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RESEARCH ARTICLE

A Real-Time Railway Traffic Management Approach Preserving Passenger Connections

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ABSTRACT This paper addresses the real-time Railway Traffic Management Problem (rtRTMP), which involves adjusting train timetables during perturbations. Perturbations in railway networks often lead to significant delays, necessitating strategies to minimize their propagation. An important objective of traffic management is to facilitate passenger transfers through connecting trains, which may become difficult when traffic is disturbed. Pursuing this objective, the paper focuses on mitigating train delays by reducing connection times during transfers without compromising connections. To achieve this, we extend an existing Mixed-Integer Linear Programming (MILP) formulation for the rtRTMP by introducing two alternative enhancements. Moreover, we pursue the same delay mitigation by extending an Ant Colony Optimization algorithm for the Train Routing Selection Problem (TRSP): this problem reduces the number of alternative routes to be considered for trains, making rtRTMP instances tractable. We assess the efficiency of the proposed enhancements in reducing the total train delay while preserving passenger connections in multiple instances representing traffic in the Lille-Flandres station control area, located in the north of France. The results demonstrate that the integration of these enhancements, in both the TRSP and the rtRTMP, results in a significant reduction in delay propagation.

INDEX TERMS Ant colony optimization, connection time, passenger connections, real-time railway traffic management problem (rtRTMP), rescheduling, train rerouting.

I. INTRODUCTION

The efficient and reliable operation of railway systems heavily relies on continuous traffic monitoring and control by dispatchers. Operations are based on a meticulously designed timetable that includes essential details such as train arrival and departure times, routes, sequencing, and planned connections. However, unexpected events, such as delays or technical problems, frequently disrupt schedules. In response to these unexpected events, dispatchers play a pivotal role in making rescheduling decisions to either reinstate the original timetable or create a new one that compensates for system disturbances, ensuring the smooth operation of the railway system. Indeed, a measure of the system reliability is delay propagation, which can be limited thanks to wise rescheduling decisions.

The real-time Railway Traffic Management Problem (rtRTMP) [1] addresses the challenge of adjusting train timetables during perturbations. It involves resolving conflicting requests from multiple trains that share sections of track. As real-time traffic scenarios pose unique challenges due to their unpredictable nature — stemming from factors such as varying passenger demands, unexpected delays, and rapidly changing operational conditions — dispatchers need rtRTMP algorithms for assistance. These algorithms must be designed not only to provide fast solutions but also to address the practical challenges that frequently arise in railway operations, including the consideration of passenger

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connections: solutions must account for passengers changing trains at an intermediate station to travel from an origin to a destination.

This paper focuses on passenger connections in the rtRTMP. Connections involve two trains — the feeder and the receiver — with the station where the connection occurs referred to as the connecting station. Receiver trains shall not depart earlier than the arrival of the feeder train, plus a minimum connection time. This minimum connection time represents the necessary time for passengers to transfer between trains. In the timetable definition, a buffer is usually incorporated to ensure that the time between the planned arrival of the feeder and the planned departure of the receiver is longer than the minimum connection time. This is done to foster the robustness of the timetable connections. However, if the feeder train experiences a significant delay beyond this buffer, its delay propagates to the receiver. Hence, while it is possible to drop passenger connections to avoid excessive delay propagation [2], imposing strict adherence to connections may result in significant delay propagation [3]. This paper addresses the challenge of preserving passenger connections while minimizing delay propagation. Specifically, we explore the relationship between minimum connection time and platform selection, emphasizing that closer platforms correlate with shorter minimum connection times for passengers.

This paper introduces two enhancements to the Mixed-Integer Linear Programming (MILP) formulation at the basis of the algorithm named RECIFE-MILP [4], to incorporate passenger connections within the rtRTMP solution. In RECIFE-MILP, platform selection for connecting trains at stations is determined by the chosen routes; as in the rest of the literature allowing for train rerouting, train timings are set to ensure a sufficiently large connection time to allow passengers to transfer seamlessly between any possible pair of platforms. The two enhancements we propose, named Platform Compatibility (PC) and Variable Connection Time (VCT), optimize the platform assignment process and consider connection times consistent with these assignments. PC narrows down the available platform pairs for connecting trains to those compatible with a small value for the minimum connection time provided as input. In VCT, a more flexible approach is adopted, making the minimum connection time dependent on the platforms actually chosen for connecting trains.

In addition, to effectively address challenges posed by control areas with trains having multiple possible alternative routes, the paper proposes refinements for the Train Routing Selection Problem (TRSP) [5]. The TRSP's role is to identify promising routing alternatives for each train. The proposed refinements aim to incorporate connection constraints into the TRSP and select the train alternative routes in coherence with the PC and VCT enhancements. By refining the state-of-the-art TRSP model by Pascariu et al. [6], the paper aims to enhance the overall performance of the rtRTMP solution.

To evaluate the advantages resulting from the proposed enhancements, we conduct an extensive series of experiments on the Lille-Flandres control area, a complex and highly congested French station. Our results demonstrate a substantial reduction in delay propagation thanks to the implementation of the two proposed enhancements.

In summary, the main contributions of this paper are the following:

- We address the rtRTMP, focusing on minimizing delay propagation and facilitating efficient passenger transfers.
- Our proposed enhancements, PC and VCT, optimize platform assignments to improve passenger connection efficiency.
- We refine the TRSP to integrate connection constraints, complementing the PC and VCT enhancements.
- Through a case study at Lille-Flandres, we demonstrate a significant reduction in overall delay, validating the effectiveness of our proposed enhancements.

The remainder of this paper is structured as follows. Section II explores the relevant literature, providing insights into the motivations behind this research. Section III formalizes the rtRTMP and outlines the classic RECIFE-MILP approach, with additional details available in Appendix A. Sections IV and V delve into the two enhancements proposed in this paper. Section VI illustrates the extension of the TRSP. Section VII presents our chosen case study, focusing on the Lille-Flandres control area in northern France. Section VIII details the results of our analysis. Lastly, Section IX discusses the conclusion of our work and suggests future research directions.

II. LITERATURE REVIEW

The rtRTMP has received significant attention in recent decades, with research addressing both operation and passenger perspectives. Operation-oriented approaches focus on preserving service punctuality, optimizing operational costs, and minimizing train delay propagation. Passenger-oriented approaches consider passenger-related data. Works such as Törnquist [7], Fang et al. [8], and Qu et al. [9] provide a comprehensive review of rtRTMP literature, covering modeling choices, solution strategies, and problem types. Surveys by Josyula and Törnquist Krasemann [10] and Sharma et al. [11] specifically delve into approaches considering passenger-oriented aspects.

The rtRTMP has been studied using a range of models, including integer programming [12], [13], MILP [4], [14], [15], [16], [17], and alternative graphs [18], [19], among others. Additionally, these studies vary in the types of traffic disturbances they address. Some focus on relatively minor disturbances, termed perturbations, allowing for a return to the original timetable with modest adjustments [14], [20]. Others deal with major disturbances, termed disruptions, caused by events such as train breakdowns, significant infrastructure failures, or line interruptions. These disruptions necessitate significant modifications to the original schedule [13], [17], [21], [22], [23].

While existing studies mostly focus on operation-oriented approaches, efforts to address passenger-oriented concerns have been ongoing for some time. For instance, Schöbel [24] first introduce the concept of delay management within the context of passenger transfers. The paper delves into strategies for accommodating delayed feeder trains by determining whether receiver trains should wait for a delayed feeder train or depart on time. Subsequent research by Schöbel [20] further develops this concept by incorporating constraints to account for track capacity. Additionally, Dollevoet et al. [25] expand on these efforts by incorporating the modeling of station capacities into their research.

Despite the progress made in both operation-oriented and passenger-oriented research, there exists a notable gap in the literature addressing passenger connections, particularly regarding the optimization of platform selection during train rerouting. Existing studies, such as those by Dollevoet et al. [26] and König and Schön [27], have explored the possibility of rerouting passengers in the network to let them reach to their destinations in case of disruption, but overlook train rerouting to different platforms within the station to constrain minimum connection time. However, optimizing platform selection during train rerouting can help prevent delay propagation: if the chosen platforms allow for a short minimum connection time, the receiving train may experience less waiting time when the feeder train is delayed.

To the best of our knowledge, our paper represents the first effort to consider the rerouting of connecting trains within a station, exploring the relationship between minimum connection time and platform selection to minimize delay propagation and preserve passenger connections. Our approach employs a microscopic representation of railway infrastructure, and we propose considering the minimum connection time as a function of the alternative routes of connecting trains, assuming that connections cannot be broken.

III. rtRTMP AND CLASSIC RECIFE-MILP MODEL

In this section, we elaborate on the problem considered in this paper.

We model the rtRTMP with a microscopic representation of the infrastructure, dividing tracks into track circuits. Each track circuit identifies the smallest section of track where the presence of a train is automatically detected. Sequences of track circuits, separated by signals, form what is known as block sections. These signals dictate train driver actions through their aspects, such as proceeding at the scheduled speed (green), braking (yellow), or stopping (red).

A train needs a certain amount of time to traverse a track circuit, dependent on rolling stock and infrastructure, which is called running time. After the head of the train exits the track circuit, the time necessary for the tail of the train to clear it is named the clearing time. To ensure safe separation and operational feasibility, the interlocking and signaling systems secure the correct positioning of switches in track circuits, if any, and the appropriate aspects of signals. According to the blocking time theory [28], and in the case of signaling with the three previously mentioned aspects, track circuits are reserved when the train enters the preceding block section, along with the so-called formation time. This formation time encompasses the duration necessary for the train driver to observe the clear aspect of the signal protecting the block. Additionally, to ensure safe separation after the tail of the train leaves a track circuit, the circuit remains unavailable for other trains for release time. Utilization time refers to the time during which a track circuit is available solely for the movement of one train, thus preventing access for other trains. Utilization time includes reservation time, running time, clearing time, formation time, and release time.

A train route consists of a sequence of track circuits linking an origin to a destination within a control area, possibly including intermediate stations where the train is scheduled to stop. Each train is initially assigned a default route as defined in the timetable. However, there are typically multiple alternative routes available for a train in addition to the default one. These alternative routes share the same origin, destination, and intermediate stations as the default route, passing through different track circuits.

For each train travelling within a control area, the original timetable specifies entrance and exit times, as well as arrival and departure times for scheduled stops at stations. In cases of traffic perturbations (primary delays), a train traveling at the scheduled speed may request access to a track circuit concurrently with another train, leading to a conflict. This conflict can be resolved by introducing unscheduled waiting time for one of the two trains (secondary delays) or by changing train routes within the control area. The rtRTMP is the problem that deals with potential conflicts in real-time by retiming, reordering, and rerouting trains. The objective of the rtRTMP is to provide a revised traffic plan that minimizes train delay propagation. Notably, in our modeling approach, passenger connections are maintained as per the original timetable.

As mentioned in the introduction, we adopt the RECIFE-MILP model as the basis for our proposal. RECIFE-MILP is founded on the MILP formulation proposed in Pellegrini et al. [4], [29] to solve the rtRTMP. In the rest of this section, we present the information necessary to outline the contribution of this paper. For a comprehensive description of the complete model, we direct the reader to Appendix A.

The decision to utilize the RECIFE-MILP model stems from its proven efficacy, flexibility, and alignment with the objectives of our research. This model has been extensively validated and applied in previous studies focused on the rtRTMP, demonstrating its capability to optimize train schedules and minimize delays [4], [29]. Furthermore, RECIFE-MILP model offers a robust mathematical framework based on MILP, facilitating systematic modeling and solution of complex rescheduling challenges.

One of the key advantages of RECIFE-MILP lies in its flexibility regarding the objective function definition, allowing us to concentrate on minimizing train delay propagation—a central focus of our research. Moreover, the model integrates various constraints, encompassing factors such as delays, minimum travel durations, and train separation, ensuring the accuracy and feasibility of routing decisions. Its adaptability to accommodate extensions and enhancements enables us to address issues related to passenger connections.

In RECIFE-MILP, timing decisions are handled using non-negative continuous variables. These variables include the start and end utilization times, the start occupation time, and the longer travel times in track circuits. Binary variables in the model serve two distinct roles: they capture train routing decisions, considering the choice of routes among alternative options, and ordering decisions, defining the precedence relationships between trains possibly sharing track circuits.

The MILP model integrates several constraints to maintain the accuracy of train routing and scheduled timings. These constraints account for various factors, including delays, minimum travel duration on track circuits, and train separation. The model also manages scenarios involving train turnaround, joins, splits, and train connections. The RECIFE-MILP model is flexible in terms of objective function definition, provided it remains a linear function. Here, we consider the typically used total delay to be minimized.

In our paper, we focus on the passenger connection constraint, which establishes the rules for passenger connections within the network. To provide a basis for our model extensions, we introduce the relevant sets and variables:

- T: the set of trains;
- R_t: the set of routes available to train $t \in T$, with $R = \cup_{t \in T} R_t$ the total set of routes;
- TC^r: the set of track circuits belonging to route $r \in R$;
- S_t: the set of stations where $t \in T$ has a scheduled stop;
- TC^s: the set of track circuits belonging to station s;
- $c(t, t', s)$: indicator function equal to 1 if there is a connection between feeder train $t \in T$ and receiver train $t' \in T$ in station $s \in S_t \cap S_{t'}$, otherwise 0;
- $mc_{t,t',s}$: minimum connection time between $t \in T$ and $t' \in T$ in $s \in S_t \cap S_{t'}$;
- $rt_{r,ty,tc}$: free-network running time of $tc \in TC^r$ along $r \in R$ for a train of type ty;
- $p_{r,tc}, s_{r,tc}$: track circuits preceding and following $tc \in TC^r$ along $r \in R$;

The variables we use include the binary routing variables and continuous variables used to define the travel time:

- $x_{t,r}$: binary variable equal to 1 if train $t \in T$ uses route $r \in R_t$, 0 otherwise;
- $o_{t,r,tc}$: time at which $t \in T$ starts the occupation of $tc \in TC^r$ along $r \in R_t$.

The connection constraints are represented by the following equation:

$$\sum_{r' \in R_{t'}, tc' \in TC^{r'} \cap TC^s} o_{t',r',s_{r',tc'}} \geq \sum_{\substack{r \in R_t, \\ tc \in TC^r \cap TC^s}} o_{t,r,tc} + (mc_{t,t',s} + rt_{r,ty_t,tc}) x_{t,r} \quad \forall t, t' \in T, s \in S_t \cap S_{t'} : c(t, t', s) = 1. \tag{1}$$

Constraints (1) ensure a minimum separation of duration $mc_{t,t',s}$ between the arrival of t at the end of the track circuit it uses to stop at station s and the departure of t', if they are in connection. Remark that the departure of t' corresponds to the time it starts occupying the track circuits that follow the one it uses to stop in TC^s.

The classic RECIFE-MILP model (hereafter referred to as RECIFE-MILP CL) performs rerouting without considering the walking distance between platforms and their configuration, and hence the specific connection time. The value of $mc_{t,t',s}$ in Constraints (1) is a predetermined fixed value provided as input. The absence of a direct relationship between rerouting and minimum connection time necessitates setting the minimum connection time to a sufficiently large value in RECIFE-MILP CL to accommodate rerouting for any combination of routes, and hence platforms.

Next, we provide an example to illustrate the variability and impact of the minimum connection time. The illustration in Fig. 1 depicts a simplified station layout with five platforms, each identified by the corresponding track circuit where trains make stops. Table 1 provides the walking time distances between pairs of platforms for passenger transfers within the station. For simplicity, we consider walking distance as the sole factor when determining the minimum connection time in this example. Walking distance is measured in time units. It depends on walking speed, so a conservative speed has to be considered when setting it, based on slow walking speed. Moreover, the specific station facilities and layout must be taken into account: for example, the availability of escalators and lifts will typically impact walking distance.

In RECIFE-MILP CL, the minimum connection time for connecting trains t and t' must correspond to the maximum walking time distance between platforms, set at 9 minutes in this instance (the walking distance between TC-1 and TC-5). This allows using any pair of platforms for t and t', without compromising the feasibility of transfers. This implies that, for example, if train t (feeder) is scheduled to arrive at 7 am and train t' (receiver) is set to depart at 7:11 am, the feeder train t has a 2-minute buffer to avoid delay propagation. If train t arrives by 7:02 am, train t' can still depart on time. However, if train t arrives later, say at 7:05 am, the model enforces a departure time for train t' at 7:14 am to adhere to the minimum connection time, resulting in a 3-minute delay propagation. Reducing the value of the minimum connection time may mitigate or even prevent this delay propagation.

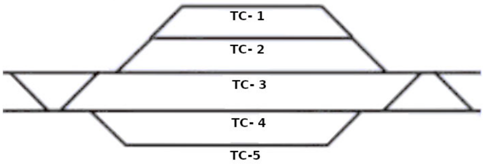


FIGURE 1. Simple station representation.

In the next sections, we introduce two enhancements to RECIFE-MILP CL aimed at reducing the minimum connection time.

TABLE 1. Platforms and walking distance in minutes..

Track Circuits	TC-1	TC-2	TC-3	TC-4	TC-5
TC-1	0	2	4	7	9
TC-2	2	0	2	5	7
TC-3	4	2	0	3	5
TC-4	7	5	3	0	2
TC-5	9	7	5	2	0

IV. PLATFORM COMPATIBILITY ENHANCEMENT (PC)

In this section, we introduce our first enhancement, the Platform Compatibility (PC) one, designed to reduce the minimum connection time while preserving the practical feasibility of passenger connections. The PC enhancement involves considering a fix minimum connection time, as in RECIFE-MILP CL. However, unlike RECIFE-MILP CL, where the minimum connection time is set equal to the maximum time required for passengers to walk between the farthest platforms available for connecting trains, in the PC enhancement, the minimum connection time is typically set to be smaller. By reducing the minimum connection time, we increase the buffer that can be exploited to reduce delay propagation, as discussed in Section III. To preserve the feasibility of the solution, we limit the pairs of platforms that connecting trains can use: connecting trains are restricted from using routes that pass through track circuits serving platforms with a walking distance incompatible with the fixed minimum connection time. The degree of limitation on pairs of usable routes varies depending on the fixed minimum connection time, which is an input parameter for the model.

For the PC enhancement, we introduce a new set of constraints into the RECIFE-MILP formulation. Specifically, we define the following set:

$\overline{TC}_{tc}^{t,t'}$ Set of track circuits that are forbidden for train $t' \in T$ if train $t \in T$ stops in tc.

The definition of this set depends on the fixed minimum connection time parameter. In addition to this set, we add the following constraints:

$$\sum_{r \in R_t : tc \in TC^r} x_{t,r} + \sum_{r' \in R_{t'} : \exists tc' \in TC^{r'} \cap \overline{TC}_{tc}^{t,t'}} x_{t',r'} \leq 1$$
$$\forall t, t' \in T, s \in S_t \cap S_{t'} : c(t, t', s) = 1,$$
$$tc \in TC^s, \overline{TC}_{tc}^{t,t'} \neq \emptyset \quad (2)$$

For two connecting trains t and t' at station s, Constraints (2) ensure that if t uses a route passing through track circuit tc, t' cannot use a route passing through a forbidden track circuit in $\overline{TC}_{tc}^{t,t'}$.

Alongside this set of constraints, we also use Constraints (1) with the fix value of $mc_{t,t',s}$ provided as input.

In the example depicted in Fig. 1 and detailed in Table 1, let us consider a scenario where the minimum connection time is set at 8 minutes. Taking the example of connected trains t (feeder) and t' (receiver), if train t stops in TC-5, t' is prohibited from stopping in TC-1, and vice versa, because the maximum time required for passengers to walk between the two corresponding platforms is more than 8 minutes (9 minutes). Instead, for any other pair of platforms, no additional constraint needs to be set as the minimum connection time of 8 minutes is higher than the specific walking time (Table 1). In this scenario, considering that t is scheduled to arrive at the station at 7 am and t' is scheduled to depart at 7:11 am, t has a buffer time of three minutes to absorb the propagation of a potential delay at the arrival of t' at the station. The effect of the first enhancement is in this case an increase in the buffer time by one minute, compared to RECIFE-MILP CL.

If the fix minimum connection time is further reduced to five minutes, TC-1 can only be paired with TC-2 and TC-3, while TC-2 cannot be paired with TC-5. Under these conditions, the buffer times extend to six minutes, offering greater potential to reduce delay propagation, at the cost of reduced rerouting flexibility.

The impact of the PC enhancement depends on two factors: the number and characteristics of alternative routes for connecting trains, and the specified input value for the fix minimum connection time. A decrease in the fix minimum connection time can lead to increased buffer times, aiding in minimizing delay propagation. However, this reduction may also limit rerouting options for connecting trains, potentially affecting traffic and increasing the propagation of delays.

We will evaluate the validity and effects of the PC enhancement by comparing it with RECIFE-MILP CL, which represents the state of the art, and our second proposed enhancement, described in the following section.

V. VARIABLE CONNECTION TIME ENHANCEMENT (VCT)

In this section, we introduce our second enhancement, the Variable Connection Time (VCT) one, aimed at reducing the minimum connection time while maintaining the flexibility of train routing choices. In VCT, we consider the minimum connection time as a variable depending on the platforms selected by the two connecting trains. We introduce binary variables indicating the pair of platforms selected by the connecting trains, and relate these variables to train routing choices through a set of new constraints. These constraints replace the management of passenger connections in RECIFE-MILP CL. Unlike PC, which imposes restrictions on train routing, VCT preserves the full flexibility of routing choices.

The formulation of VCT includes the following variables:

- $w^{t,t'}_{tc,tc'}$: binary variable equal to 1 if trains t and t' use track circuits tc and tc' to stop at station $s \in S_t \cap S_{t'}$: $c(t,t',s) = 1$, otherwise 0;
- $MCT^{t,t'}_{tc,tc'}$:minimum connection time to be respected if t and t' stop at track circuits tc and tc', respectively.

For the VCT enhancement, we remove Constraints (1) from the original model and add the following new constraints. Additionally, Constraints (2) is not used in the revised model.

$$\sum_{\substack{r'\in R_{t'}\\ tc'\in TC^{r'}\cap TC^{s}}} o_{t',r',s_{r'},tc'} \geq \sum_{\substack{r\in R_{t}\\ tc\in TC^{r}\cap TC^{s}}} (o_{t,r,tc} + rt_{r,ty_t,tc}x_{t,r}) + \sum_{\substack{tc'\in TC_{t'}\cap TC^{s}\\ tc\in TC_{t}\cap TC^{s}}} w^{t,t'}_{tc,tc'} MCT^{t,t'}_{tc,tc'}$$
$$\forall t,t' \in T, s \in S_t \cap S_{t'} : c(t,t',s) = 1, \quad (3)$$

$$w^{t,t'}_{tc,tc'} \geq \sum_{r\in R_t : tc\in TC^r} x_{t,r} + \sum_{r'\in R_{t'} : tc'\in TC^{r'}} x_{t',r'} - 1$$
$$\forall t,t' \in T, s \in S_t \cap S_{t'} : c(t,t',s) = 1,$$
$$tc' \in TC_{t'} \cap TC^{s}, tc \in TC_t \cap TC^{s}, \quad (4)$$
$$w^{t,t'}_{tc,tc'} \leq \sum_{r\in R_t : tc\in TC^r} x_{t,r}$$
$$\forall t,t' \in T, s \in S_t \cap S_{t'} : c(t,t',s) = 1,$$
$$tc' \in TC_{t'} \cap TC^{s}, tc \in TC_t \cap TC^{s}, \quad (5)$$

$$w^{t,t'}_{tc,tc'} \leq \sum_{r'\in R_{t'} : tc'\in TC^{r'}} x_{t',r'}$$
$$\forall t,t' \in T, s \in S_t \cap S_{t'} : c(t,t',s) = 1,$$
$$tc' \in TC_{t'} \cap TC^{s}, tc \in TC_t \cap TC^{s}. \quad (6)$$

Constraints (3) ensure that t arrival and t' departure are separated by the minimum connection time associated to the used track circuits in the connecting station s.

Constraints (4), (5) and (6) work together to ensure that the binary variable $w^{t,t'}_{tc,tc'}$ accurately represents the use of specific track circuits by trains t and t'. Constraints (4) guarantee that the binary variable $w^{t,t'}_{tc,tc'}$ equals 1 only if trains t and t' simultaneously use routes that pass through the corresponding track circuits tc and tc'. Constraints (5) and (6) set upper bounds on $w^{t,t'}_{tc,tc'}$ based on the routing decisions of trains t and t' respectively: they ensure that the binary variable can be 1 only when the respective track circuits are used.

To illustrate the application of VCT, we revisit the example presented in Fig. 1 and Table 1. The minimum connection time will be 7 minutes if t and t' stop at TC-1 and TC-4, and 9 minutes if they stop at TC-1 and TC-5. As a consequence, the buffer time allowing the reduction of delay propagation varies with the choice of the train routes.

It is important to highlight that, compared to RECIFE-MILP CL, this enhancement offers the most realistic representation for modeling the minimum connection time. As it can significantly increase buffer times unless two far platforms are chosen for connecting trains, it offers the potential to effectively minimize delay propagation while preserving complete rerouting flexibility. However, this enhancement introduces greater complexity to the model due to the incorporation of additional variables and constraints.

VI. TRAIN ROUTING SELECTION PROBLEM (TRSP)

The TRSP serves as a preprocessing step to limit the routes used in the rtRTMP. The objective of this preprocessing is to address the computational challenges arising from the large number of alternative routes. In particular, the TRSP is a combinatorial optimization problem that involves the selection of a tailored subset of routes for each train from the available alternatives. In the TRSP, routes are chosen based on cost estimation associated with potential train delays that may arise from their use. These selected routes are the only ones used in the subsequent rtRTMP solution. By doing so, the search space of the latter problem is reduced. Indeed, all solutions that are feasible when considering the selected subsets of routes are also feasible when all available routes can be used. On the contrary, some solutions that can be found when the rtRTMP can exploit all re-routing possibilities are excluded from the search space resulting from the TRSP preprocessing, particularly if the train routes chosen in these solutions are not among those selected by the latter.In this paper, we extend the TRSP model proposed by Pascariu et al. [6], based on the construction graph of Samà et al. [5].

Let us consider a set T of k trains requiring to traverse a railway infrastructure within a certain time window. The TRSP is modeled as the minimum weight clique problem in a k-partite graph $G = (V, E)$. A clique is a complete subgraph in which every pair of vertices within it is connected by an edge. A vertex $v \in V$ in this graph represents an alternative train route. The vertices are grouped into k partitions such that for each train we have an independent set of all alternative train routes. Two vertices $v_i, v_j \in V$ are connected by an edge $e_{ij} \in E$ if they belong to different trains and represent *coherent* routes. In the model by Pascariu et al. [6], two routes are coherent if no rolling stock reutilization constraints apply, or in case of rolling stock reutilization constraints, coherence is established when the last track circuit of the first train's route corresponds with the first track circuit of the second train's route. Considering the nodes and vertices so defined in the construction graph, the k-vertex cliques in the construction graph identify feasible combinations of train routes. The set Γ encompasses all such feasible combinations.

Vertex and edge costs are used in the TRSP to select the subset $S_p \subset \Gamma$ of the p minimum cost k-vertex cliques. The vertex cost $u_i : V \rightarrow \mathbb{N}$ accounts for the potential train delay due to the longer travel time required for the selected route $v_i \in V_t$ compared to the default route $v_d \in V_t$, typically the one assigned in the timetable. This cost is computed as the positive difference between the train minimum running time along v_i and the one along v_d. The minimum travel time is defined as the time required for the train to complete its journey along the route without facing any conflicts. The cost assigned to each edge $w_{ij} : E \rightarrow \mathbb{N}$ represents the potential train delay due to the estimated train scheduling decision when considering train routes v_i and v_j, linked by e_{ij}. This cost consists of two components.

The *fixed component* is calculated for pairs of train routes sharing sections of the infrastructure. The model of Pascariu et al. [6] calculates this component based on potential delay. Potential delay is calculated as the time difference between the end of utilization by the first train and the start of utilization by the second train on the shared section. The second passing train is the potentially delayed train. The smallest value among the two maximum potential delays obtained with the two possible passing orders of the two trains is selected as the optimized ordering decision estimated. If several track sections are common to the two trains along the routes corresponding to the vertices connected by the edge, the highest minimum potential delay is used in the fixed component of the cost.

The *clique-dependent component* is computed after each clique has been built. This component accounts for the potential delay propagation resulting from the interaction of all train routes within the clique. In [6], it is computed as follows. After selecting a clique, each positive fixed component assigned to e_{ij} in the clique is propagated to edges connecting the route of the potential delayed train (v_i) with any other vertex (v_h) in the clique that shares common track sections with it. This generates a clique-dependent cost component on edge e_{ih} in the set of incident edges of v_i. If e_{ih} has a positive cost, the clique-dependent component is the maximum between the propagated w_{ij} and the current potential delay w_{ih}. If e_{ih} has no potential delay according to the fixed cost component but the routes v_i, v_h share track sections, the propagated cost w_{ij} is added to w_{ih}: the estimated time difference between the two trains is reduced, possibly causing a potential delay on the most penalizing common section.

To effectively determine the best routes for trains in real-time, i.e., those that minimize the objective function of the rtRTMP, it is crucial for the potential train delays estimated in the TRSP to exhibit a strong correlation with the rtRTMP model. The model by Pascariu et al. [6] has been demonstrated to accurately estimate the impact of chosen routes for the rtRTMP model of RECIFE-MILP [4] by taking into account the current traffic situation, predicted delays, and network-specific constraints. However, passenger connections have never been considered so far in the TRSP literature.

We propose the extension of the model by Pascariu et al. [6] to include passenger connections and align it with the novel formulations for the rtRTMP proposed in Sections IV and V. In particular, we introduce three alternative variants: TRSP-CL, TRSP-PC and TSRS-VCT in consistency with RECIFE-MILP CL, RECIFE-MILP PC and RECIFE-MILP VCT, respectively.

First, we extend the concept of coherent routes to define the combinations of alternative routes that can be selected depending on how train connections are treated. This defines the edges existing in the construction graph. In particular, in TRSP-PC, when two trains are linked by a passenger connection constraint, we define their routes as coherent if the minimum connection time between the platform of the feeder train and that of the receiving train is smaller than or equal to the established fixed minimum connection time.

Second, a *Passenger Connection* building block is applied in the computation of the edge costs to consider the potential delays due to the temporal constraints linking trains involved in passenger connections. In particular, this building block intervenes in both the fixed and the clique-dependent components of the cost computation. In the fixed component, it ensures the respect of the minimum connection time between the arrival of the feeder train and the departure of the receiving train.

The cost accounting for this potential delay is computed for each pair of alternative routes $v_i, v_j \in V$ corresponding to trains involved in a passenger connection and linked by $e_{ij} \in E$. It is calculated as a fixed cost for all variants TRSP-CL, TRSP-PC, and TRSP-VCT as follows. Consider a passenger connection at station s, where t is the feeder train, t' is the receiving train, $v_i \in V_t$, and $v_j \in V_{t'}$. The cost of e_{ij} is determined as the difference between the minimum connection time (*connectionTime*) and the time interval between the arrival of t at s traveling on v_i (arr_{t,s,v_i}) and the departure of t' from s traveling on v_j (dep_{t',s,v_j}), assuming that the trains run undisturbed in the network:

$$w_{ij} = \max(0, connectionTime - (dep_{t',s,v_j} - arr_{t,s,v_i})) \tag{7}$$

In (7), the *connectionTime* corresponds to: the timetable minimum connection time for TRSP-CL, the fix minimum connection time for TRSP-PC, and the corresponding platform minimum connection time on v_i and v_j for TRSP-VCT.

In the clique-dependent component, the Passenger Connection building block propagates the potential departure delay of the receiving train to trains it may have conflicts with. Indeed, if w_{ij} is positive, the receiving train t' is delayed at its departure from the connecting station. We propagate this potential delay to each train t^* traveling on a route $v_k \in V_{t^*}$ having common track sections with $v_j \in V_{t'}$. Let us consider each edge e_{jk} incident in v_j. If e_{jk} has a positive fixed cost component w_{jk}, the clique-dependent cost is calculated as the maximum between the propagated cost w_{ij} and the current w_{jk}. Otherwise, if e_{jk} has no potential delay, the propagated cost w_{ij} is added to w_{jk} reducing the potential time distance on the critical common section:

$$w_{jk} = \begin{cases} max(w_{ij}, w_{jk}) & \text{if } w_{jk} > 0, \\ w_{jk} + w_{ij} & \text{otherwise.} \end{cases} \quad (8)$$

In this paper, we use Pascariu et al. [6]'s parallel pACO-TRSP algorithm to solve the three alternative TRSP variants.

VII. EXPERIMENTAL SET-UP

In this section, we begin with the presentation of the case study and the experimental setup we consider for the assessment of our proposed enhancements for the rtRTMP and TRSP models in Section VII-A. Then, in Section VII-B, we describe how we analyze solution delays in the assessment.

A. CASE STUDY

We use a case study that includes the station area of Lille Flandres, in France, illustrated in Fig. 2. This case study encompasses a 12-kilometer-long infrastructure. It comprises 299 track circuits, 734 block sections, and 2409 routes. Lille Flandres serves as a hub that connects local, intercity, and high-speed trains, both at the national and international levels. We consider a set of 35 instances, each representing one-hour traffic in a realistic context. The considered one-hour periods start every 20 minutes between 6 and 9 am. We choose this time window because it contains the morning peak hours. The obtained instances include between 35 and 45 trains, and 6 to 12 passenger connections. The minimum connection times in this station span from 2 to 9 minutes.

Within each time period, we introduce five distinct perturbation scenarios targeting the feeder train in each passenger connection. In each scenario, the perturbation is applied to the entrance time of feeder trains in the control area. The first scenario introduces a delay equal to the difference between the feeder train's scheduled arrival time and the scheduled departure time of the receiving train, including delays ranging from 10 to 20 minutes for each feeder train in each connection, affecting approximately 6 to 13 trains. In the following, we indicate this scenario as scenario 0 for the null difference between the scheduled connection time and the feeder delay. The remaining four scenarios consist of delays alternatively 3 minutes longer, 3 minutes shorter, 6 minutes longer, and 6 minutes shorter than the delay applied to the feeder train in scenario 0. These scenarios aim to provide a comprehensive understanding of the models performance in handling different degrees of perturbations, ranging from minor variations to more substantial perturbations. These scenarios are named scenario 3, scenario m3, scenario 6 and scenario m6, respectively.

Our experiments are executed on a system equipped with an Intel Xeon Gold 6226R 2.90GHz processor and 250 GB of RAM. We utilize the Linux Ubuntu distribution version 20.04.4 LTS and implement the formulations using IBM ILOG CPLEX Concert Technology for C++. In particular, the formulations are implemented within the RECIFE-MILP solver [29] and use the same solution process: in the first (at most) 30 seconds of computation, the solver addresses the train scheduling problem, assuming that each train adheres to its timetable route; the best train scheduling solution is employed to minimize the big-M coefficient and serves as warm start in the subsequent step, where both the train scheduling and routing problems are addressed. We employ IBM ILOG CPLEX version 12.6.

B. SOLUTION DELAY ANALYSIS

In assessing the proposed enhancements, our goal is to compare their impact on traffic when implementing the solutions generated with the different models. During operations, these solutions are intended to be implemented following three principles:

1) The route indicated in the solution is used for each train;
2) The passing order indicated in the solution is imposed for each pair of trains sharing one or more track circuits;
3) In connections, the receiving train departs not earlier than its scheduled departure time and as soon as all transferring passengers have boarded, unless it has to wait to respect an imposed passing order right after departure.

Indeed, the third principle is consistent with what is modeled in the VCT enhancement, and hence in the train delays computed in its solutions: the variable minimum connection times represent the actual time needed for transferring passengers to alight from the receiving trains. Instead, in CL and PC, the minimum connection time used in the solution evaluation is possibly more conservative, depending on the platform actually chosen for the trains. For a fair comparison in the operational context, we need to eliminate the additional conservativeness from the impact assessment. To do so, after producing the CL and PC solutions, we produce the corresponding *VCT recomputed solutions*: we assess the delay of the solution generated with the model implementing the VCT enhancement, imposing routes and passing orders from the original CL (or PC) solution.

Furthermore, to carefully analyze the impact that the classic model and the two enhancements may have in practice, we study the *optimized secondary delay* [30] deriving from the returned solutions.This delay is caused by rescheduling decisions in response to train conflicts arising from primary delays [31], which are independent of traffic. It accounts for the propagation of delays through the network as primary delays cascade and affect subsequent train services. We measure optimized secondary delays by excluding primary delays and unavoidable delays due to connections from the total delay. First, we subtract the entrance delay values assigned to feeder trains in the specific scenarios. Indeed, entrance delays remain constant when solving the problem using CL and the two enhancements, and nothing can be done to avoid or mitigate them. Second, we subtract from the total delays the unavoidable delays due to passenger connections (*unavoidable connection delay*). This calculation assumes that feeder trains start their journey

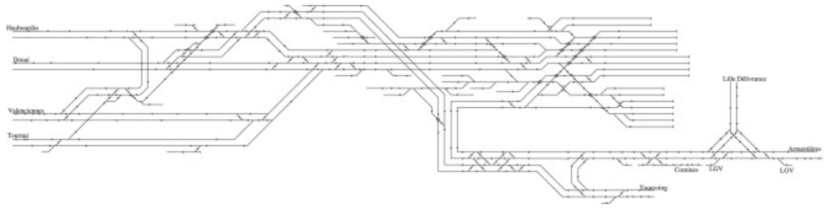


FIGURE 2. Lille Flandres station area.

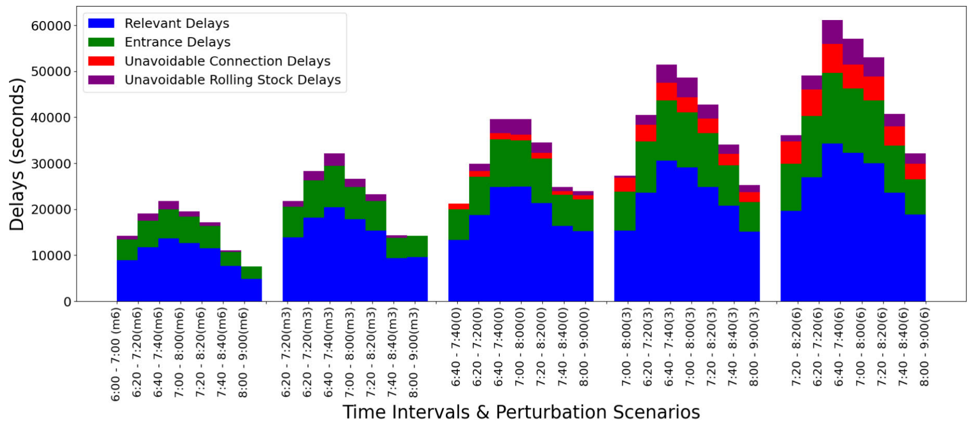


FIGURE 3. Stalked histogram for calculation of relevant delay.

as soon as possible, considering their entrance delay. They follow the shortest available route to the station, stop on a track circuit that allows them to use the smallest possible minimum connection time with the receiving trains, and depart as soon as possible. Third, we subtract from the total delays the unavoidable ones for the trains resulting from the reutilization of rolling stock from feeder trains (*unavoidable rolling stock delay*). In this case, the minimum connection time is replaced by the minimum process time required by the reutilization action (turnaround, split, or join).

In the remainder of the computational analysis, we refer to the resulting optimized secondary delay as the *relevant delay*.

Fig. 3 illustrates the delay decomposition based on the results obtained from RECIFE-MILP CL across the 35 instances considered in our study. The methodology follows the approach outlined in the literature [29], with a computation time limit of three minutes. The figure presents the total delay, the relevant delay, and the three components subtracted from the total delay to derive the relevant one. Additionally, the figure illustrates the evolution of delays in response to increasing perturbation magnitudes.

The results show a distinctive hill-shaped profile within each perturbation scenario: at peak time (instance representing traffic between 6:40 and 7:40), the delay is larger than in the other periods. This pattern is due to the higher number of trains in the control area: the increased number of connections leads to a higher total entrance delay, resulting in both larger delays due to connections (depending on the magnitude of the perturbations) and the occurrence of more conflicts in the station area.

The figure highlights the expected increase of unavoidable delays with increasing perturbation magnitudes. Unavoidable connection delays become remarkable beyond a specific perturbation magnitude (scenario 0). As expected, they increase in scenarios m3 and m6.

Summarizing, in the next section, we compare the performance achievable with the proposed enhancements in terms of relevant delay in the VCT-recomputed solution. By doing so, we assess their potential impact in operations. Moreover, we analyze the difference in their performance looking at the delay they may actually have the possibility to reduce. For readability, in the following we will refer to the VCT-recomputed solution corresponding to a CL (PC) solution, simply as the CL (PC) solution itself.

VIII. COMPUTATIONAL RESULTS

This section comprehensively compares the impact of applying solutions found through CL, PC, and VCT. In this comparison, we consider various settings to fully understand the impact of the proposed enhancements on traffic management. First, consistent with the literature [29], we allocate three minutes as the available computational time for each RECIFE-MILP approach: RECIFE-MILP CL, PC, and VCT.

With this setting, the application of PC and VCT results in a 2.98% and 3.24% reduction, respectively, in the average relevant delay compared to CL, across the 35 instances described in Section VII-B. Specifically, CL achieves an average relevant delay of 18732 seconds, PC of 18173, and VCT of 18124. The statistical significance of the difference between these results is confirmed by the Wilcoxon signed-

TABLE 2. Average number of rtRTMP variables and constraints RECIFE-MILP directly applied to the instances described in Section VII-A (no prior TRSP solution).

	Fixed Timetable Route			All Available Routes		
	Cont. Var.	Binary Var.	Const.	Cont. Var.	Binary Var.	Const.
CL	5,939	460	9,871	595,824	33,039	995,669
PC	5,939	460	9,871	595,824	33,039	995,743
VCT	5,939	460	9,871	595,824	34,679	1,000,273

rank test, with detailed information provided in Table B.1 in Appendix B.

A consistent characteristic is observed in the solutions of the three approaches: in all instances, trains strictly follow their timetable routes. This happens because RECIFE-MILP solves the problem in two steps, as introduced in Section VII-A. In the first step, it solves the rtRTMP without rerouting, using the timetable routes as fixed. This solution serves as a warm start for the second step, where all available routes are considered. Due to the three-minute time limit and the difficulty of the instances, RECIFE-MILP fails to find a feasible solution to improve the warm start in the second step. Although routes are not changed, both the PC and VCT approaches lead to a reduction in relevant delays compared to CL. This reduction results from different decisions regarding reordering and retiming due to the different minimum connection times used in the three approaches. The fixed and longer minimum connection time in CL often results in RECIFE-MILP imposing the receiver trains to pass after other trains in the station area. However, when the VCT recomputation is performed, it becomes evident that such order was not the best choice. The same problem emerges for PC, although the smaller minimum connection time used here reduces its impact. The limited rerouting possibilities available with PC have no impact here, as no rerouting is actually done in any solution, as explained above. VCT produces the best results, as it allows RECIFE-MILP to make the best decisions given the minimum platform-specific connection time. Table 2 presents the average number of rtRTMP variables and constraints for both the first step (using fixed timetable routes) and the second step (considering all available routes) in RECIFE-MILP. As indicated in the table, the considerable number of constraints and variables in the second step as compared to the first step, hinders exploration of the solution space within the specified time.

To analyze the impacts of the enhancements when a more thorough exploration of rerouting options is possible, we consider a second setting for the experiments: we extend the time limit to seven hours, aiming to approach the optimal solution in the second step of RECIFE-MILP.

Here, we obtain the following average relevant delays: CL has a relevant delay of 17749 seconds, PC of 16779 seconds (representing a 5.35% improvement over CL), and VCT shows a performance similar to CL with a relevant delay of 17752 seconds. These results represent reductions of 5.54%, 7.56%, and 2.07% for CL, PC, and VCT, respectively, compared to the corresponding values of the 3-minute time limit experiments.

We observe that the smaller improvement of VCT is due to its optimality gap, which is notably higher than that of CL and PC: 24.05% compared to 14.81% and 12.29%, respectively. The increased complexity of VCT, with more constraints and variables, makes the exploration of its search space less efficient. The Wilcoxon signed-rank tests presented in Table B.1 in Appendix B indicate that the performance of RECIFE-MILP PC is significantly different from that of RECIFE-MILP CL, while the difference is not significant between the latter and RECIFE-MILP VCT.

The noticeable decrease in PC's average relevant delay compared to CL is due to its enhanced ability to exploit available train routes, testified by the smaller optimality gap it achieves. This adds to the better ability of PC in setting appropriate passing orders as explained for the results obtained in the first setting. Nonetheless, the results emphasize that, despite allocating a 7-hour computation time, RECIFE-MILP still faces challenges in thoroughly exploring solutions for the Lille-Flandres station, especially for the VCT.

To further analyze the different impact of our two enhancements, in the third experimental setting, we solve the TRSP in 30 seconds as a preprocessing step for rtRTMP. Then, we solve the rtRTMP in seven hours. To ensure a consistent comparison between RECIFE-MILP CL, PC and VCT, we use the same model for the TRSP preprocessing in this setting. This ensures that all three RECIFE-MILP approaches have the same sets of routing alternatives for each train. Specifically, we use TRSP-PC to guarantee that RECIFE-MILP PC has a relevant number of possible solutions, similar to the other approaches. Indeed, if we used either TRSP-CL or TRSP-VCT, we might obtain a set of alternative routes to be considered in RECIFE-MILP such that, for a pair of connecting trains, only one or a few pairs stop at platforms that are close enough to be simultaneously allowed in RECIFE-MILP PC. In the experiments, we restrict the number of routes to be returned by the TRSP to a maximum of 10 alternative routes per train, following, and allocate a computation time of 30 seconds for solving the TRSP [6].

In Table 3 we show the average number of variables and constraints to be dealt with in the second step of the three RECIFE-MILP approaches when using the TRSP in the preprocessing. Comparing the data in Table 3 with the values from the first setting presented in Table 2, we can observe a significant reduction. As in the first setting, here PC shows a marginal increase in the number of constraints with respect to CL, while VCT exhibits more substantial increments in both the number of binary variables and constraints.

TABLE 3. **Average number of variables and constraints in RECIFE-MILP (second step) for the experiments using the TRSP as a preprocessing (third setting).**

	Cont.Var.	Binary Var.	Const.
CL	40,206	10,313	96,516
PC	40,206	10,313	96,601
VCT	40,206	10,318	97,496

The results show notable improvements with respect to the experiments in which all available routes are considered, in the second setting. RECIFE-MILP CL achieves an average relevant delay of 15838 seconds, representing a 15.45% reduction compared to the 3-minute experiments and 10.76% compared to the 7-hour no-TRSP ones. RECIFE-MILP PC shows further improvement with an average relevant delay of 15167 seconds: a 19.82% reduction compared to the 3-minute experiments and 9.71% compared to the 7-hour no-TRSP ones. For RECIFE-MILP VCT, the average relevant delay is 13992 seconds, corresponding to a 22.80% reduction compared to the 3-minute experiments and 21.1% compared to the 7-hour no-TRSP ones. When considering only this third experimental setting, RECIFE-MILP PC shows a reduction in the average relevant delay of 4.24%, and RECIFE-MILP VCT of 11.26% with respect to RECIFE-MILP CL. The statistical significance of these differences is confirmed by the Wilcoxon signed-rank tests, as presented in Table B.1 in Appendix B. The optimality gaps obtained for RECIFE-MILP CL, RECIFE-MILP PC, and RECIFE-MILP VCT are 5.9%, 6.4%, and 9.1%, respectively. We remark that these are local optimality gaps since they consider a search space limited by the selected routes.

Fig. 4 compares the relevant delay for each approach with and without TRSP, providing a direct indication of TRSP's impact. Fig. 4a depicts the overall values, while Fig. 4b illustrates the difference for each approach with and without TRSP. In the boxplots, the line for each represents the median. The box itself represents the interquartile range, showing the spread of the middle 50% of the data. The whiskers extend to the minimum and maximum values within a specified range. Outliers, if present, are represented as points beyond the whiskers.

In these figures, we observe that the medians of the relevant delay distributions of all approaches exploiting the TRSP preprocessing are lower than even the lowest median found among the three approaches in the experiment conducted without TRSP. Focusing on each RECIFE-MILP approach separately, the boxplots in Fig. 4b show that, for both RECIFE-MILP PC and RECIFE-MILP VCT, the relevant delay always improves in the experiments with the TRSP compared to the experiments without TRSP, with the low whiskers lying above 0 and no outliers.

To assess the potential of the proposed enhancements in a possible deployment context, in the fourth experimental setting, we solve the combined TRSP and rtRTMP in three minutes: the TRSP is solved in 30 seconds, and the rtRTMP in the remaining 150. Here, we use each enhancement for the solution of both TRSP and rtRTMP, resulting in three overall enhanced approaches: CL, PC, and VCT.

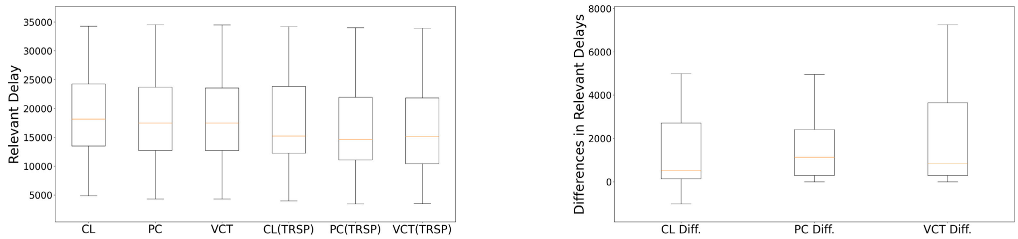
The results of these last experiments show the following average relevant delays: 17412 seconds for CL, 16647 seconds for PC, and 16215 seconds for VCT. As expected, these delays are larger than those achieved when RECIFE-MILP is executed for seven hours after the TRSP preprocessing, due to the reduced computation time. However, they still outperform the results obtained when no TRSP is considered, both in three minutes and seven hours. This fourth experimental setting shows that the two enhancements yield notably improved results compared to CL, with PC and VCT achieving average reductions of 4.39% and 6.87% in the relevant delay compared to CL. Remarkably, despite the short time limit, the reduction in the number of alternative routes obtained with the TRSP preprocessing allows RECIFE-MILP VCT to satisfactorily explore the search space and obtain the best results. The statistical significance of these improvements is supported by the results of Wilcoxon signed-rank tests, as presented in Table B.1 in Appendix B.

Table 4 provides a concise summary of the relevant delays and optimality gaps observed across the four experimental settings considered in this section. The percentage reduction values (% Red.) in Table 4 refer to the enhanced performance of PC and VCT in minimizing relevant delays as compared to CL.

Interestingly, except for the first setting in which RECIFE-MILP does not manage to exploit rerouting regardless the approach considered, PC always brings an average improvement around 5%. Instead, VCT clearly suffers from the increased complexity of the model when all alternative routes are considered. When this complexity becomes tractable thanks to the TRSP preprocessing, VCT finds the best results. Its improvement with respect to the current state of the art used in a number of publications and studies (RECIFE-MILP CL executed for three minutes without the application of the TRSP preprocessing) is in average of 13.5%.

IX. CONCLUSION AND FURTHER RESEARCH

This paper introduces two enhancements to RECIFE-MILP, an algorithm based on mixed-integer linear programming for real-time traffic management (rtRTMP). The enhancements, Platform Compatibility (PC) and Variable Connection Time (VCT), aim to efficiently exploit train rerouting at stations to facilitate passenger transfers and ultimately minimize delay propagation. On the one hand, PC optimizes the platform assignment process by narrowing down available platform pairs for connecting trains, considering only close ones. This allows for the use of a fixed value for the minimum connection time smaller than the one required when all platform pairs can be used, as done in the state of the art.



(a) Relevant delays.

(b) Differences in relevant delays.

FIGURE 4. Comparison with and without prior TRSP solution (7 hours of computation time) (a) Relevant delays, (b) Difference in relevant delays: RECIFE-MILP minus RECIFE-MILP with TRSP.

TABLE 4. Relevant delays in seconds and optimality gaps across different experiments.

Time	TRSP	CL	% Gap	PC	% Gap	% Red.	VCT	% Gap	% Red.
3 mins	×	18732	100	18173	100	2.98%	18124	100	3.24%
7 hrs	×	17749	15	16799	12	5.35%	17752	24	-0.02%
7 hrs	✓	15838	6	15167	6	4.24%	13992	9	11.66%
3 mins	✓	17412	11	16647	11	4.39%	16215	17	6.87%

On the other hand, VCT adopts a more flexible approach, considering the minimum connection time based on the chosen platforms for connecting trains. This comes at the cost of a larger number of variables and constraints. Aiming to exploit the potential of these enhancements despite the difficulty of rtRTMP instances in complex stations, the paper proposes consistent enhancements for the Train Routing and Scheduling Problem (TRSP). This problem is solved as a preprocessing step in the rtRTMP solution, selecting subsets of route alternatives for each train to be used by RECIFE-MILP. A variant of a state-of-the-art algorithm for the TRSP, ACO-TRSP, was developed to integrate the enhancements.

We assessed the performance of the proposed enhancements on instances representing perturbed traffic conditions in the Lille-Flandres station area in France. We considered different time intervals during peak hours, including many passenger connections. In an experimental analysis, both the PC and VCT enhancements demonstrated their capability to reduce relevant delays compared to RECIFE-MILP CL. This was particularly true when the TRSP preprocessing was applied, allowing RECIFE-MILP to satisfactorily explore the search space. Our results showed that the VCT enhancement consistently outperformed both CL and PC when such satisfactory exploration was possible. In particular, with the short computational time available for making decisions in actual traffic management, satisfactory exploration was possible only when the TRSP preprocessing was applied. Indeed, the available number of alternative routes for trains in the considered case study is extremely large, which makes optimized decision-making very difficult. This is typically the case in most large stations serving as hubs for passenger connections.

From a practical perspective, our experimental analysis indicates that railway system operators can leverage the proposed enhancements to optimize train rerouting at stations, thereby minimizing delay propagation, facilitating passenger transfer, and enhancing overall service reliability. The reduction in relevant delays observed in our experiments underscores the potential for significant operational improvements in complex station environments with many passenger transfers, particularly in reducing delay propagation in case of perturbations.

In future research, we aim to explore several methods to enhance the efficiency of the proposed enhancements. Firstly, we plan to investigate the introduction of valid inequalities to improve performance, especially in large and complex instances. This is crucial for ensuring real-time applicability in practical scenarios. Secondly, we intend to delve into the implementation of connection drop strategies, exploring potential penalties for such occurrences or passenger reassignment. Additionally, we aim to extend our study to consider the impact of uncertainties in real-time traffic management, incorporating stochastic elements into the models to enhance their robustness and effectiveness in dynamic operational environments.

APPENDIX A
RECIFE-MILP FORMULATION

In this Appendix, we detail the RECIFE-MILP formulation for the rtRTMP, introduced in Pellegrini et al. [4], [29]. The MILP formulation uses the sets, parameters and variables reported in Table 5, 6 and 7 respectively.

All these variables are imposed to be non-negative.

The RECIFE-MILP model minimizes the total secondary delay suffered by trains in the network:

$$\min \sum_{t \in T} D_t. \tag{A.1}$$

TABLE 5. Sets.

Symbol	Description
T	The set of trains
Θ	The set of train types
R_t	The set of routes available to train $t \in T$, with $R = \cup_{t \in T} R_t$ the total set of routes;
TC_t	The set of track circuits which can be used by train $t \in T$
TC^r	The set of track circuits belonging to route $r \in R$
$OTC_{ty,r,tc}$	The set of track circuits such that, if a train $t \in T$ of type $ty \in \Theta$ traverses them along $r \in R_t$ and has its head at their end, it holds that t's tail has not yet left tc. $OTC_{ty,r,tc} = \{tc\}$ if t is shorter than tc itself
S_t, $TCS_{t,s}$	The set of stations where $t \in T$ has a scheduled stop and set of track circuits that can be used by t for stopping at $s \in S_t$

The model has to respect the following sets of constraints:

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

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

$$o_{t,r,tc} = o_{t,r,p_{r,tc}} + l_{t,r,p_{r,tc}} + rt_{r,ty_t,p_{r,tc}} x_{t,r} \quad \forall t \in T, r \in R_t, tc \in TC^r, \tag{A.4}$$

$$o_{t,r,s_{r,tc}} \geq \sum_{s \in S_t : tc \in TCS_{t,s} \cap TC^r} d_{t,s} x_{t,r} \quad \forall t \in T, r \in R_t, tc \in \bigcup_{s \in S_t} TCS_{t,s}, \tag{A.5}$$

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

$$D_t \geq \sum_{r \in R_t} o_{t,r,tc_\infty} - sched_t \qquad \forall t \in T, \tag{A.7}$$

$$\sum_{r \in R_t} x_{t,r} = 1 \qquad \forall t \in T, \tag{A.8}$$

$$\sum_{\substack{r \in R_t, tc \in TC^r: \\ p_{r,tc} = tc_0}} o_{t,r,tc} \geq \sum_{\substack{r \in R_{t'}, tc \in TC^r: \\ s_{r,tc} = tc_\infty}} o_{t',r,tc} + (ms_{t,t'} + rt_{r,ty_{t'},tc}) x_{t',r} \quad \forall t, t' \in T : i(t', t) = 1, \tag{A.9}$$

$$\sum_{r \in R: s_{r,tc_0} = tc} x_{t,r} = \sum_{r \in R_{t'}: p_{r,tc_\infty} = tc} x_{t',r}$$

TABLE 6. Parameters.

Symbol	Description
tc_0 and tc_∞	Dummy track circuits representing entry and the exit locations of the infrastructure considered
$sched_t$	Scheduled arrival time of train $t \in T$ at destination;
ty_t	Type corresponding to train t (train characteristics)
$init_t$, $exit_t$	Earliest time at which train $t \in T$ can be operated and earliest time at which it can reach its destination given $init_t$, the route assigned in the timetable and the intermediate stops
$i(t', t)$	Indicator function equal to 1 if t' and t use the same rolling stock and t results from the turnaround, join or split of t', 0 otherwise
$c(t, t', s)$	Indicator function equal to 1 if there is a connection between feeder train $t \in T$ and receiver train $t' \in T$ in station $s \in S_t \cap S_{t'}$, otherwise 0;
$ms^s_{t,t'}$	Minimum separation between the arrival and the departure of trains t and t' using the same rolling stock
$mc_{t,t'}$	Minimum connection time between $t \in T$ and $t' \in T$
$rt_{r,ty,tc}$, $ct_{r,ty,tc}$	Free-network and clearing running of $tc \in RT^r$ along $r \in R$ for a train of type $ty \in \Theta$
$ref_{r,tc}$	Reference track circuit for the reservation of $tc \in TC^r$ along $r \in R$, depending on block section structure and interlocking system
$bs_{r,tc}$	Block section including track circuit $tc \in TC^r$ along route $r \in R$
for_{bs}	Formation time for block section bs
rel_{bs}	Release time for block section bs
$e(tc, r)$	Indicator function equal to 1 if track circuit $tc \in TC^r$ belongs to either the first or the last block section of $r \in R$, 0 otherwise
$dw_{t,s}$, $a_{t,s}$, $d_{t,s}$	Minimum dwell time, scheduled arrival and scheduled departure times for train $t \in T$ at station $s \in S_t$

TABLE 6. ***(Continued.)*** **Parameters.**

$p_{r,tc}$	Track circuit preceding $tc \in RT^r$ along $r \in R$
$s_{r,tc}$	Track circuits following $tc \in RT^r$ along $r \in R$
w_t	Weight of train t delay
M	A large constant

TABLE 7. **Variables.**

Symbol	Description
$sU_{t,tc}$	Continuous positive variable representing the time at which $tc \in TC_t$ starts being utilized by $t \in T$
$eU_{t,tc}$	Continuous positive variable representing the time at which $tc \in TC_t$ ends being utilized by $t \in T$
$x_{t,r}$	Binary variable equal to 1 if train $t \in T$ uses route $r \in R_t$, 0 otherwise
$y_{t,t',tc}$	Binary variable equal to 1 if train $t \in T$ utilizes track circuit tc before train t', such that index t is smaller than index t' ($t \prec t'$), with $tc \in TC_t \cap TC_{t'}$, and 0 otherwise
$o_{t,r,tc}$	Time in which $t \in T$ starts the occupation of $tc \in TC^r$ along $r \in R_t$
$l_{t,r,tc}$	Longer stay of $t \in T$'s head on $tc \in TC^r$ along $r \in R_t$, due to dwell time and scheduling decisions (delay)
D_t	Delay suffered by train t when exiting the infrastructure

$$\forall t, t' \in T : i(t', t) = 1, tc \in TC_t : p_{r,tc} = tc_0, \tag{A.10}$$

$$\sum_{\substack{tc \in TC_t: \\ \exists r \in R_t, p_{r,tc} = tc_0}} sU_{t,tc} \leq \sum_{\substack{tc \in TC_{t'}: \\ \exists r \in R_{t'}, s_{r,tc} = tc_\infty}} eU_{t',tc}$$

$$\forall t, t' \in T : i(t', t) = 1, \tag{A.11}$$

$$\sum_{\substack{r' \in R_{t'}, \\ tc' \in TC^{r'} \cap TC^s}} o_{t',r',s_{r',tc'}} \geq \sum_{\substack{r \in R_t, \\ tc \in TC^r \cap TC^s}} o_{t,r,tc} + (mc_{t,t'} + rt_{r,ty_t,tc}) x_{t,r}$$

$$\forall t, t' \in T, s \in S_t \cap S_{t'} : c(t, t', s) = 1, \tag{A.12}$$

$$sU_{t,tc} = \sum_{r \in R_t : tc \in TC^r} (o_{t,r,ref_{r,tc}} - for_{bs_{r,tc}} x_{t,r})$$

$$\forall t \in T,\ tc \in TC_t : (\nexists t' \in T : i(t', t) = 1) \vee (\forall r \in R_t : ref_{r,tc} \neq s_{r,tc_0}), \tag{A.13}$$

$$eU_{t,tc} = \sum_{r \in R_t : tc \in TC^r} o_{t,r,tc} + \sum_{tc' \in TC^r : tc \in OTC_{ty_t,r,tc}} l_{t,r,tc'} + (rt_{r,ty_t,tc} + ct_{r,ty_t,tc} + rel_{bs_{r,tc}}) x_{t,r}$$

$$\forall t \in T, tc \in \cup_{r \in R_t} TC^r, \tag{A.14}$$

$$eU_{t,tc} - M(1 - y_{t,t',tc}) \leq sU_{t',tc}$$

$$\forall t, t' \in T, t \prec t',\ tc \in TC_t \cap TC_{t'} : i(t, t') \sum_{r \in R_t} e(tc, r) = 0 \wedge\ i(t', t) \sum_{r \in R_{t'}} e(tc, r) = 0, \tag{A.15}$$

$$eU_{t',tc} - M y_{t,t',tc} \leq sU_{t,tc}$$

$$\forall t, t' \in T, t \prec t',\ tc \in TC_t \cap TC_{t'} : i(t, t') \sum_{r \in R_t} e(tc, r) = 0 \wedge\ i(t', t) \sum_{r \in R_{t'}} e(tc, r) = 0. \tag{A.16}$$

Constraints (A.2) and (A.3) require that train t operates on its selected route no earlier than $init_t$ and set all track circuit occupations to 0 on the not used alternative routes. Constraints (A.4) ensure that a train can only begin using a given track circuit after completing its free-network running time in the preceding one and the longer stay it has to spend (if the route is used). In order to avoid leaving the track circuit $tc \in TCS_{t,s}$ before the scheduled departure time from station s, Constraints (A.5) and (A.6) make sure that train t that stops at s along route r spends at least its minimum dwell time on tc. When train t leaves the infrastructure, Constraints (A.7) quantify non-negative delays. Constraints (A.8) choose a single route for train t.

Constraints (A.9), (A.10) and (A.11) are used to guarantee consistency for trains using the same rolling stock, i.e., the respect of the minimum separation time between their arrival and departure, the use of the same arrival and departure track-circuit, and the overlapping utilization times to maintain the track-circuit occupied during the turnaround, as discussed below.

Constraints (A.13) state that a train utilization of a track circuit starts as soon as the train starts occupying track circuit $ref_{r,tc}$ along one of the routes including it, minus the formation time. Indeed, if t results from t', Constraints (A.11) ensure that the track circuit where the turnaround takes place starts being reserved by t as soon as t' arrives. However, t needs to wait at least for a time ms before departing. The occupation of the used track circuit by t is however starting from its actual departure, for guaranteeing the coherence of the occupation variables and the running time (A.4). Hence, t's reservation starts much earlier than its occupation. In Constraints (A.14), the utilization of a track circuit lasts till the train exits it along any route, plus the release time. If the train is long enough to keep occupying the track circuit when

TABLE 8. Wilcoxon test results for comparison between different experimental configurations and approaches.

Time	TRSP	Comparison	p-value	(μ)	LCI	UCI
3 mins	×	CL vs PC	1.87e-07	517	363	714
		CL vs VCT	1.18e-07	556	393	772
		PC vs VCT	0.0086	136	52	281
7 hrs	×	CL vs PC	1.6e-06	830	537	1236
		CL vs VCT	0.72	52	-229	254
		PC vs VCT	1.9E-05	-894	-1355	-570
7 hrs	✓	CL vs PC	5.09e-06	711	494	909
		CL vs VCT	2.5e-09	1792	1368	2255
		PC vs VCT	1.6e-06	1131	703	1540
3 mins	✓	CL vs PC	4.4e-07	640	372	1034
		CL vs VCT	3.4e-06	1118	651	1537
		PC vs VCT	0.014	332	62	927

TABLE 9. Wilcoxon test results: Difference between RECIFE MILP CL and application of the VCT enhancements to TRSP and rtRTMP (Runs of three minutes).

p-value	(μ)	LCI	UCI
5.821e-11	2582.25	1206	3208

its head is at the end of the following ones (the ones included in set $OTC_{ty_t,r,tc}$), also the longer stay of the train on these further track circuits has to be accounted for.

Finally, Constraints (A.15) and (A.16) make sure that two trains do not use the same track circuit at the same time.

APPENDIX B
WILCOXON SIGNED RANK TEST

In this appendix, we conduct a statistical analysis using the Wilcoxon signed-rank test. In Table 8, we present the results of the test for the four experimental settings described in Section VIII, in which we compare the performance of the classic approach for traffic management (CL) to that of our enhancements: Platform Compatibility (PC) and Variable Connection Time (VCT).

Table 9 presents the Wilcoxon test results for the comparison between the initial state-of-the-art RECIFE-MILP CL approach and the best proposed enhancement: VCT applied both to the rtRTMP and the TRSP.

We use the p-value, pseudomedian (μ), Lower bound of the Confidence Interval (LCI), and Upper bound of the Confidence Interval (UCI) to get insights in analysis. The p-value quantifies the strength of evidence against the null hypothesis. Lower values, typically below $1 - \text{CI}/100$, indicate stronger evidence against the null hypothesis and thus statistical significance. The μ value serves as a robust estimate of the central tendency of data, particularly in non-normally distributed datasets. LCI and UCI together form a range within which a parameter is likely to fall with a certain level of confidence (95% CI). In our case, the parameter is the difference in relevant delay between two different approaches. This range provides a measure of the precision and uncertainty of estimates. The signs within the range (positive or negative) indicate the likely direction of the impact on relevant delay. If the confidence interval spans both positive and negative values (crosses zero), it indicates that there is no statistically significant effect on the relevant delay, and the direction of the impact is less clear.

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