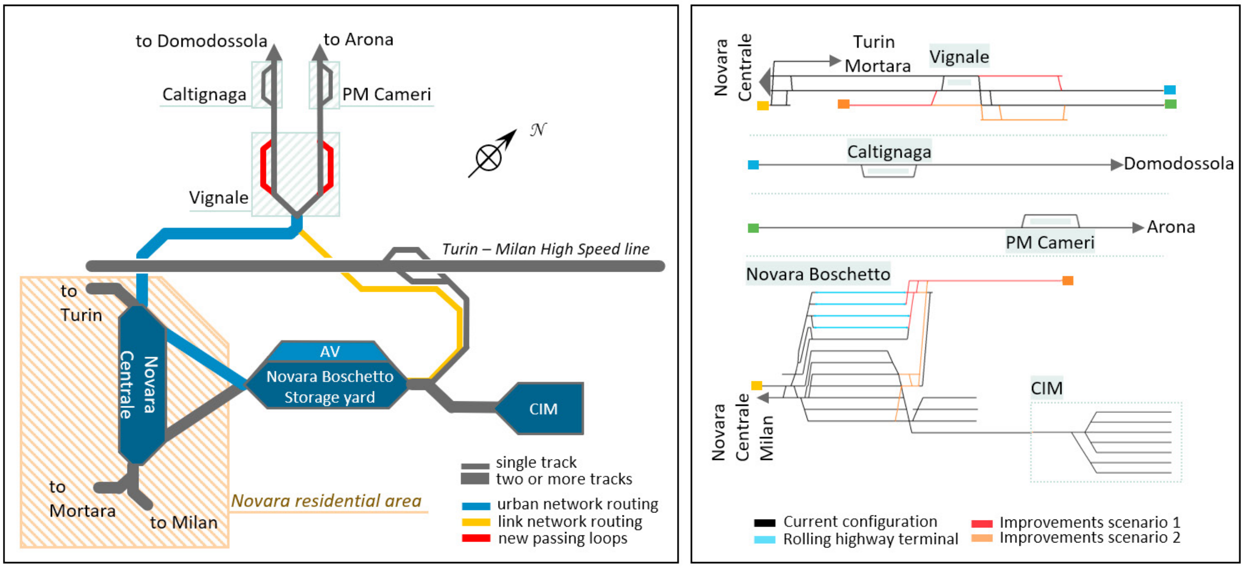

Figure 1 Case study: the proposed infrastructure model

includes the two major railway stations of Novara Centrale (the passenger terminal) and Novara Boschetto (the freight yard, linked to the *CIM* intermodal terminal and to the rolling highway terminal AV), plus two 20-km sections of the north-bound railway towards the Swiss border, with some minor stations. A preliminary Origin/Destination survey of the node's rail freight traffic highlighted the predominance of traffic on the northern routes. On the remaining routes, freight traffic resulted negligible, reason why they are not considered in this study. On the considered lines, it is used the ETCS Level 1 based on fixed balises (automatic block signaling integrated with the Italian *Sistema Controllo Marcia Treni* - SCMT control system).

Saturation is performed with freight trains, setting the passenger timetable of October 25th, 2018 as a fixed constraint. 10 sets of saturating train instances (STIs) have been used to implement three saturation strategies, as displayed in Table 1. The analysis is carried out by modelling two infrastructure scenarios (SI1 and SI2), which reproduce the gradual implementation of the infrastructure improvements, in order to point out the impact of each one. Fig. 1 shows the microscopic model of the infrastructure, highlighting the interventions introduced in each scenario. As described in Section 2, the same infrastructure can be operated by different timetable patterns, resulting in a different number of train paths obtained with saturation. We therefore saturate the two infrastructure scenarios with different operational sub-scenarios (Table 1) regarding the following features:

- *Buffer times*, in order to assess how higher expected stability of the saturated timetable results in lower number of freight paths. The buffer time currently used by RFI to timetabling purposes in the Novara area is 120 seconds.
- *Saturation strategies*, i.e., priority given to different types of trains (O/D in Table 1) and to the usage of different network routings (NR in Table 1). RFI provided a priority pattern in which a similar priority is accorded to AV and CIM trains, modelled with the saturation strategy SS1. We considered also SS2 and SS3 in which a higher priority is given to AV and CIM trains, respectively. We also foster the utilization of the new direct link between Novara and Vignale (link routing, L) instead of the old itinerary through the Novara passenger station (urban routing, U).
- *MaxSat* sets the maximum number of saturating trains that can be scheduled by a single call of the saturation function. If no limit is set (big *M*, in Table 1) the maximum number of trains which can be scheduled is returned.
- *Process times* at freight terminals, defined by a minimum value and a maximum value. Ranges PT0 are those provided as a reference by RFI. Ranges PT1, PT2, PT3, PT4 have been obtained by decreasing PT0. Considering lower minimum values implies that technological/operative improvements are applied to yard operations. On the other side, process times greater than the minimum values are typically required by mere timetable schedule needs, especially with highly utilized full-line sections.

Table 1 Saturation train instances (STIs) features: origin/destination (O/D); network routing (NR, link L or urban U); process time (PT), *loc* is the location to which the processing time refers; priority implemented in saturation strategy (SS); maximum number of schedulable trains (maxSat).

STI	O/D	NR	Process Time min/max (h)						Priority			maxSat		
ID			loc	PT0	PT1	PT2	PT3	PT4	SS1	SS2	SS3	SS1	SS2	SS3
1	AV – Domo.	L	AV	1/1.5					1	1	3	11	M	11
2	AV – Arona	L	AV	1/1.5					1	1	3	8	M	8
3	CIM – Domo.	L	NB CIM NB	0.1/5 5/10 0.1/5	0.1/5 3.5/6 0.1/5	0.1/5 2/4 0.1/5	0.1/2.5 3.5/6 0.1/2.5	0.1/2.5 2/4 0.1/2.5	1	2	1	14	14	M
4	CIM – Arona	L							1	2	1			
5	CIM – Domo.	U							2	3	2			
6	CIM – Arona	U							2	3	2			
7	NB yard – Domo.	L	NB	1/10					3	4	4	M		
8	NB yard – Arona	L	NB	1/10					3	4	4	M		
9	NB yard – Domo.	U	NB	1/10					4	5	5	M		
10	NB yard - Arona	U	NB	1/10					4	5	5	M		

Operational scenarios

Scenario	0.1	0.2	0.3	0.4	0.5	0.6	1	2	3.1	3.2	3.3	3.4
Scenario Infra	SI1	SI1	SI1	SI2	SI2	SI2	SI2	SI2	SI2	SI2	SI2	SI2
Buffer time	0	60	120	0	60	120	120	120	120	120	120	120
Saturation strategy	SS1	SS1	SS1	SS1	SS1	SS1	SS2	SS3	SS3	SS3	SS3	SS3
Processing time	PT0	PT0	PT0	PT0	PT0	PT0	PT0	PT0	PT1	PT2	PT3	PT4

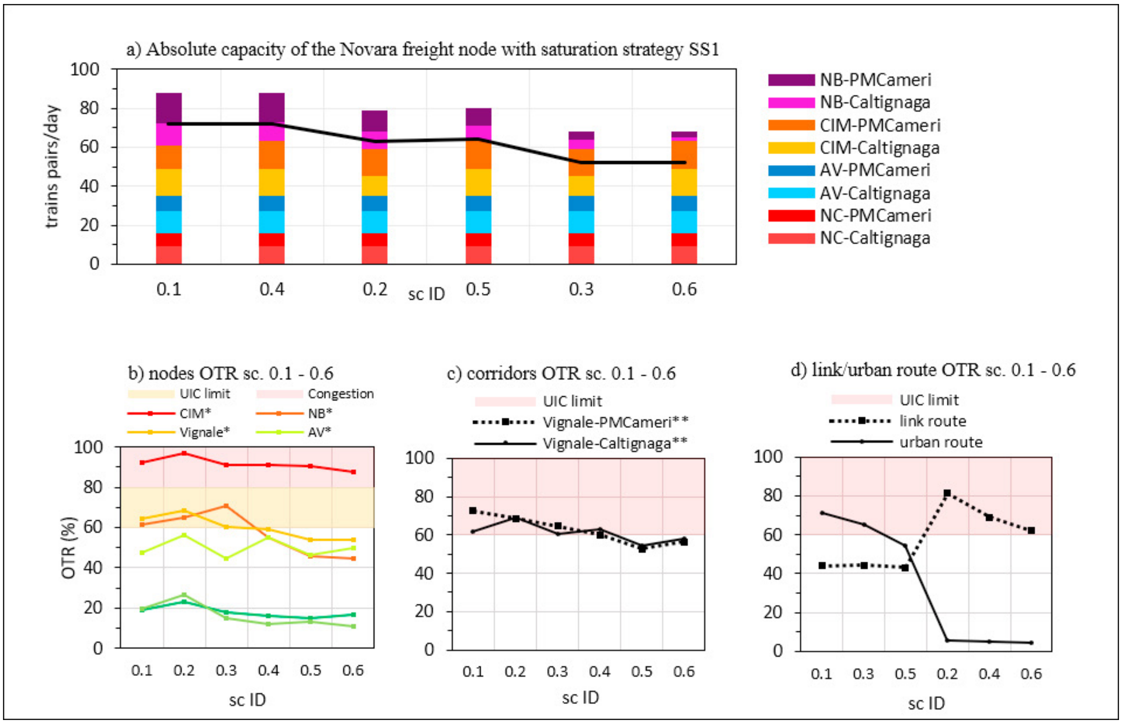

Figure 2 Capacity of the Novara freight node with saturation strategy SS1 (a); occupation Time Rate (OTR) of the infrastructure of: (b) nodes; (c) lines; (d) link route/urban route; (*station tracks + switch area; **including Vignale station).

4. Experimental results

Experiments are performed on a computer with Intel(R) Core(TM) i7-8850 2.59 Hz CPU with 16 GB RAM, on Microsoft Windows 10 (64 bit) OS.

Fig. 2a displays the absolute capacity (in terms of pairs of trains/day) of the studied network calculated through the application of saturation strategy SS1. It results that the rolling highway terminal can match the RFI objective (*maxSat* in Table 1) to operate a maximum of 11 and 8 pairs of trains in all scenarios. CIM records an increase of saturating trains, higher in infrastructure scenario SI2 than SI1. We deduce that the infrastructural interventions of SI2 facilitate the access to the CIM terminal, thus increasing its capacity. Furthermore, a relatively low number of saturating trains is scheduled to/from the Novara Boschetto yard, due to their lowest priority in the saturation strategy. The black line in Fig. 2a shows the trend of the total number of saturating trains with the buffer time. When the buffer time increases, there is a significant decrease of the scheduled paths, with a ratio of about -14% per each 60 sec step. Considering the same buffer time, it can be observed that the infrastructural improvements introduced between SI1 and SI2 do not produce a significant increase in the overall capacity. By contrast, at a local level the analysis of the saturated timetables reveals that the activation of the Vignale-Novara Boschetto link diverts significant traffic from the current urban route (Fig. 2d).

Fig. 2b shows the Time Occupation Rate (OTR) calculated on main nodes and corridors. Scenarios 0.1 to 0.6 highlight that the station tracks areas of CIM and Novara Boschetto represent the real bottleneck of the system, for the following reasons: the high dwell times required by terminal/shunting operations; the relatively low number of available tracks. Comparing the calculated OTR values with the thresholds recommended by the UIC 406R leaflet, it emerges that the stability requirements are satisfied by imposing a buffer time of 120 seconds only (Fig. 2c). In general, the OTR values are rather high. This is due to the fact that the considered lines are single-track, and in the saturated timetables intensive traffic is forced to use all available capacity. In SI2, the NB-Vignale link route exceeds the OTR threshold even with a 120 sec buffer time (Fig. 2d). On the other hand, dealing with freight traffic only, lower punctuality can be accepted in comparison with mixed traffic lines, as stated by RFI analysts. Moreover, in case of delays, the two siding loops in Vignale would represent a "capacity buffer" to avoid disruptions of passenger services.

Scenarios 1 and 2 (operative scenarios, in Table 1) allow for a straightforward comparison between the number of scheduled AV and CIM trains. It emerges how saturation strategies SS1 and SS2 entail different priority allocations with respect to AV (26 and 4, respectively) and CIM train pairs (30 and 34, respectively). It is worthwhile to point out how, with these saturation strategies, a single CIM pair consumes more capacity than an AV one: to accommodate 4 more CIM train pairs, 22 AV train pairs would be lost. This is because the sidings and switch areas of Novara Boschetto yard are partially shared by both AV and CIM trains, even if whose capacity consumption is mainly affected by CIM trains. The latter observation entails extra shunting movements. Therefore, it can be stated that this area represents a bottleneck that cannot be relieved by modifying operative constraint, like the traffic pattern.

Scenarios 3 focus on the influence of the process times on the overall capacity. Decreasing the process times in the CIM terminal (scenarios 3.1 and 3.2, with PT1 and PT2 respectively, as provided in Table 1) makes it possible to schedule more CIM trains, with respect to scenario 0.6. In the latter case, lower dwell times in CIM tracks permit a higher turn-over of trains. Differently, decreasing the maximum process times in NB yard (scenarios 3.3 and 3.4, with PT3 and PT4 respectively, as indicated in Table 1) produces a negative effect on the saturation process: the constraint set is hardened, thus resulting in less saturating trains.

The elapsed computation time is reported by Table 2 for each scenario. It can be observed that the computation time is higher on scenarios in which stricter constraints apply to the scheduling problem. For instance, increasing the buffer times from 0 to 120 seconds produces computation times about four times higher. This effect is particularly evident when dealing with scenarios 3, whose computation times are about 5 times higher than that of scenario 0.6.

Table 2 Computation time in hours for each scenario.

Computation time for each scenario												
ID sc.	0.1	0.2	0.3	0.4	0.5	0.6	1	2	3.1	3.2	3.3	3.4
Comp. time (h)	1.0	1.6	4.3	0.8	1.7	4.1	4.6	4.6	19.2	22.2	17.2	23.1

5. Conclusions

The paper presented an approach for capacity analysis based on the microscopic simulation and saturation of the timetable, which considers rail operations interactions in interconnected freight nodes. The model combines a MILP formulation for the timetable saturation problem with a saturation strategy layer. The latter considers priorities between the different network areas and the train types to be used during the saturation process. The proposed approach is applied to analyze the potential effects on capacity for some recent infrastructure improvements planned by Rete Ferroviaria Italiana (RFI) on the rail freight node of Novara, Italy.

It results that the considered interventions only modestly increase the overall capacity of the node, but succeed in diverging significant traffic at local level. The UIC-compression analysis highlights that the actual bottleneck of the system lies in the sidings and switch areas of Novara Boschetto yard, even with different timetable patterns.

Despite the good accuracy of the solution computed by the proposed method, the microscopic simulation of such a complex railway node requires several hours of computation. To reduce the computation time dedicated to simulations, future research should be focused on limiting the number of evaluated alternative train routes for each saturating train path. Anyhow, RFI analysts recognized that the use of an integrated capacity evaluation method based on simulation and optimization might permit to analyze, test, and assess different traffic scenarios in a rather time-efficient way, with respect to conventional analysis.

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