

Capacity analysis for a railway node using microscopic cyclic timetabling

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Abstract—Evaluating railway capacity is a challenging task due to the high complexity of the railway system, which involves various critical interdependent components. This paper presents an innovative approach to assessing the capacity of a railway node by iteratively evaluating the ability of its infrastructure to cover different combinations of train line frequencies. For each combination, an optimization problem is formulated to assess the node’s capacity by verifying whether a feasible timetable can be built, possibly introducing deviations with respect to a strictly cyclic timetable. To assess such feasibility, we consider a microscopic representation of the infrastructure. For this purpose, a mixed-integer linear programming model is utilized, allowing minor adjustments in train arrival and departure times while aiming to minimize the cumulative deviation from a strictly cyclic timetable. An experimental study conducted on the Pierrefitte-Gonesse railway node in France demonstrates the ability of our approach to quantify capacity under different combinations of line frequencies. In addition, the approach allows for the highlighting of how local rerouting can enhance capacity utilization.

I. INTRODUCTION

Stations and complex railway junctions, known as railway nodes, are often identified as bottlenecks in railway networks. The sustainability of rail transport, with its lower greenhouse gas emissions compared to road transport, has led to a growing demand for both passenger and freight rail services. Indeed, many European countries aim to shift a significant portion of their transportation from other modes to rail by 2030 [8], resulting in increased saturation of railway networks, especially at railway nodes. In order to absorb this growing demand, there are two possibilities: either improving the utilization of node capacity or extending the existing node track layout [6]. Before implementing either solution, a tool is required to assess the current node capacity.

The literature offers various definitions of railway capacity. The most widely accepted is theoretical capacity, defined as the maximum number of trains that can operate on a given infrastructure within a specified time period [7]. Various methods have been proposed for evaluating railway capacity. The evaluation of capacity through optimization methods is based on saturated and optimized timetables, which are usually established using mathematical programming approaches, particularly integer programming [3].

In this paper, we address the challenge of analyzing the capacity of a railway node through an iterative approach: it tests the limits of the node infrastructure under growing *line* frequencies. In particular, we consider multiple lines, where each line is defined by origin and destination stations, a stopping pattern, a travel time, a train type, and a frequency. For each line, a set of trains must be scheduled, respecting the frequency as much as possible and using either the default route or a different one from a set of alternatives. For each combination of line frequencies, we study the ability of the node infrastructure to accommodate the timetable derived from that combination: we attempt to build the best timetable that satisfies the combination as closely as possible, i.e., such that the time interval between two successive trains operating the same line is as regular as possible and that all operational constraints are respected. In the approach we propose, for a given line combination, frequencies are progressively increased until operational constraints become too stringent, emptying the search space. The maximum number of trains that we manage to schedule defines the node’s capacity. Clearly, this capacity depends on the characteristics of the line combinations in terms of route, stop patterns, and train type features. For the evaluation of a single combination, we propose a Mixed-Integer Linear Programming (MILP) model for microscopic cyclic timetabling, based on an existing model for real-time traffic management named RECIFE-MILP [5]. This model uses a microscopic representation of the infrastructure to account for specific features of the railway signaling system, such as the sectional route release mechanism of the interlocking system [14]. New cyclic timetabling constraints are introduced to ensure consistent spacing between trains operating the same line. In order to highlight the ability of the proposed MILP model to provide valuable insights into capacity analysis, we perform an experimental study on the French railway junction of Pierrefitte-Gonesse, considering various combinations of line frequencies. The results showcase how capacity changes across combinations, suggesting that our approach may be an effective decision-support tool for railway management. Furthermore, the results show the positive impact of local rerouting on increasing the capacity utilization of the node.

The rest of the paper is organized as follows: Section II reviews related works on capacity assessment methods. Section III provides a description of the optimization problem and a numerical example. Section IV is dedicated to the MILP model. Section V presents the experimental study and the preliminary results. Finally, we propose a conclusion and

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some perspectives for future research.

II. LITERATURE REVIEW

In [2], railway capacity assessment methods are classified into three categories. The first category includes analytical methods, which use mathematical formulas based on specific parameters, such as minimum headway times. These methods are typically applied to simpler railway lines and nodes, providing rough capacity assessments for both existing and projected infrastructures. Some of the most well-known analytical methods are UIC 406 and CUI [2], which serve as the basis for many other analytical assessments. UIC 406 systematically analyzes train schedules through timetable compression to determine capacity utilization over specific line sections and time periods, while CUI offers a more flexible framework that can adapt to various operational scenarios. The second category focuses on simulation methods that are used to consider uncertainties and stochastic behavior of systems or their components. Such a method is used in [3], where an automated tool named MOM analyzes capacity by considering train speed and station distances for saturated networks. Another work is presented in [4], where the RTC software is used to evaluate the impact of different train types on capacity. The third category corresponds to optimization methods which involve the use of mathematical modeling to enhance the efficiency of railway operations by addressing specific sub-problems such as train scheduling, routing, and track allocation [2].

Optimization methods are useful to maximize the number of trains and overall transportation performance. One important work in this area is [1], which introduces the concept of absolute capacity. The generic optimization model proposed aims to maximize the total throughput between all input-output location pairs, taking into account factors such as train mixes, lengths, dwell times, signals, and headway conditions. In [9], the authors expand the concept by developing multi-objective mathematical models that simultaneously optimize different train types such as passenger and freight trains. This method enables sensitivity analyses to evaluate how different train mixes affect the overall capacity of the railway system. Other optimization works focus on timetabling approaches, where the goal is to construct a saturated timetable. For example, [10] models the problem of estimating railway capacity as a hybrid time-space network that integrates both timetable and vehicle circulation constraints. A mathematical optimization problem is formulated to compute a saturated timetable that maximizes overall transportation performance. Some timetabling approaches, such as those of [11] and [12], deviate from the periodic event scheduling framework by focusing on minimizing the timetable cycle time. In the last work, the proposed MILP model addresses a timetable cycle, combining train timetabling and platforming problems, aiming to minimize both the timetable cycle time and the total journey time of all trains within one timetable cycle.

To the best of our knowledge, there is no work that proposes assessing the capacity of a railway node using

microscopic cyclic timetabling, that incorporates a highly detailed modeling level. We present a contribution to fill this gap.

III. PROBLEM DESCRIPTION

This study focuses on the problem of evaluating the capacity of a railway node through the evaluation of the number of trains that can be scheduled following a cyclic timetable. We model this problem by considering the node's track layout in all its details, using what is typically called microscopic representation of the infrastructure. In the model, we incorporate all relevant operational constraints, in particular those linked to signaling systems and interlocking rules [14]. In addition to the node layout and the operational constraints description, the input of the problem includes the relevant combinations of line frequencies to be included in the cyclic timetable. Each line is characterized by origin and destination locations, stopping patterns, a travel time, a train type, and the frequency of the operated trains. The objective is to identify the maximum number of trains that can be operated as a function of the relevant combinations. The combinations that allow the identification of feasible cyclic timetables and include the maximum number of trains define capacity.

In our model, we consider the possibility of identifying a timetable that is not *strictly* cyclic. In a strictly cyclic timetable, the node entry and exit times of the trains operating a line are all separated by an interval equal to the *line cycle time*, i.e., the ratio between the *timetable cycle time* and the frequency of the line. If such a strictly cyclic timetable is not feasible according to the operational constraints, the train separation can be modified. This modification results in what is called *deviation* in this paper. We consider this possibility, as typically some tolerance is accepted on strict cyclicity by railway undertakings. In addition, the total deviation necessary to obtain the feasibility of a timetable can serve as an indicator of capacity saturation. The larger the deviations, the more constrained the use of capacity. This makes it possible to adopt more rigid definitions of railway capacity, taking into account not only the number of trains that can operate but also the regularity with which they can do so.

As a sub-problem of the capacity evaluation one, we search for a cyclic timetable minimizing total deviation. Hereafter, we will refer to this sub-problem as the *cyclic timetabling* one. In line with the capacity evaluation, we model this sub-problem considering a microscopic representation of the infrastructure and of train movements. Considering all operational constraints, the objective of the cyclic timetabling problem is the minimization of the total deviation.

The problem of cyclic timetabling is defined as follows: Given a timetable cycle time H , a train line l , and a train line frequency F_l , the line cycle time, denoted as P_l , is defined as $P_l = \frac{H}{F_l}$. This value represents the regular time interval between two consecutive trains operating the train line l . Let a_t be the arrival time and d_t be the departure time of a train t . For any two consecutive trains: train t_1 followed by train

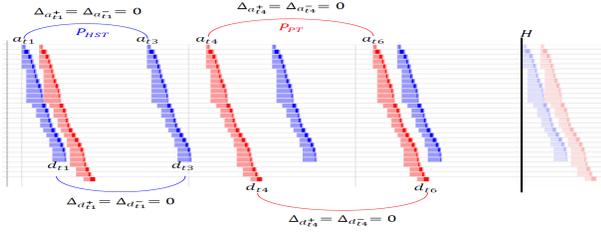


Fig. 1. Blocking time diagram of a strictly cyclic timetable given the line frequencies $(F_{PT}, F_{HST}) = (3, 4)$

t_2 operating the same train line l , the aim is to minimize:

- The difference between the line cycle time P_l and the actual arrival interval $a_{t_2} - a_{t_1}$. If the difference is positive, it is denoted as Δa_t^+ , and if the difference is negative, it is denoted as Δa_t^- .
- The difference between the line cycle time P_l and the actual departure interval $d_{t_2} - d_{t_1}$. If the difference is positive, it is denoted as Δd_t^+ and if the difference is negative, it is denoted as Δd_t^- .

Figures 1 and 2 illustrate the problem of cyclic timetabling through an example involving two cases at the Pierrefitte-Gonesse node used in our experimental study. Two lines are considered, each with distinct characteristics. The first line is operated by passenger trains (PT), while the second line uses high-speed trains (HST). In the first case, the line cycle time is maintained, while in the second case, unavoidable deviations appear. The optimal timetables for both cases are represented in a space-time diagram, also known as a blocking time diagram, showing track utilization over time. Time is displayed vertically and spatial location horizontally, with PT line in red and HST line in blue. Figure 1 showcases the first case, where the target line frequencies is $(F_{PT}, F_{HST}) = (3, 4)$, demonstrating a strictly cyclic timetable in which the line cycle time is maintained between all successive pairs of trains for both lines. In contrast, Figure 2 illustrates the complexity that emerges when the frequency is increased to $(F_{PT}, F_{HST}) = (3, 5)$. To accommodate an additional HST train, the second PT train must be shifted by 11 seconds to maintain the feasibility of the timetable and avoid overlapping. This deviation compresses the interval between the shifted PT train and its predecessor, resulting in a positive periodicity deviation, as the actual interval becomes smaller than the ideal one. Conversely, the interval between the deviated PT train and its follower expands, leading to a negative periodicity deviation. Consequently, the optimal and most regular timetable for the second case has a total deviation of 44 seconds.

To address the cyclic timetabling problem, we use a MILP model for microscopic cyclic timetabling. This model incorporates cyclic timetabling constraints to ensure that trains operating the same train line are scheduled at regular intervals during timetable cycle. It also considers capacity and operational constraints, ensuring a precise microscopic representation of the infrastructure incorporating the signaling system, where routes are divided into blocks and

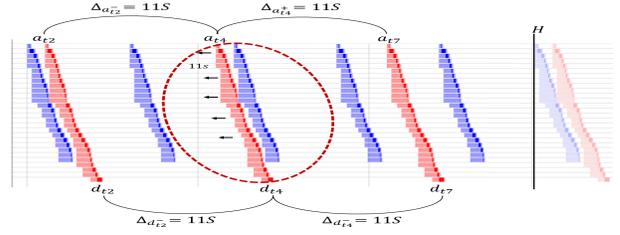


Fig. 2. Blocking time diagram of a non-strictly cyclic timetable given the line frequencies $(F_{PT}, F_{HST}) = (3, 5)$

further into track-circuits, and the interlocking system, a crucial safety feature that controls the signaling system to prevent train accidents. These constraints are identical to those in RECIFE-MILP, which is dedicated to real-time railway traffic management [5].

IV. MIXED-INTEGER LINEAR PROGRAMMING FORMULATION

Let us introduce the notations we suggest adopting.

Sets:

- \mathcal{L} Set of train lines.
- $\mathcal{T}(l)$ Set of trains operating the train line $l \in \mathcal{L}$, with $\mathcal{T} = \cup_{l \in \mathcal{L}} \mathcal{T}(l)$.
- $\mathcal{R}(l)$ Set of routes assigned to train line $l \in \mathcal{L}$, with $\mathcal{R} = \cup_{l \in \mathcal{L}} \mathcal{R}(l)$.

Parameters:

- H Timetable cycle time.
- F_l Frequency of the train line l within the timetable cycle time H .
- P_l Line cycle time of train line l ($P_l = \frac{H}{F_l}$).
- $\beta_{t,l}$ Indicator function equal to 1 if train t operating the train line l is the last train of the timetable cycle.
- f_t Train immediately following train t and operating the same train line. If train t is the last in the timetable cycle, its following one is the first train of the timetable cycle.
- σ_r, λ_r The first and last track-circuits in route $r \in \mathcal{R}$, respectively.
- $\rho_{r,t,tc}$ Free-network running time of track-circuit tc along r for train t .

Decision variables:

a_t	Arrival time of train t at the railway node.
d_t	Departure time of train t from the railway node.
$\Delta a_t^+, \Delta a_t^-$	Continuous variables indicating the possible positive, respectively negative, deviations from the line cycle time in the actual time interval between the arrival of train t and that of its successor at the node.
$\Delta d_t^+, \Delta d_t^-$	Continuous variables indicating the possible positive, respectively negative, deviations from the line cycle time in the actual time interval between the departure of train t and that of its successor from the node.
$o_{t,r,tc}$	Time in which train t starts the occupation of track-circuit tc along route r .

The presented model is an adaptation of the RECIFE-MILP model designed to address the microscopic periodic planning problem, which can be formulated as follows.

$$\min \sum_{t \in \mathcal{T}} (\Delta a_t^- + \Delta a_t^+ + \Delta d_t^- + \Delta d_t^+) \quad (1)$$

subject to:

$$a_t = \sum_{r \in \mathcal{R}(l)} o_{t,r,\sigma_r} \quad \forall l \in L, t \in \mathcal{T}(l), \quad (2)$$

$$d_t = \sum_{r \in \mathcal{R}(l)} o_{t,r,\lambda_r} + \rho_{t,r,\lambda_r} x_{t,r} \quad \forall l \in L, t \in \mathcal{T}(l), \quad (3)$$

$$\Delta a_t^+ \geq (a_{f_t} - a_t + H \beta_{t,l}) - P_l \quad \forall l \in L, t \in \mathcal{T}(l), \quad (4)$$

$$\Delta a_t^- \geq P_l - (a_{f_t} - a_t + H \beta_{t,l}) \quad \forall l \in L, t \in \mathcal{T}(l), \quad (5)$$

$$\Delta d_t^+ \geq (d_{f_t} - d_t + H \beta_{t,l}) - P_l \quad \forall l \in L, t \in \mathcal{T}(l), \quad (6)$$

$$\Delta d_t^- \geq P_l - (d_{f_t} - d_t + H \beta_{t,l}) \quad \forall l \in L, t \in \mathcal{T}(l). \quad (7)$$

$$\Delta d_t^+, \Delta d_t^-, \Delta a_t^+, \Delta a_t^- \in \left[0, \frac{P_l}{2}\right] \quad \forall l \in L, t \in \mathcal{T}(l). \quad (8)$$

(I) Time-related constraints

(II) Constraints from rolling stock changes

(III) Capacity constraints

The objective function seeks to minimize the total deviations from the line cycle time in the timetable for each train's arrival and departure times. By reducing these deviations, the model aims to construct a timetable that closely aligns with the desired strictly cyclic timetable while accounting for operational constraints. These constraints include capacity limitations, rolling stock requirements, and time-related factors as detailed in [5], as well as additional periodicity constraints specified in this study.

Constraints (2) and (3) define the arrival and departure times for each train at the railway node. The arrival time is precisely determined by the moment when a train t begins occupying the first track-circuit on its assigned route σ_r , while the departure time encompasses the start of the last track-circuit occupation λ_r , and the running time across that track-circuit. The remaining constraints measure the differences between the actual time intervals and the line cycle time for train arrivals and departures of the same train line. Constraints (4) calculate positive arrival deviations, occurring when the actual time interval between the arrival of a train and its successor of the same train line is larger than

the line cycle time. This means that the train arrives later than the ideal schedule, where the time difference between its arrival and the arrival of its successor of the same line respects the line cycle time. Constraints (5) calculate negative arrival deviations, occurring when the actual arrival interval is smaller than the line cycle time. This means that the train arrives earlier than the ideal schedule, based on the line cycle time. Constraints (6) measure positive departure deviations, occurring when the actual departure interval exceeds the line cycle time. This suggests that the train departs later than the ideal schedule. Constraints (7) measure negative departure deviations, occurring when the actual departure interval is less than the line cycle time. This implies that the train departs earlier than the ideal schedule. Constraints (8) ensures that all deviations are positive and limited by the upper bound $\frac{H}{2}$. In order to model the circulation of trains and address the microscopic planning problem, the model uses RECIFE-MILP through constraints (I), (II), and (III).

V. EXPERIMENTAL STUDY

The experimental study is conducted using data from a real node of the French railway network, the Pierrefitte-Gonesse junction. The track layout of this junction is shown in Figure 3. This node is traversed by a mix traffic, including passenger trains (PT), high-speed trains (HST), and freight trains (FT).

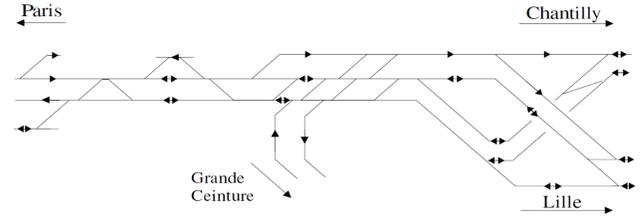


Fig. 3. Pierrefitte-Gonesse junction track layout

This experimental study aims to provide preliminary computational results for analyzing the capacity of the junction in two types of scenarios: a homogeneous and a heterogeneous ones. We consider three train lines with varying frequency: PT line is operated by passenger trains going from Paris to Lille and vice versa; HST line is operated by high-speed trains going Paris to Chantilly; FT line is operated by freight trains going from Grande Ceinture to Chantilly. The homogeneous scenarios consider only one train line, establishing an upper bound for capacity. In contrast, the heterogeneous scenarios incorporate combinations of different lines, more accurately reflecting real-world operations. By comparing these scenarios, we can quantify the impact of traffic heterogeneity on capacity. To do so, we run the proposed model in two modes: First, the Fixed Routing mode, which considers only the default routes assigned to each train line; and second, the Rerouting mode, which starts with the default routes and then explores additional possibilities using alternative routes. The experiments are conducted on an Intel Core i7-8665U 4.8 GHz processor with

24 GB of RAM, running Ubuntu 22.04. The implementation of the model was done in C++ using IBM ILOG CPLEX Concert Technology.

A. Homogeneous traffic scenarios

In the homogeneous scenarios, the MILP model is run iteratively in the Fixed Routing mode, progressively increasing the frequency of trains for the considered line until infeasibility is reached. A time limit of 10 minutes is set for each iteration. The results indicate that the node can accommodate 25 PT trains, 28 FT trains, and 38 HST trains in each direction. Remark that the default routes for opposite directions use independent track-circuits without overlapping. Moreover, They are nearly identical in terms of length, number of blocks, and track-circuits and running times. This implies equal minimal headway (time separation) in the two directions and then the same maximum number of trains in both directions. This is the upper bound on the node capacity.

B. Heterogeneous traffic scenario

We test a heterogeneous scenario that considers two lines: PT and HST ones. Both lines are considered to operate only in the forward direction. The PT line operates from Paris to Lille, and the HST line from Paris to Chantilly. The default routes for both lines share a significant portion of the track. However, the one for the PT line is significantly longer than that of the HST line. The MILP model was run iteratively in both Fixed Routing and Rerouting modes, testing various train line frequencies for both PT and HST lines. A time limit of 10 minutes was set for each iteration of the Fixed Routing execution mode, while the iteration time limit for the Rerouting mode was restricted to 1 hour. The results are visualized through two heat maps, each corresponding to an execution mode. The x-axis of the heatmaps represents the frequency of trains for the HST line, while the y-axis represents the frequency of trains for the PT line. Each cell in the heat map represents the cumulative deviations for the given line frequency combination. The color scale ranges from dark blue for zero deviation, light blue for deviations less than 1000 seconds, light red for deviations between 1000 and 2000 seconds, and dark red for deviations greater than 2000 seconds. The heatmap in Figure 4 reports the results obtained in the Fixed Routing execution mode, while the second heatmap in Figure 5 displays the results obtained in the Rerouting execution mode.

The first finding when observing the results presented in Figure 4 is the ability of the MILP model to identify the line frequency combinations that allow to reach strictly cyclic timetables corresponding to dark blue cells in the heatmap. Another interesting finding provides insight on the node capacity is provided by the border, which limits the feasibility region in the heatmap and identifies the maximal frequencies that can be handled. At this border, capacity utilization is maximal, so incrementing line frequency leads to infeasibility. This occurs when the cumulative track utilization of the trains is higher than the timetable cycle time.

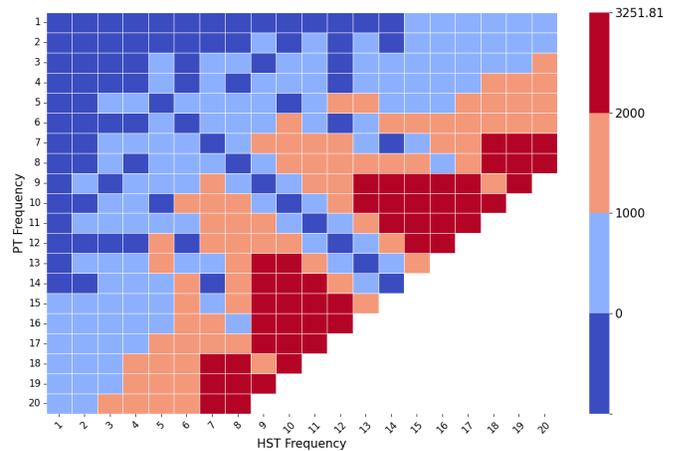


Fig. 4. Cumulative deviations results for HST and PT with Fixed routing mode

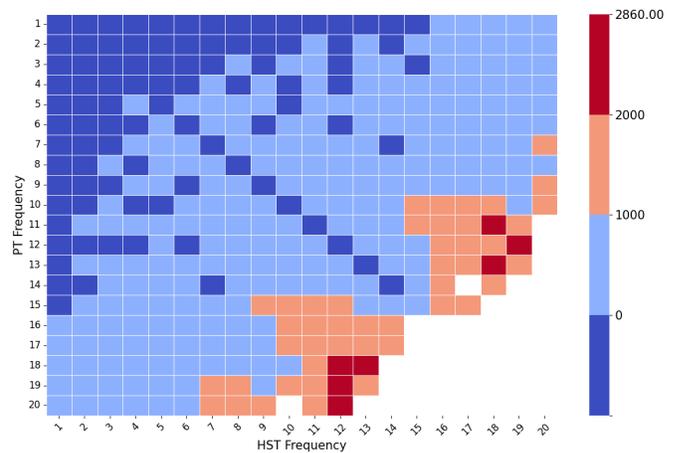


Fig. 5. Cumulative deviations results for HST and PT with Rerouting mode

Besides, there is symmetry in deviations around the diagonal of the heatmap. In other words, swapping the frequency of PT line with that of HST line in the major part of cells results in the same total deviation. This symmetry can be explained by the interchangeability of lines once the timetable cycle capacity is large enough to accommodate all trains. This symmetry holds true above the borders, where the combinations are all symmetric. However, there are some exceptions at the borders, such as the pair (8, 20) versus (20, 8), where the symmetry breaks down. This difference can be explained by variations in train characteristics. Additionally, the timetable is nearly saturated at this level.

The results presented in Figure 5, obtained from the Rerouting mode, demonstrate significant improvements over the Fixed Routing execution mode. These include an expansion of the feasible area in the heatmap, with new cells appearing below the previous boundary obtained in the Fixed Routing mode, a general reduction in cumulative deviation illustrated by an enlarged blue area, and a decrease in the maximum cumulative deviation from 3251.81 seconds to 2860 seconds. These improvements underscore the impact

of alternative routes on optimizing capacity utilization. The heatmap also reveals some blank cases that represent instances where the time limit was insufficient to achieve feasibility.

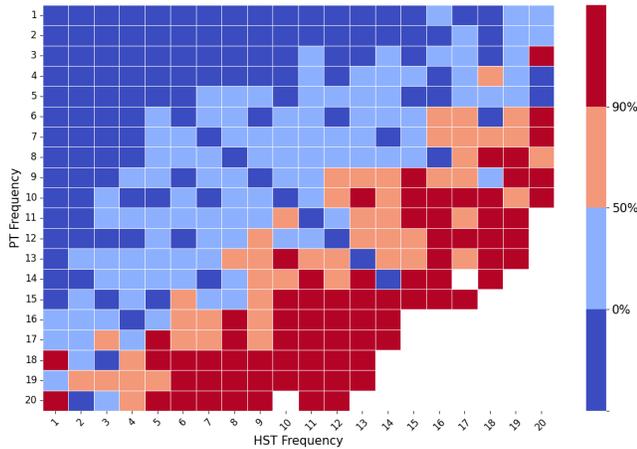


Fig. 6. Gap results for HST and PT with Rerouting mode

The analysis of the Fixed mode and Rerouting mode reveals significant differences in solution quality due to the number of considered routes. In the Fixed mode, only the default route is considered for each line, resulting in a gap of 0% and optimal solutions for all the combinations of line frequencies. In contrast, the Rerouting mode considers the set of alternatives. Specifically, it considers a total of six routes for the PT line (including the default route) and thirteen routes for the HST line (including the default route). This significantly increases the complexity of the problem, as reflected in the heatmap shown in Figure 6. The heatmap uses a color scale to represent the gap magnitudes: dark blue for 0% gaps (optimal solutions), light blue for gaps under 50%, light red for gaps between 50% and 90%, and dark red for gaps of 90% or higher. At the boundary of feasible solutions, gaps exceed 90%, with some cases reaching 100%, represented by blank cells in the heatmap. This indicates extreme computational challenges at the capacity limits. As line frequencies increase, gaps grow, showing how alternative routes and line frequencies complicate the problem, especially near capacity limits. This suggests that heuristic approaches may be needed.

CONCLUSION AND PERSPECTIVES

This paper presents a novel approach to assessing railway node capacity using a MILP model for microscopic cyclic timetabling with realistic infrastructure representation and cyclic timetabling constraints. The model's effectiveness was showcased through an experimental study with real data of the Gonesse railway junction, considering different traffic scenarios. Our approach may provide interesting management insights for policymakers to evaluate capacity utilization in presence of several combinations of line frequencies. The results highlight the positive impact of rerouting on capacity.

Future work will focus on leveraging this model to evaluate potential node reconfigurations. Since our results highlighted the benefits of alternative routing options, and reconfiguration typically introduces more routes, we aim to use our model to assess the capacity gains from various infrastructure layout modifications. This research direction will provide railway planners with a powerful tool for evaluating node capacity at the strategic level. Additionally, given the computational challenges observed in the Rerouting mode, especially for high-frequency combinations, we plan to develop and implement heuristic approaches, aiming to find optimal solutions more efficiently, complementing our proposed MILP model.

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