A Review of Robustness and Recovery Approaches for Railway Hub Planning Problems*

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Abstract

Railway hubs are among the most complex parts of the railway network, where different lines intersect, passenger flows mix, and rolling stock must be shunted and cleaned. With many railway operations merging, disturbances and disruptions have a particularly significant impact here. Algorithms for railway hub planning must thus be designed with robustness in mind, and effective rescheduling algorithms should be available to recover from delays. However, the railway hub has not been explicitly defined in the literature, and no review has been conducted of approaches to railway hub planning. Therefore, this review paper defines the railway hub planning problem and presents a taxonomy of integrated operations and the associated subproblems from the literature. We analyze peer-reviewed papers up to November 2025, categorizing them as either robustness- or recovery-focused. While each paper addresses a subset of the railway hub operations, we find that no studies consider the entire railway hub. We conclude that more work is needed to plan servicing tasks and personnel at the railway hub, and multiple common delay sources remain unaccounted for. Finally, we argue that future work should take a holistic view of the entire railway hub, using hybrid methods to plan all interconnected components and processes.

Keywords: Railway Hub Planning problem, Robust planning, Plan recovery, Train Routing and Platforming Problem, Train Unit Shunting Problem, Rolling Stock Planning

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1. Introduction

Railway networks are densely connected systems with many components requiring careful coordination. The critical points in these networks are the railway hubs [1], where multiple lines intersect, different operators and passenger flows mix, and a variety of operations must be facilitated, from cleaning trains to coupling train units, to meeting the right demand at any given time of day. With increasing travel demand and network connectivity, the operations performed at these hubs become even more critical. As these hubs are the center of operations, they are also most prone to disturbances and disruptions, including train delays, infrastructure failures, and rolling stock breakdowns. At the same time, railway hubs are often located in urban areas, leaving little room for infrastructure expansion to alleviate capacity constraints.

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Therefore, it is important that railway hub plans are created to reduce cascading delays and that methods are available to recover from disrupted operations. To the best of our knowledge, no explicit definition of the railway hub has been provided in the literature, and no previous review has been conducted on approaches to the railway hub planning problem in general, or on its robustness or recovery. This survey thus focuses on these critical railway hubs and how they can provide reliability and resilience to the entire network.

While the railway hub as a whole has been considered in several studies, it remains an under-researched topic, with many associated subproblems examined in different contexts. This survey brings together these works, formally establishes the Railway Hub and the Railway Hub Planning problem, and presents a taxonomy of the subproblems and related work. We refer to a *railway hub* as an area surrounding a major train station, including any shunting yards and nearby smaller stations [2]. To arrive at realistic conclusions, we take a microscopic perspective on this area, considering all individual tracks, switches, and signaling constraints at the individual level. *Railway Hub Planning* (RHP) is the problem of coordinating all rolling stock logistics in a railway hub—platform assignment, shunting yard parking, routing, train composition matching, service tasks, and safety/signaling constraints—together with the rostering of the personnel needed to carry them out. While Shi et al. [3] already mentioned the first five as included in the railway hub problem, personnel scheduling is also a vital aspect of realistic planning [4]. Moreover, when taking a microscopic perspective, the safety guarantees of the systems must be accounted for [5]. Creating the plan for the railway hub thus requires a broad overview of the area, so we consider the problem from the railway operators' perspective. As the railway hub is an intersection point for different railway operators, all rolling stock that traverses the hub is considered. However, some trains may be regarded as 'fixed': these trains cannot be altered, but the planning problem does account for them to avoid conflicts (e.g., a freight train passing through the station). In practice, the railway hub planning problem primarily considers passenger trains.

The literature on railway hub planning problems currently spans several interrelated domains, including platform assignment (the Train Platforming Problem) [6] and shunting operations (the Train Unit Shunting Problem) [7], as well as the rolling stock coordination in the hub (the Rolling Stock Planning problem) [8] and disruption management (the Railway Traffic Management problem) [9]. While a few studies have considered a joint model of these operations, they are mostly studied separately [3]. Especially service task operations are often overlooked, though they are particularly important to include in planning procedures in dense railway networks such as those in the Netherlands. In practice, these problems are integrated into a single planning and operational challenge, while previous work often considers only a subset. We bring together approaches to this challenge, focusing on how they handle disturbances in operation. Our literature review shows that a holistic view of available methods to address this integrated challenge is currently missing.

We consider two stages of railway hub planning: the planning and the execution phases. These stages are often distinguished by railway operators in practice, so we also consider these two planning phases separately. The planning stage ends when a complete plan is constructed that is feasible in practice, with all details known, and the plan is executable. Once the plan is made and changes are made, then we refer to these methods as 'during execution'. In practice, all kinds of things could happen, causing smaller delays or more significant disruptions; therefore, we want to account for them as much as possible, both in the plan and in our responses during execution. When dealing with uncertainty in the planning phase, we refer to *robustness* in planning approaches; in the execution phase, we use the term *recovery*, which are the two types of resilience we consider in this survey. We discuss both approaches separately and categorize previous research accordingly.

To obtain deeper insights into available methods for robust planning and recovery during operations, we performed a structured literature review, considering 308 papers, of which 57 were selected, divided into 14 papers on robustness and 43 papers on recovery. The selection criteria concentrated on the definition of the railway hub, the focus on operational planning, and taking a microscopic perspective. For each paper, we categorized it by resilience type and the included subproblems. Then, we analyzed the solution algorithms used, the investigated delay sources, and the different robustness objectives used to address them. We show which current methods are promising for providing robust plans and recovery approaches for the entire railway hub. In consultation with researchers from the railway companies in the Netherlands, we compared our findings with current needs and practices. Furthermore, we identify a gap between state-of-the-art research and real-world practice that must be addressed to integrate algorithmic optimization methods into daily practice. This gap can be found in both the integration of different problem types and the types of disruptions and disturbances that can be accounted for in the state-of-the-art research.

This paper presents five main contributions. First, we formally define the railway hub planning problem and present a novel taxonomy of its subproblems. Second, we analyze the current literature and distinguish approaches that focus on robustness or recovery in railway hub planning (sub)problems. Third, we identify a research gap in solving the railway hub planning problem, particularly in robustness and recovery approaches. Fourth, we discuss the different types of disturbances and disruptions identified in the literature. and which often occur in practice. Fifth, we categorize the solution methods used in previous work and propose the best approach to solving the railway hub planning problem.

The rest of the paper is organized as follows: We first present several preliminaries and important terms from the literature used throughout the paper. Further, we formally define the Railway Hub and the associated planning problem. The next section discusses related work on other reviews of the Railway Hub Planning problem, as well as surveys on robustness and recovery methods for the subproblems. We then explain our method for selecting the literature and the filtering criteria used. Based on the selected papers, we analyze several high-level statistics and present a taxonomy of railway hub subproblems. Then, we evaluate the papers for the robustness and recovery categories separately, and discuss the different types of disturbances and disruptions considered. The two categories are compared based on the solution methods used, and we analyze the most promising methods for solving the Railway Hub Planning Problem. Finally, we discuss the results and provide our conclusions on the operations of the railway hub, which remain understudied, as well as the most interesting solution-method category to extend toward the complete railway hub planning problem.

2. Scope of the Paper

This paper considers approaches that focus on planning a railway hub, or part thereof. Specifically, we analyze previous work that focuses on the robustness of a plan or provides a recovery approach. The planning for a railway hub occurs at three levels, as is customary for railway companies [10]. The first level is *strategic* planning, which happens far in advance and focuses on long-term investments and decisions, such as infrastructural capacity requirements. The second level is *tactical* planning, where decisions are made on how and when to allocate resources to the fixed infrastructure; this phase still occurs before execution and can be completed several hours before [11]. The third level is *operational* planning, which adjusts the plan in response to actual events, such as day-to-day disturbances. We focus only on the tactical and operational planning phases, which primarily relate to robustness and recovery.

We distinguish robustness and recovery approaches by the planning level at which they operate. *Robust planning* aims to create a schedule that can absorb delays, including enough detail to be executed in practice (e.g., track assignments, running time calculations), thereby focusing on the tactical planning stage. The robustness of a plan or schedule is defined by

Carey and Carville [12][p.666] as a measure of "exogenous delays causing the least knock-on delays". We extend this to say that a robust plan remains as close as possible to the original plan when faced with exogenous delays. *Recovery planning* takes a feasible schedule and works to maintain its feasibility in the face of ongoing operational changes, thereby focusing on the operational planning stage. Plan recovery can thus be defined as railway rescheduling [13]. Finally, we refer to the collection of robust and recovery planning as *resilient planning*: the ability of a railway system to provide effective train operations in normal conditions and in the face of delays.

When considering delays, we distinguish between two types: disturbances and disruptions, which differ in the scale of the delays and the impact on the plan. They are defined by Cacchiani et al. [13][p.16] as follows: "Disturbances are relatively small perturbations of the railway system that can be handled by modifying the timetable, but without modifying the duties for rolling stock and crew. Disruptions are relatively large incidents, requiring both the timetable and the duties for rolling stock and crew to be modified." A third type of impact is classified as disasters, most commonly natural disasters such as earthquakes or floods, but also including cyberattacks. These events often render entire parts of the network unavailable, stretching far beyond a single railway hub. While disasters are not specifically excluded from this survey, they hardly appeared in search results focused on railway hubs and are thus not considered.

The rolling stock we consider typically consists of *train units*, which are sets of carriages that cannot be uncoupled during operations and can usually power themselves. These train units can be driven at both ends and coupled with other compatible units that share the same characteristics. These characteristics apply to most rolling stock used for passenger trains in Western Europe [14] and align with those of Electric Multiple Units used in China's high-speed railways [15].

3. Railway Hub Planning Problem

This section formally establishes the Railway Hub (Definition 3.1) and the integrated Railway Hub Planning Problem (Definition 3.2) by taking a microscopic perspective on a well-studied, relatively large area, grounded in previous studies [2, 3].

Definition 3.1. A *Railway Hub* is the infrastructure of a station area of a (major) passenger railway station with more than two platforms, one or more surrounding passenger train shunting yards, and possibly any smaller stations in the area, including all tracks, switches, and signaling systems.

An example of a railway hub is shown in Figure 1, which is the Utrecht Central Station area in the Netherlands. This hub includes the main Utrecht Centraal station, shown in the middle, with two main shunting yards: 'CTW' on the left and 'OZ' on the right, and a few shunting tracks at the top ('LS'). The hub also includes smaller stations where no Intercity trains stop, such as Utrecht Zuilen ('Utz'). The station connects five lines: one to Gouda, one to Amsterdam, one to Hilversum/Amersfoort, one to Geldermalsen, and one to Arnhem. The railway hub encompasses all these components from a microscopic perspective, including the individual tracks and switches, the signaling system, and, for each track, known attributes such as exact length.

The term *railway hub* was previously used in the work by Shi et al. [3], Hanou et al. [16], and Yan et al. [17]. Moreover, Wang et al. [1] used the term *multi-station railway hub* to indicate a similar operating area, though not considering the shunting yards. Other terms used to describe a similar area are 'station zone' [6], 'control area' [18], and 'railway node' [19]. In freight traffic, the term 'railway container hub' is used, but it specifically includes container yards and the

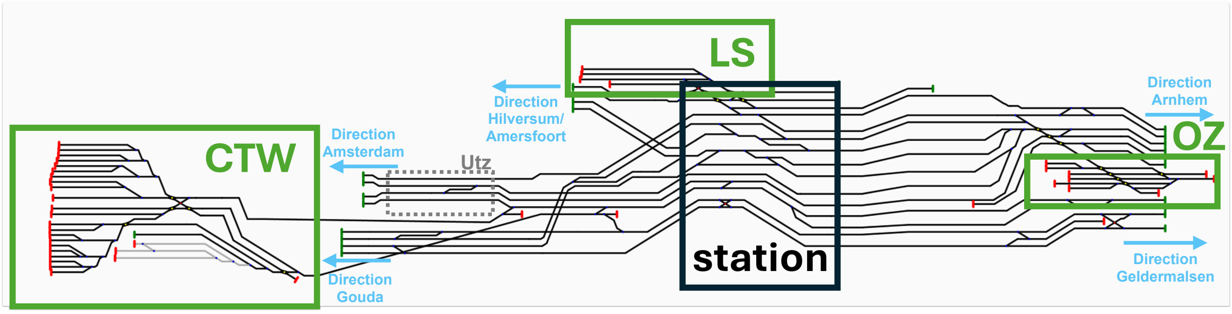

Figure 1: Railway hub of the Utrecht Central station area in the Netherlands. Highlighted in green are the different shunting yards connected to Utrecht Central station (highlighted in black). Highlighted in gray is the nearby smaller station of Utrecht Zuilen.

components required to move containers [20], which is too specific for our perspective of a railway hub. The railway hub is also often associated with an 'interlocking area' [21], including the crossing of railway lines [22], or the area controlled by a single traffic dispatcher. While metro stations with depots, or urban transit systems, also seem very similar, tracks in these areas typically do not intersect and are used in only one direction [23]. While this simplifies the problem, thus excluding them from this survey, our results are still relevant to metro stations with yards and intersecting tracks.

3.1. The Railway Hub Planning Problem

Creating a plan for the Railway Hub Planning (RHP) problem belongs to the *tactical* planning phase, and the execution of the plan belongs to the *operational* planning phase. The Railway Hub Planning problem includes different types of operations (Definition 3.2), although a subset of these was solved in different problems introduced previously in the literature. The taxonomy of the subproblems is presented in Section 6. The different operations are discussed in more detail below.

Definition 3.2. The *Railway Hub Planning* (RHP) problem concerns planning all logistics movements of rolling stock within a Railway Hub and rostering the required yard personnel to execute them. This includes the following operations:

- the platform assignment within the station,
- the parking at nearby shunting yards when the train is not in use,
- the routing of the rolling stock through the entire area
- the matching of the correct passenger train compositions to the required train series,
- the service task operations, such as cleaning and small maintenance tasks,
- the scheduling of personnel to perform the railway hub operations, and
- the operations to ensure the safety of the entire system using signaling constraints.

The rolling stock considered in the RHP problem includes all trains that use any part of the railway hub's infrastructure at some point during the scenario. However, some of these are planned in the RHP problem while others are merely taken as input to form constraints. The planned trains thus include all passenger trains scheduled to stop at the main station, all trains scheduled to stop at one of the smaller stations, all trains parked at the shunting yards, and all trains moving between the stations and the shunting yards. Yet, all trains passing through a station or yard in the hub without stopping are treated as dynamic obstacles. For example, in the example of the Utrecht hub from Figure 1, we include the sprinter lines from and to Utrecht Centraal, stopping at Utrecht Zuilen; all Intercity lines stopping at Utrecht Centraal; all international trains that stop at Utrecht Centraal; while freight trains, international or inspection trains that do not stop at Utrecht Centraal, are regarded as obstacles. Finally, we do not explicitly consider freight train scheduling, so classification yards are not included in the railway hub.

The RHP problem encompasses all logistical operations within the hub, which are discussed in order of additional detail. The first set of operations is the **platform allocation**. Trains that are required to stop at one of the stations of the railway hub must be assigned a platform at the station. Often, not all platforms are accessible from all incoming tracks, as seen in Figure 1, so this must be accounted for when allocating platform tracks.

Second, the **parking operations** mostly occur at the shunting yards, where trains are parked when not used in the timetable operations. While a lot of research has been done on optimal parking placement, practical concerns are relevant here as well, usually related to other operations that must be performed. For example, some parking tracks have shorter routes to the servicing platforms, where trains can be cleaned, so parking trains here that actually require a service task is often preferred.

The third set of operations is the **routing of trains**, which is in fact the most important operation. However, in many approaches to solving (parts of) the railway hub planning problem, routing is considered last. All trains that travel through the railway hub must be safely routed, which includes trains that only drive through, as well as trains that are shunted away. Moreover, trains must be routed within a shunting yard, for example, when service tasks are performed, and the train is moved to a specific track or to couple two train units together.

Fourth, we consider the so-called **matching problem** for passenger trains. This concerns matching incoming rolling stock to the train compositions required for the train series at the station. To create a feasible matching, train compositions must often be coupled or decoupled to form the correct type of rolling stock. Usually, more than one train unit of the same type is present at the shunting yard, so different choices can be made that, in turn, impact the other operations, such as routing.

The fifth set of operations we discuss is **service task operations**. These include, for example, maintenance and cleaning tasks performed at shunting yards, usually on designated tracks specific to the type of service task. Activities also include external cleaning of rolling stock (at a wash track), the internal cleaning done by yard personnel who walk around the shunting yard [3], and small maintenance tasks, some of which require a specific track.

We also consider the **scheduling of yard personnel**. As the RHP problem focuses on operations within a hub, we do not include conductors or drivers of trains driving only through the hub. We do need to schedule both drivers at the shunting yards, and drivers to shunt trains between the station and the yard. Furthermore, we need to schedule crews at the shunting yards to perform the various service tasks, where each task type can be performed by only a few staff members.

Finally, we include the operations for determining the ordering of trains and ensuring safety, using the **signaling constraints**. By modifying the scheduled signals, the ordering of trains arriving at and leaving the station area can be altered. Different constraints can be used to ensure safe operations, each requiring different details. Railway safety systems are categorized by Theeg and Vlasenko [24] as 1) track-free detection, 2) interlocking, 3) signaling systems, and 4) automatic train protection. However, as we consider an entire railway hub and the safety operations in shunting yards are not always reported, we use a simpler distinction between the safety systems. We distinguish between microscopic and macroscopic block signaling protection, where the macroscopic perspective is implemented by accounting for headway time, which is "the time interval between two successive trains to guarantee operational safety" [25]. Microscopic block signaling is modeled using blocking time calculations. Finally, some areas may not be protected with signals, which we indicate with 'signal-free area', especially in shunting yards.

While each of these operations by itself is seemingly simple to solve, their interactions result in a very complex problem [26]. As for the shunting operations themselves, this problem was shown to be NP-hard without the service task scheduling [27]. Moreover, even a simpler version with trains arriving at a dead-end track shunting yard and departing in a first-in-last-out fashion is already NP-hard when accounting for train lengths [28]. Both service task and yard personnel scheduling problems can be modeled as flexible job-shop scheduling problems [14], which are also NP-hard [29]. Finally, the routing of trains through a railway station was proven NP-hard by Zwaneveld et al. [10].

These operations form the base of the taxonomy we present in Section 6. Based on the initial results of our literature search, we determine which problems discussed in other studies solve a subset of these operations and how this relates to the RHP problem.

4. Related Work

This section includes other literature surveys on robustness and recovery in part of the railway hub identified through our literature search (see Section 5). As these mostly focused on railway traffic management or are somewhat older, we also discuss additional related work, including a general overview of resilience methods in railway systems, a specific survey on robustness in railways, and two reviews of other related problems of the Railway Hub Planning problem. However, to the best of our knowledge, no previous review has been conducted on approaches to the Railway Hub Planning problem in general, or on their robustness or recovery.

4.1. Literature Reviews from Query

The first consideration of computer-aided recovery approaches to train dispatching was surveyed by Goodman and Takagi [30]. Although they studied a wide range of railway systems, they did not specifically consider railway hubs. The approaches at the time ranged from heuristic systems defined by expert rules to mathematical models and genetic programming, which the authors noted as useful directions for future research, though they did not advocate for a specific direction. A more extensive review of both recovery and robustness approaches for freight shunting and timetabling problems was later done by Cicerone et al. [31]. They considered papers along a 'recoverable robustness' model, describing whether a system is robust with respect to (limited) recovery capabilities. This still fits better with our definition of robustness than with recovery, since these are precomputed before execution. They found several papers addressing recoverable robustness for individual problems and concluded that this framework can be effective across different types of optimization problems. However, they did not look into applications with more extensive problem formulations, such as the Railway Hub Planning problem. Continuing, the timetable design and associated traffic management problem settings were further studied by Hansen [32], who noted that the use of queuing models and micro-simulation tools had successfully improved the timetable's robustness, where exact blocking time calculations are key. However, more detailed and accurate models remain desired to improve the efficiency of traffic management.

Recovery approaches were studied in a broader problem scope, referred to as an 'online setting', potentially in a 'dynamic environment', in the sense that "perturbations, and prognosis of future statuses of the network, are known in a probabilistic and time-dependent manner only" [33][p.1]. The scope included studies on train path scheduling, crew rescheduling, rolling stock circulation, and delay management in a dispatching area with a microscopic perspective. They concluded that most research focused on one of these subproblems rather than on integration.

The lack of integration was also noted by Dai et al. [34], who reviewed the state-of-the-art literature on dynamic rescheduling and train control in high-speed railway systems. However, their integrated model suggestion does not fully address the challenges of railway hub planning. Noting that a single optimization method often falls short in solving the increasingly detailed practical problem, they advocated a combination of solution methods, including mathematical programming, artificial intelligence algorithms, and simulations.

Furthermore, the train dispatching problem, or railway traffic management problem, has been specifically studied in depth. The objective is to create a conflict-free schedule with no overlapping blocking times. Lamorgese et al. [35] reviewed rescheduling approaches and noted the discrepancy between the literature and practice, as few railway operators actually used dispatching support at the time. While some promising methods were identified, initial disappointing failures and caution about the risks inherent in innovation led to slow adoption of optimization approaches in practice. Second, Versluis et al. [36] specifically examined differences in the available literature on moving-block signaling compared to fixed-block signaling. These differed in the lack of conflict-detection and resolution models that accurately describe railway operations when using moving-block signaling based on absolute braking distances. They identified a research gap in studies that account for moving-block headway by modeling infrastructure continuously and incorporating speed dynamics. Third, Zhan et al. [37] discussed train dispatchers' responses to disturbances and disruptions. Although they examined only changes in arrival/departure time at the stations, they also considered integration with rolling stock and crew rescheduling, especially when responding to disruptions. They analyzed potential uncertainties in real-time timetable rescheduling and advocated for more microscopic modeling approaches as well as hybrid solution methods combining the strengths of data-driven, robust/stochastic optimization and heuristics. Finally, data-driven approaches were specifically considered by Wen et al. [38]. The studied subjects focused on timetable rescheduling, delay propagation, and delay distribution, as data-driven methods are particularly helpful for identifying delay patterns. Integrating multiple data sources yielded the most accurate predictions to support dispatchers' decisions, and the authors argue that model-based deep learning methods provide an interesting future approach to train dispatching.

4.2. Related Literature Reviews

Another literature review on resilience in railway transport systems was created by Bešinović [39]. He classified robustness metrics and approaches, creating a taxonomy. He highlighted the level of uncertainty to which transport networks are exposed during operation. One of his conclusions was that, for the railway network, mathematical optimization approaches tend to be the most suitable for addressing robustness challenges.

In terms of robustness, Lusby et al. [40] conducted a survey covering the entire railway planning setup. They considered the work of all involved stages in railway planning, from network design to crew rostering. The need to integrate planning problems across the different stages was also highlighted. They concluded that most reviewed works focused on robustness measures for individual problems and did not consider holistic robustness measures. Moreover, they did not go into detail about the recovery phase or how robustness approaches relate to recovery-phase algorithms, nor did they discuss the types of disturbances/disruptions considered.

Considering the (limited) integration of different problem components, Kamenga et al. [41] reviewed solution algorithms for the generalized train unit shunting problem. They identified four components of the shunting problem: matching, track assignment, routing, and maintenance planning. From a systematic literature comparison, they determined that at the time, none of the reviewed papers addressed all of these problems simultaneously. Similarly, Zhang et al. [42] provided a systematic comparison of related studies to the Train Platforming Problem, which assigns a platform to trains entering a railway station. After comparing studies on the Train Platforming Problem, Train Unit Shunting Problem, and Train Timetabling Problem (the latter of which assigns arrival and departure times at railway stations to trains for a specific line), they concluded that at that time, no research had addressed the simultaneous routing and scheduling of both trains and locomotives, especially given the safety guarantees of interlocking systems. As locomotive operations result in additional routing and scheduling tasks for dispatchers, this limits the extent to which models can be combined to form a complete perspective.

4.3. Research Gap

In light of these surveys, we see that significant work has already been done investigating the robustness and recovery of different types of railway problems. However, no review was found specifically examining railway hub problems, nor did it focus on robustness and recovery. Moreover, no explicit definition of the railway hub was provided in the literature. Specific parts of the railway hub were reviewed, both in the general sense and tailored to robustness and recovery approaches, but the overall connection is missing. Therefore, we formulate the following research questions that this survey aims to answer.

RQ1 What subproblems of the Railway Hub Planning problem have been considered in the literature?

RQ2 What types of disturbances and disruptions have been solved by previous solution methods for the Railway Hub Planning problem?

RQ3 What are known approaches to provide robustness and recovery in the Railway Hub Planning problem or its subproblems?

RQ4 Which types of disturbances or disruptions are best handled with robustness and which types require recovery approaches?

RQ5 What solution methods are most promising for contributing to resilient solutions to the entire Railway Hub Planning problem?

Section 6 presents the taxonomy of the operations of the railway hub planning problem and related subproblems, based on the reviewed papers (RQ1). The answers to RQ2, RQ3, and RQ4 are combined and presented individually for the approaches tackling robustness (Section 7) and recovery (Section 8). Finally, we answer RQ5 in Section 9, discussing the overall outlook for solving the railway hub planning problem with respect to robustness and recovery.

5. Literature Selection and Analysis

This section first discusses the literature selection and filtering criteria. Next, we present the main results, categorizing the papers into robustness or recovery approaches, and analyze several statistics to gain insight into the differences between the two approaches to dealing with uncertainty.

5.1. Selection and Filtering Criteria

We analyzed papers that discuss the Railway Hub Planning problem, using Definition 3.1 to determine which papers address the railway hub or a part thereof. Therefore, we constructed a search query that selected papers focusing on at least one of the operations (as discussed in Definition 3.2). Moreover, the focus is on robustness and recovery methods for the RHP, so we specified different terms used to describe this. We thus also exclude papers that solely

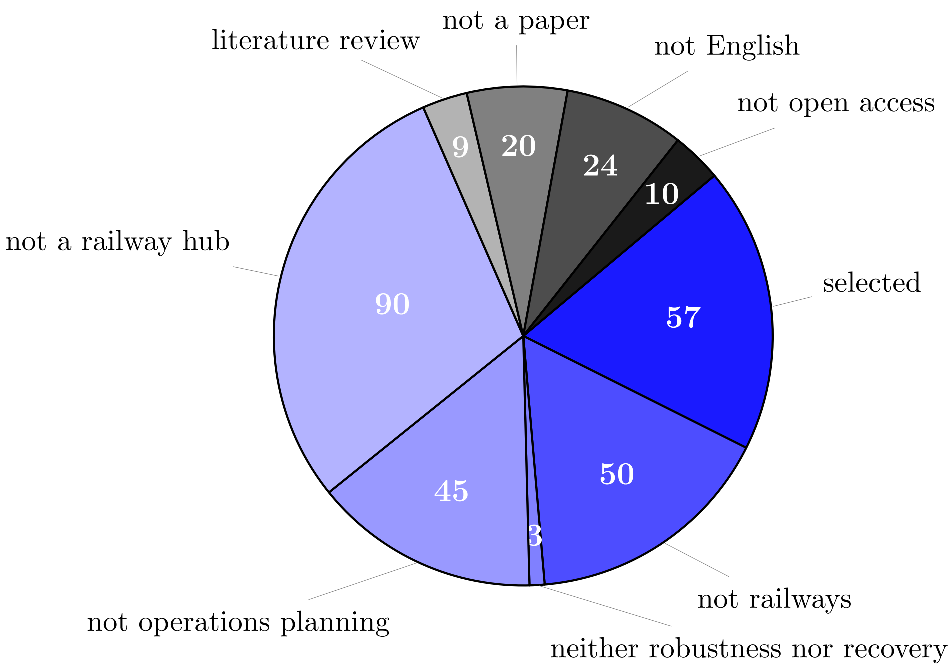

Figure 2: Pie chart showing the categorization of all papers, 308 in total.

provide a solution to the Railway Hub Planning problem without focusing on the robustness or recovery. This resulted in the following query, which we systematically executed in the Scopus database on November 21, 2025.

> (“train” OR ”railway”) AND (“shunting” OR “platforming” OR “dispatching” OR “railway hub” OR “station routing” OR “train routing” OR “station interlocking”) AND (“robust” OR “resilience” OR “robustness” OR “resilient” OR “recovery” OR “replanning” OR “rescheduling” OR “replan” OR “recover” OR “reschedule” OR “disruption management”)

The query above resulted in a set of 308 papers and Figure 2 shows the categorization of them. We selected 57 papers in our review, while the identified literature reviews are discussed in Section 4. Papers that were excluded straightaway were conference proceedings, papers that were not available in English, or papers that were not open access, as the latter could not be found online for study. An example of a paper that did not consider railways talked about ‘training models’, and papers that did not consider operations planning often considered problems such as traction energy efficiency or battery charging in electric locomotives. Excluded railway papers that do not consider railway hubs often focus on large railway networks that treat stations solely as nodes or model tracks as bidirectional edges. We assessed whether the proposed level of abstraction provided sufficient detail for a microscopic perspective, taking into account the actual infrastructure, including signals and interlocking stages. Some papers considered the railway hub area but did not discuss operational planning (e.g., focusing on infrastructure decisions), and a few did not address robustness or recovery in their approaches. Finally, while passenger train shunting movements are crucial operations in the Railway Hub Planning problem, we do include papers that do not study these movements but focus on other passenger train movements in the hub area. These papers are still relevant as their methods could be extended to the shunting movements to solve a more complete version of the RHP problem.

5.2. Results

To handle disturbances in railway hubs, it is important to deal with uncertainties either when creating the plan or in response to them. Therefore, we categorize the 57 analyzed papers into either robustness-focused solutions (14 papers) or recovery approaches (43 papers). Figure 3 shows the spread over the years of when these papers were published. Sections 7 and 8 further delve into the details of these papers, distinguishing between the robustness-focused and recovery-focused papers, respectively.

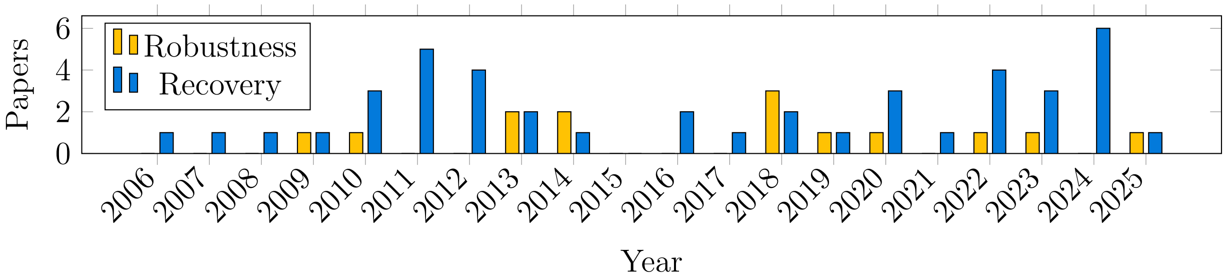

Figure 3: Overview of the number of papers per year of publication for the selected literature: 14 papers about robustness and 43 about recovery.

Figure 4 reports four statistics of the analyzed papers that provide more insights into the uncertainty dealt with, as well as the planning horizon and the signaling constraints, which provide a measure of safety to the solutions. First, we consider the **delay scale**, whether the paper focuses on minor disturbances or larger disruptions (or both). This provides an interesting distinction: robustness-focused papers consider only disturbances, which we classified as delays in small daily operations, whereas recovery approaches also consider disruptions or both types of delays. Because robustness is computed up front, it is easier to account for daily disturbances than for disruptions that may be larger in magnitude. As such, recovery papers often consider more operational characteristics, while robustness papers focus on tactical characteristics. While smaller disturbances are often easier to handle, disruptions pose a greater challenge for railway systems, which might explain why more research has focused on recovery approaches than on robustness. Second, we report on the **delay type** considered; we find that the robustness papers focus only on temporal delays, mostly accounting for track unavailability due to failure, blockage, or being set to out-of-use. In the recovery approaches, we see a wider range of disruption types considered as inputs. Third, we analyze the **planning horizon**, how much time is accounted for in the plan. We see that most of the recovery approaches focus on a short horizon, where we took the 'Hours' category to be up to 8 hours, the 'Day' category up to 48 hours, and anything longer was marked as 'Week'. For three papers, no planning horizon was mentioned. The only paper that considered a very long planning horizon was a robustness paper, as this is planned further in advance than the recovery approaches. Fourth, we discuss the **signaling constraints**, which ensure safety in the system. Constraints accounted for in robustness approaches are more distributed, whereas recovery approaches more often account for the microscopic signaling model, thereby providing a stronger safety guarantee. This makes sense because recovery approaches are more often used in real time, so the required safety level is higher because they are applied much more quickly.

6. Taxonomy of the Railway Hub Planning Problem

This section presents one of our main contributions: the taxonomy of the railway hub planning problem and its operations (Definition 3.2). Many previous studies considered only a few of these, but often not all at once. Our taxonomy includes the problems discussed in the papers we reviewed, how they relate to each other, and their relevance to the operations of the

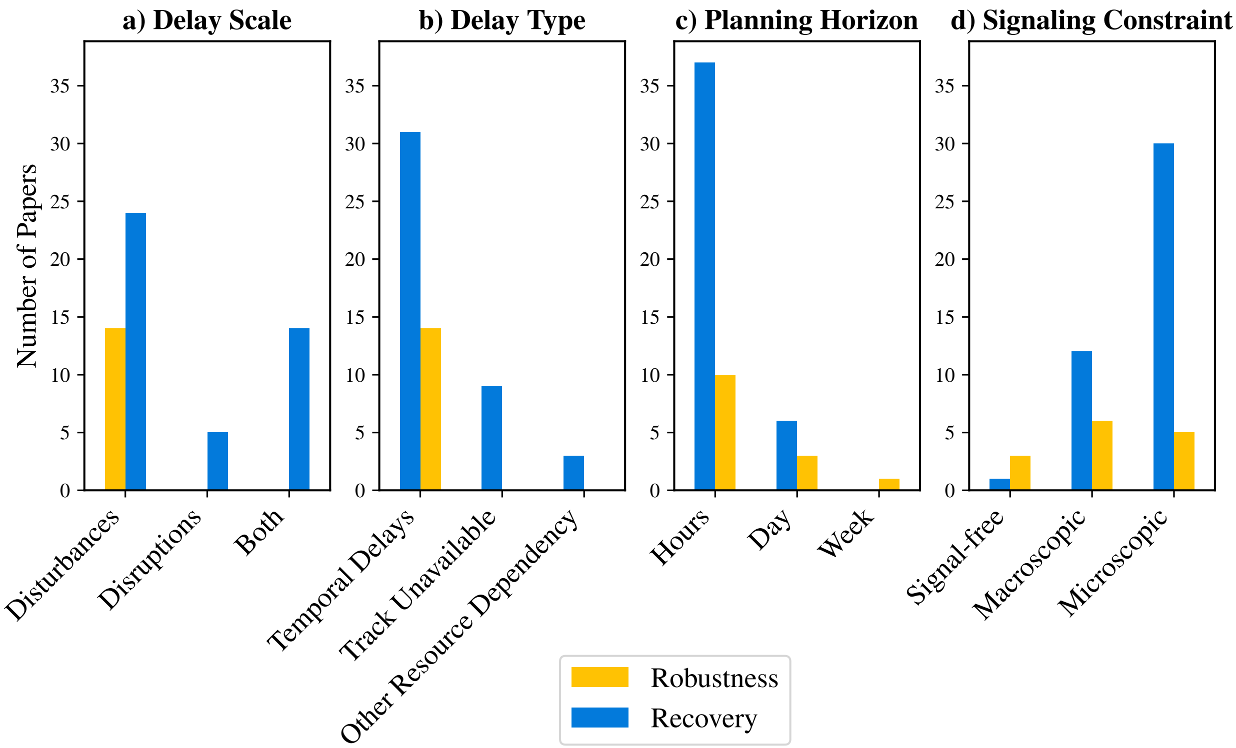

Figure 4: Reporting four statistics of the 57 analyzed papers. a) shows the delay scale. b) shows the type of delay factors considered. c) shows the considered planning horizon. d) shows the implemented signaling constraints.

railway hub planning problem. Table 1 lists the different problems discussed in the literature, which are further discussed below. For some problem formulations, we do not include all variants in the taxonomy; we include only those used to structure our literature survey. Figure 5 visualizes the taxonomy, where each node is one of the operation types of the Railway Hub Planning problem, and the groups form other problems from the literature, which are thus subproblems of the RHP.

Table 1: Overview of the different subproblems considered with the operations that are included in these subproblems. Problem abbreviations are mentioned in Section 6. The operations are platform allocation, parking, routing, matching, service task scheduling, yard personnel scheduling, and signaling constraints.

Subproblem	**Platform**	**Park**	**Route**	**Matching**	**Service**	**Personnel**	**Signal**
TPP/TAP	✓	✓					
TRP		✓	✓				
TRPP	✓	✓	✓				
TUSP		✓	✓	✓			
TUSPwSS		✓	✓	✓	✓		
TUSPwSPS		✓	✓	✓	✓	✓	
RTM/TDP		✓	✓				✓
RSP	✓	✓	✓	✓			
RSPH	✓	✓	✓	✓		✓	

As the RHP is planned during the tactical phase and executed in the operational phase, we assume the timetable for trains operating at the train stations is provided. The first problem to consider is then the assignment of trains to platforms at the stations, also known as the *Train Platforming Problem* (TPP) or the *Track Allocation Problem* (TAP) [6]. In this problem, the routes are assumed to be somewhat fixed, so the choice of platform determines the route to follow. Somewhat contrary to this is the assumption that the platform is given and the route through the station area must still be determined, known as the *Train Routing Problem* (TRP) [6]. These two problems are usually considered together, so we discuss them as the combined *Train Routing and Platforming Problem* (TRPP) in the remainder of this survey. While safety must obviously be ensured in this problem setting, this category focuses on a single railway station as a subset of the railway hub, and safety can usually already be guaranteed with conflict-free schedules, as is done for shunting operations.

The subproblems considered in previous studies for shunting operations differ. The Train Unit Shunting Problem was originally proposed by Lentink et al. [7], who named the four subproblems as routing, parking, service task scheduling, and personnel scheduling. However, in many subsequent works, service task scheduling and yard personnel scheduling were often not considered, so we leave these as extended versions. Moreover, while Lentink et al. [7] did not explicitly name the matching problem, we believe this is crucial as a previous solution for the matching may become infeasible, for example, if the matched train is blocked [41].

We thus define three variants of this problem. First, *Train Unit Shunting Problem* (TUSP) considers three main subproblems: i) assignment of the parking tracks in the shunting yard, ii) routing of trains within the shunting yard, and iii) matching: the rearrangement of train units among different trains. Second, the problem can be extended to the *Train Unit Shunting Problem with Service Scheduling* (TUSPwSS) by also considering the scheduling of service tasks (cleaning and small maintenance) for individual train units, which entails that the train unit must also be routed to the designated servicing track and the service task must be explicitly scheduled [26]. Moreover, the personnel required to perform the service task must be present, as well as drivers for the shunt movements, and their schedules must also be created, as previously discussed by van den Broek et al. [4], who also considered the coupling and decoupling of train units as a separate subproblem. So, we refer to a third variant as the *Train Unit Shunting Problem with Service and Personnel Scheduling* (TUSPwSPS). Although these problems are often named differently in freight shunting yards (or marshaling yards) [43], the operations do not vary, so we adhere to the definitions given here.

Surrounding the railway station, the *Railway Traffic Management* (RTM) focuses on creating a conflict-free schedule with no overlapping blocking times, which includes three subproblems: i) the routing problems through the station, ii) defining the train orders at specific points in the network, and iii) ensuring the minimal distance headway between trains for safety [9]. This is also referred to as the *Train Dispatching Problem* (TDP). Compared to the Train Routing and Platforming problem, this formulation has a more explicit focus on the interaction between rolling stock and different areas of control.

While the shunting problem has often been considered separate from the station area operations, Kamenga et al. [41] considered these together in the *Generalized Train Unit Shunting Problem* (G-TUSP), which they categorized as the pre-operational planning phase, as it is not considered during operations, but a plan is only created shortly (between six days and four hours) before execution. The subproblems of the G-TUSP are referred to as the Train Matching Problem, the Track Assignment Problem, the Shunting Routing Problem, and the Shunting Maintenance Problem, similar to the TUSPwSS as proposed by van den Broek et al. [26]. So, we adhere to the TUSPwSS definition, which includes the same subproblems as the G-TUSP.

Finally, we discuss the *Rolling Stock Planning* (RSP) problem. The general problem can be described as planning which rolling stock to schedule for specific lines, providing sufficient seats for passengers, while managing operational costs [8]. However, this formulation focuses on network-level optimization, which is thus not very relevant to railway hub planning. On the other hand, Kamenga et al. [41] described the rolling stock planning problem as ensuring that train units are managed correctly to facilitate timetable execution, focusing on the station level. So, we use this definition of rolling stock planning and refer to it as the *Rolling Stock*

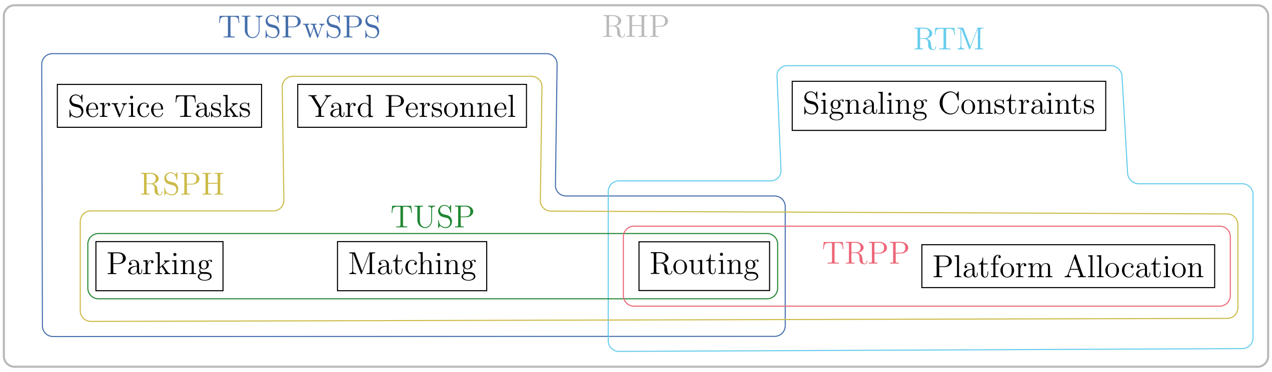

Figure 5: Taxonomy of subproblems related to the Railway Hub Planning problem.

Planning in the Hub (RSPH) problem, in which train units must be handled between arrival at the station and departure. This also requires the personnel scheduling to ensure that trains are actually moved between the yard and the station on time. The RSPH is actually quite closely related to the TUSP, because they also consider whether trains must be temporarily parked.

6.1. Taxonomy Analysis

From Figure 5, we see that the routing aspect is actually included in every subproblem. This demonstrates what we stressed before, that routing is a crucial part of the Railway Hub Planning problem. However, just because it is included in almost every subproblem does not necessarily imply that the methods solving these subproblems also focus on the routing aspect. Furthermore, we see that signaling constraints are not specifically considered in all subproblems; they are considered only in the RTM and in the RHP. For guaranteed safe systems, this is an important subproblem to solve. We also highlight the personnel scheduling operations that are included in the TUSPwSPS subproblem and the RSPH. As all of these subproblems require personnel to operate, it is important to take this into account to ensure the plan is actually feasible to execute, also for the personnel involved. In practice, all of these subproblems of the RHP need to be addressed, and while this can be done sequentially, they depend on each other. A fully integrated approach could thus provide more realistically feasible solutions, which is why we seek solution methods that enable it, as discussed in Section 9.

7. Robustness

Our main contribution is the distinction between robustness and recovery approaches for the RHP problem. This section analyzes the selected papers that focus in depth on robustness. We identified 14 papers that investigate ways to incorporate robustness into planning algorithms for railway hub problems. For each subproblem of the RHP, Table 2 shows an overview of the previous work; in particular, we look at the delay types considered. Finally, the individual subsections for the subproblems discuss the solution methods used and determine to what extent these methods solve a part of the RHP problem.

Table 2: Problem and delay types studied by papers in the Robustness category.

Problem	Type	Papers
RHP	-	-
TRPP	Delays	Bešinović and Goverde [44] Caprara et al. [45] Caprara et al. [46] Dewilde et al. [6] Dewilde et al. [47] Liebchen et al. [48] Yan et al. [17] Zeng et al. [49]

Continued on next page

Problem	Type	Papers
TUSP	Delays	Gilg et al. [50] Peer et al. [51]
TUSPwSS	Delays	van den Broek et al. [52] He et al. [53]
TUSPwSPS	Delays	van den Broek et al. [4]
RTM	Delays	Quaglietta et al. [54]
RSPH	-	-

7.1. Train Routing and Platforming Problem (TRPP)

We found several papers that investigated the train scheduling problem. Although they do not include shunting movements, these papers consider passenger train movements in the larger hub area that remain relevant to the railway hub planning problem. First, Dewilde et al. [47] investigated only the routing problem, assuming that the platform assignment is fixed. Next, Liebchen et al. [48] considered the most basic complete version of the train platforming problem. They have a station with a set of platforms and a set of trains. Each train needs to be assigned a route from its entrance track to a platform, and then from its platform to its departure track. The chosen platform also needs to be determined, and this version of the problem is studied by Caprara et al. [45, 46]. It is the most basic version of the platforming problem that includes enough details to be applicable to real-world planning problems, but does not yet include all of the small details present in the real-world application. Several papers have proposed extensions to these formulations. First, Dewilde et al. [6] allowed their model to make small modifications to the timetable. Furthermore, they looked at larger station areas where each train has to pass through multiple stations. Then, Bešinović and Goverde [44] developed a very detailed model of the infrastructure and tried to balance the use of the different pieces of infrastructure. Zeng et al. [49] included track utilization rules used by train dispatchers and train coupling/decoupling relations at the station area. Lastly, Yan et al. [17] considered a version of the TRPP in which they looked at a collection of railway stations and had to find a platform at one of those stations for every train, while accounting for passenger transfers between the different stations.

When we consider the types of robustness these problems addressed, we see that most focused exclusively on delays. They tried to account for these delays with different methods. One of the methods used is finding a measure of the robustness in the plan (such as the buffers or the weighted total real travel time) and adding it to the objective [6, 47, 49, 45]. Caprara et al. [45] experimented with adding backup routes for trains. Moreover, Liebchen et al. [48], Caprara et al. [46], Bešinović and Goverde [44] considered delay scenarios where they minimized the delay. They achieved this by adding a delay propagation model to their solution algorithm, which was used to estimate the total expected delay. The only paper that considered a different type of uncertainty was the work by Yan et al. [17], which considered uncertainty in passengers' transfer times. Although it does not affect train operations, it is important for service quality.

Most of the above papers used mathematical optimization methods to solve the TRPP. They used a MILP formulation in which, for each train, they introduced a binary variable for each possible route or platform assignment. Then, constraints were introduced to ensure that incompatible routes (e.g., overlapping routes) are not selected simultaneously. The papers differed in how they modeled robustness and how they solved models with these robust extensions. Even with some extensions, standard MILP solvers could still solve the problem [48, 17], thus adding little extra complexity. On the other hand, Caprara et al. [45, 46] used branch-cut-and-price to break down the problem. Another method that has been successfully applied to this problem is local search. Dewilde et al. [6, 47] used local search to extend their

MIP algorithm and find better solutions in a larger solution space. Bešinović and Goverde [44] and Zeng et al. [49] used local search as their main solution algorithm for their versions of the train platforming problem. These local searches mainly operate by iteratively making small changes to a single route in the plan. We see a wide variety of solution methods used, where local search seems the most promising.

7.2. Train Unit Shunting Problem (TUSP)

We found two papers that considered the TUSP and analyzed its robustness to changes in the departure and arrival order of the trains, although they achieved this in different frameworks. First, Gilg et al. [50] focused on the parking subproblem of the TUSP. They assumed that they had a set of tracks that could be entered from one end (i.e., a dead-end track, or Last In First Out) or from both sides (i.e., a free track, or First In First Out (FIFO)). To incorporate robustness against disturbances, they included the conflict probability in their model and tried to minimize this. They successfully created a list of compromise solutions between the number of planned trains and the number of expected conflicts. Second, Peer et al. [51] included both the parking and matching subproblems in their formulation. Their algorithm determines at each arrival or departure event, where to park the incoming train, or which train to send out. They created a state-based model that is only able to look ahead to the next five incoming trains. The authors used this method to make the algorithm more robust against deviations in the arrival order. They were able to solve this problem for about 80% of the instances that they used, while the local-search baseline [55] solved more than 90% of the instances. Disruptions such as track nonavailability were not considered for the TUSP in any of the papers we reviewed.

The papers use different methods for solving their respective problems. Gilg et al. [50] used integer programming models to solve their problem. Since MILP methods work very well for pure assignment problems such as this one, they are a logical solution method. Peer et al. [51], on the other hand, used a deep reinforcement learning approach. Although this method is not often used for these problems, they chose it because it allows them to create plans that are predictable for human planners. Although these methods showed promising results, they did not outperform the state of the art and addressed only a limited problem definition.

7.3. Train Unit Shunting Problem with Service (and Personnel) Scheduling (TUSPwS(P)S)

We found two papers that discussed the TUSPwSS and one paper discussing the TUSPwSPS. In all of the papers, authors considered disturbances in the form of delays and uncertain durations of movements and service tasks. First, He et al. [53] considered a variant of the TUSPwSS based on shunting yards with a very specific layout. This is a layout where multiple sets of parallel tracks are connected via bottleneck tracks in series. To deal with uncertainties, they included stochastic parameters in their model, enabling them to solve it as a robust optimization problem. Although the authors successfully solved this problem, their approach is not easily generalizable to different types of shunting yards, which are found throughout Europe. Next, van den Broek et al. [4, 52] investigated extensions to a local search algorithm for the TUSPwSS to make the schedule more robust and to include yard personnel scheduling. The authors investigated multiple robustness measures to find out which of these measures work well to increase the robustness of the schedule. With these extensions, the authors have created an algorithm that can generate more robust shunting schedules, where van den Broek et al. [4] also includes a basic yard personnel schedule. Although both papers consider delays in train arrival times, they do not account for actual changes in the arrival order of trains. This is especially important in shunting yards, where multiple train units are stored on the same track. Disruptions such as track unavailability are also not considered.

In all three of the above-mentioned papers, the main method used to solve the problem was a local search algorithm. Local search has been successfully applied to many types of shop scheduling problems. Because the TUSP(wSPS) is closely related to these problems, local search is a prime candidate for solving them. The additional scheduling problem for yard personnel is solved using heuristics in combination with an ILP. This leaves quite some room to also include other methods when considering more detailed and realistic personnel schedules.

7.4. Railway Traffic Management (RTM)

Quaglietta et al. [54] investigated how to create more stable plans for the Railway Traffic Management problem. More precisely, they combined the Alternative graph-based tool ROMA with the simulation environment EGTRAIN to determine how to create dispatching plans that remain stable as new information becomes available. They examined the effect of the planning horizon on the stability of the created plans and how the plans change as more disturbances come in. The disturbances they considered were differences in the dwell times and departure times of the trains. They found that by changing the time horizon, they could create a trade-off between the stability of the plan and the ability of the plan to be robust against delays.

7.5. Conclusion

In investigating the state of robustness methods for each subproblem in the taxonomy, we find that for the TUSP(wSPS) and TRPP, many papers have addressed these problems while considering the robustness of the schedules. For the TRPP, all related operations are considered in the papers we reviewed. This is also the case for the TUSPwS(P)S. For the RHP and RSPH problems, considerably less work has been done on robustness, as robustness was not found at all.

If we consider the types of robustness investigated across the different papers, we see that most papers deal almost exclusively with disturbances in the form of delays, stochastic processing, and travel times. We can see that, in general, there has been quite some success in making schedules more robust against these types of disturbances. For most problems, robustness against other disturbances has either not been investigated or has been investigated only in simpler versions of the problem. We have not come across any papers that address robustness to disruptions.

For the problems for which we identified several papers, we see that two solution methods have been quite successful. First, for the TUSP(wSPS), we see that local search has been a very successful technique for solving it, as it can solve an almost complete version of that problem. And second, we see that mathematical optimization has been successfully used in many papers that solved the TRPP.

8. Recovery

Where the previous section discussed the robustness papers, this section thoroughly analyzes the selected papers that focus on recovery. We identified 43 papers that focus on the recovery methods for railway problems. We categorized them into the main railway planning problems they address. For each subproblem of the RHP, Table 3 shows an overview of the previous work, again showing the considered delay types. Finally, the individual subsections for the subproblems discuss the solution methods used and determine to what extent these methods solve a part of the RHP problem.

Table 3: Problem and delay types studied by papers in the Recovery category.

Problem	Type	Papers
RHP	Delays	Hanou et al. [16] He et al. [56]
TRPP	Delays	Ding et al. [57] García-Ródenas et al. [58] Lu et al. [59] Meng et al. [60] Pascariu et al. [61] Teng et al. [62]
	Track out of use / failure / blocked	Zeng et al. [63]
TUSP	Track out of use / failure / blocked	Sugi et al. [64]
TUSPwSS	Delays	Shi et al. [65]
TUSPwSPS	-	-
RTM	Delays	Caimi et al. [66] Corman et al. [22] Corman et al. [67] Corman et al. [68] Corman et al. [69] Corman et al. [70] Corman et al. [71] Corman et al. [72] D'Ariano et al. [73] D'Ariano et al. [74] HongTao et al. [75] Liu et al. [76] Lusby et al. [11] Martin et al. [77] Mladenovic et al. [78] Pellegrini et al. [79] Pellegrini et al. [80] Samà et al. [81] Sharma et al. [82] Wegele et al. [83] Yi et al. [84] Zhu et al. [85]
	Track out of use / failure / blocked	Corman et al. [86] Corman et al. [87] Corman et al. [88] Corman and D'Ariano [21] Corman et al. [89] Liu et al. [90]
	Other resource dependency	Liao [91] Vansteenwegen et al. [92]
RSPH	Track out of use / failure / blocked	Zhu et al. [93]
	Other resource dependency	van Lieshout et al. [5]

8.1. Railway Hub Planning (RHP)

We found two papers [16, 56] that proposed recovery methods for the RHP problem. Although these papers do not include servicing tasks or personnel, they were the only papers to consider the entire area of a railway hub. More specifically, both papers looked at the routing of trains through the railway hub, which is a crucial part of the planning process that is often overlooked. This includes movements over both the station area and the shunting yard. They studied real-life railway hubs where some trains are delayed, and focused on recovering the disturbed plan by rerouting and rescheduling the delayed trains. Both papers consider only delays and do not account for other disturbances or disruptions.

Both papers use an agent-based approach to solve the problem, modeling trains as individual agents. He et al. [56] used heuristic rules to guide the agents in their decision-making. This led to fast solutions, though these were not necessarily optimal. On the other hand, Hanou et al. [16] used a strategy in which they precomputed paths for all agents using safe intervals. This way, they created a recovery strategy for every agent at every possible time, which the agents can look up instantaneously.

8.2. Train Routing and Platforming Problem (TRPP)

We found six papers that considered recovery algorithms for the TRPP. Five of these papers considered recovery algorithms for delays, and one paper examined recovery for an out-of-service track. The delay-focused papers considered reallocating the platforms and rescheduling the timetable. They considered real-life station layouts with a realistic timetable, to which they added random delays. These delays were usually up to 10 or 20 minutes for multiple different trains. The papers differed mostly in the signaling constraints they used (varying between macroscopic and microscopic viewpoints) and the solution times they reported. In particular, Lu et al. [59] made their model compatible with different interlocking principles, solving each instance within 500 seconds with exact methods. With heuristics, they were able to find solutions of comparable quality at a fraction of the computational cost. Moreover, García-Ródenas et al. [58] addressed models that are able to solve these recovery problems more quickly. They found that with their heuristic methods, they were still able to produce high-quality solutions, thus outperforming exact methods. Instead, Zeng et al. [63] considered recovery algorithms for when tracks are out of use. As a recovery strategy, they proposed both reallocating the tracks and adjusting the timetable. Besides finding a new feasible schedule, the authors also want to balance the use of the different tracks, as well as minimize the total delay. They found that they were able to solve this problem on average within nine seconds across their considered instances.

If we consider the different solution methods used for recovery for the TRPP, we see that the most used among these papers is mathematical optimization. Similar to the robust optimization version, most mathematical models use binary route variables to enumerate all possible routes, and then choose one route per train. However, due to the fact that for recovery, the solving times need to be very quick, as this problem is handled in an online setting, many papers also use heuristic methods to solve their optimization models more quickly, such as a greedy track interchange heuristic [58], a rolling horizon decomposition [59, 62]. Due to this, we also see more papers that directly use heuristic methods such as evolutionary algorithms [57, 63] and local search [60, 61].

8.3. Train Unit Shunting Problem (with Service Scheduling) (TUSP(wSS))

Next, we consider the Train Unit Shunting Problem. We identified one paper [64] that addressed the problem without considering service scheduling. They considered a minimalist setup for the TUSP, where they only have to worry about the parking problem. They designed the model so it could handle both delays and out-of-service infrastructure. A more extensive version of the TUSPwSS was studied by Shi et al. [65], who specifically applied it to Chinese shunting stations, including the parking, routing, and service task scheduling operations. In this paper, the authors dealt only with disturbances in the form of delays, though they noted that adding shunting movements should also be considered to absorb additional disturbances. Neither of the mentioned papers considered disruptions such as service failures or changes in the incoming train units.

The two papers used quite different methods to solve their respective problems. Sugi et al. [64] used a local search method to recover disturbed schedules. This method provided a flexible model that could handle different types of disturbances with a computation time of less than one millisecond across all tested instances. Shi et al. [65] instead applied a dynamic programming approach to recover from disturbances. Although it solved all of the tested instances within 180 seconds, the number of disturbances in those instances was quite low.

8.4. Railway Traffic Management (RTM)

Due to the large number of papers we found for the RTM problem, we describe our findings for this part more generally. For a more detailed overview of which paper contains which details, please see Table A.7 in the Appendix.

First, we note that most of the RTM recovery papers we encountered studied the problem in largely the same way. Most authors focused on a station area, with some larger parts of the railway network in the surrounding area. The size of these areas varied from including only a few smaller surrounding stations to a couple of dozen. The largest differences stem from additional details, such as different priorities for different trains and communication with other dispatching areas. The different papers also used different signaling types, ranging from headway times to almost complete interlocking systems. Overall, we identified many papers that successfully solved the RTM recovery problem in realistic settings, with various objectives.

Next, we consider the different types of disturbances and disruptions encountered for the RTM recovery problem. Most of the papers in the survey primarily regarded disturbances in the form of delays. The papers that addressed these delays started from an infeasible schedule caused by them and then rescheduled it to make it feasible again while minimizing an objective, such as total delay or passenger discomfort. Besides this, we also found quite a few papers that dealt with disturbances in the form of a reduction in available infrastructure capacity. This can be in the form of out-of-use tracks and block sections, planned maintenance, or speed restrictions. To address the disruptions, the papers adopted more impactful strategies, such as longer rerouting paths and train cancellations. For all of these delay types, we have found papers that solve the RTM recovery problem in a realistic setting with fast solution times.

Finally, we discuss the different solution methods we encountered in our survey. We found that the papers we surveyed used a variety of methods to successfully solve the RTM recovery problem. These included mathematical optimization methods, branch-and-bound, and several metaheuristic methods. We highlight one method in particular, the Railway Traffic Optimization by Means of Alternative Graphs (ROMA) method. This method is based on branch-and-bound and is used in many of the papers we surveyed on the RTM recovery problem. Furthermore, this method can handle both disturbances and disruptions and can be used on large, realistic instances.

8.5. Rolling Stock Planning in the Hub (RSPH)

We found two papers on recovery for the Rolling Stock Planning problem in the hub, with use cases of larger disruptions. The first investigated decentralized dispatching strategies for dispatching rolling stock and train personnel [5]. The idea is that these local strategies in the hub can be used when large disruptions make it impossible to implement centralized plans, for example, by switching rolling stock between lines. The authors found that using dynamic strategies, in which trains are allowed to switch lines, led to more stable plans. Zhu et al. [93] made the disruptions more explicit. In their problem setting, they assumed that some network lines are completely blocked, requiring the rescheduling of rolling stock on those lines. To achieve this, rolling stock units need to be routed between the station area and the shunting yards. For this rescheduling, the authors considered both reassigning available rolling stock and adding small delays to the timetable. As these two papers had different interpretations of the RSP, they also used quite different types of algorithms. Simulation in the EGTRAIN framework was used by van Lieshout et al. [5] to assess their different dispatching strategies and found that strategies that give rolling stock greater freedom to switch between lines performed especially well. On the other hand, Zhu et al. [93] formulated the problem as an ILP and solved it using Bender's decomposition, returning a plan to each instance within five minutes.

Table 4: Categorization of different solution methods.

Solution method	Individual approaches
Mathematical programming	MILP, ILP, linear program, integer programming, Bender's decomposition, column generation, stochastic programming
Meta-heuristic	tabu search, local search, ant colony optimization, heuristic
Evolutionary	Evolutionary algorithm, genetic programming
Alternative graph	Alternative graph
State-based	Agent-based, reinforcement learning
Simulation	Simulation-based methods

8.6. Conclusion

When we consider the overall state of the literature with regard to recovery for railway hub subproblems, we see that the most work has been done on the RTM problem and the TRPP. For these two problems, we found a large number of papers covering realistic versions of these problems, with recovery algorithms that handle both disturbances and disruptions. For the other subproblems, we found considerably fewer papers. First, while the TUSP(wSS) approaches addressed both the routing and the service task rescheduling, it is unclear whether the presented algorithms can also handle a larger number of disturbances or are able to handle the rescheduling during heavier disruptions. Moreover, the yard personnel scheduling was not considered by any of these studies. Second, for the RSPH problem, we see that quite some work was done to successfully reassign rolling stock to different lines during large disruptions. However, no literature combines this with the shunting yard scheduling. Finally, we categorized two papers that do include the entire RHP definition in their model, focusing on routing in both the station and the shunting yard. However, they did not consider the other RHP operations.

Overall, we see that quite a few papers cover a wide range of disturbances and disruptions. However, there are still quite a few areas in which disruptions have not yet been considered. In particular, the TUSP(wSPS) includes many different resources, whereas the studied papers consider only temporal delays. Common daily disturbances, such as different arriving train compositions or required service tasks, are not considered, even though they have a significant impact on the plan's feasibility.

We also found a few different solution methods that seemed to have had quite some success in solving recovery problems in the railway hub. First, several papers successfully used the alternative graph method to solve the RTM problem across a wide range of delay types. Another method that was often successfully used for the RTM problem, and for other problems as well, was mathematical optimization. Often, these methods were also combined with heuristics to reduce running time. In general, we also saw that meta-heuristics were generally very useful for solving recovery problems.

9. Solution Methods

We now shift perspective to focus on the solution methods used by the different papers we reviewed. Specifically, we consider how they solve the respective robustness and recovery challenges. First, we categorize the different solution methods. Then, we distinguish between robustness and recovery papers and analyze them along the axis of their solution method. Furthermore, for the Robustness papers, we additionally mention the different robustness objectives used, see Table 5. For the recovery approaches, we instead report on their applicability in the real world based on the reported runtime (see Table 6). We complete the section with an analysis of the useful solution method for the entire RHP problem.

9.1. Solution Methods

We categorize the different solution methods used by the reviewed papers. These categories are listed in Table 4, along with the individual method names that we included in each category. These categories are not necessarily exclusive, so some papers may fall into multiple categories. However, with these categories, we aim to encapsulate the most commonly used method types. By identifying which subproblems the different papers solve and the methods they use, we determine potential methods to tackle the complete RHP problem.

The first category includes methods based on mathematical programming, such as (Mixed) Integer Linear Programs, as well as stochastic programming methods and papers that mention specific algorithms, such as column generation or Bender's decomposition. A second set of methods is based on meta-heuristics, such as local search, ant colony optimization, and tabu search. Third, we have methods that use evolutionary algorithms, including genetic programming. These methods are usually more involved than local search and are thus categorized separately. The fourth category is used to specifically indicate the papers that use an alternative graph formulation. A fifth category includes methods that search over states defined by agent-based models or reinforcement learning. Finally, we have a category of simulation-based approaches. Together, these categories cover all the approaches we identified in the literature.

9.2. Algorithmic Approaches for Robustness

Our review showed that most robust planning approaches use mathematical optimization, and our main results are summarized in Table 5. This class of methods provides exact solutions or near-optimal solutions with an optimality gap, although they usually require long computation times. Contrarily, the meta-heuristic approaches used for the TRPP and the TUSPwSS do not provide exact solutions; their computation times may be shorter, but they often do not guarantee finding a solution when one is available, so they are nondeterministic. As noted in Figure 4, all approaches account only for disturbances, not disruptions, and Table 2 shows that only a few papers consider resource availability disturbances, compared to delays.

Table 5: Solution methods for Robustness methods, showing the number of papers per robustness objectives used. As some approaches have multiple objectives, the counts do not necessarily add up to the 14 Robustness papers analyzed.

Problem	**Method**	**Robustness Objective**	**Papers**
RHP	-	-	-
TRPP	Mathematical Optimization	Buffer Time	[45] [6] [47]
		Occupation Time	[17]
		Recovery Strategy	[45]
		Scenario Delay	[46] [48]
	Meta-Heuristic	Buffer Time	[6] [49] [44]
		Occupation Balance	[44]
		Occupation Time	[44]
TUSP	Mathematical Optimization	Scenario Delay	[50]
	State-Based	Arrival Order	[51]
TUSPwSS	Mathematical Optimization	Occupation Time	[53]
	Meta-Heuristic	Buffer Time	[52]
		Delay Probability	[52]

Continued on next page

Table 5: Solution methods for Robustness methods, showing the number of papers per robustness objectives used. As some approaches have multiple objectives, the counts do not necessarily add up to the 14 Robustness papers analyzed.

Problem	**Method**	**Robustness Objective**	**Papers**
		Occupation Time	[53]
		Time Allowance	[52]
TUSPwSPS	Mathematical Optimization	Buffer Time	[4]
RTM	Simulation	Schedule Stability	[54]
RSPH	-	-	-

Algorithmic support for a more robust system requires a robust formulation in the formal model. In mathematical programming, this is often included in the model's objective function, but other approaches may also impose a robustness objective on the solution. The robustness objectives used in the different approaches differ between:

- infrastructure occupation time: minimizing the total usage time of the relevant infrastructure, such as platform and parking tracks,
- infrastructure occupation balance: making sure that the different pieces of infrastructure are used in similar amounts,
- schedule stability: the extent to which the schedule has to change in the face of disturbances,
- buffer time: the buffer time is the scheduled time between two consecutive train paths, which trains can use to catch up after a delay,
- time allowance: the time between processes of one train that allows the train to catch up,
- delay probability: determining how much total delay the schedule will likely result in,
- recovery strategy: planning with predetermined strategies for possible disturbances,
- scenario delay: the expected amount of delay based on possible delay scenarios, and
- arrival order: the order of the arriving trains is kept uncertain, and the goal is to have trains still arrive and depart at scheduled times (implicit objective).

The most-used objective is buffer time, used by eight approaches, which is the most direct way to include robustness in the plan. This method works well for problems like the TRPP, as it improves the robustness for each train separately, minimizing the propagated delay. We see that four papers minimize the infrastructure occupation time, providing buffer time in the timetable to resolve disturbances, or even leaving a free track. However, most of the papers we reviewed did not compare different robustness measures, making it difficult to find a definitive best robustness measure. This is also due to the fact that different papers might use different ways of measuring the robustness of a created schedule. Nevertheless, van den Broek et al. [52] compared different robustness measures for the TUSPwSS and found their correlations with two simulation measures. They concluded that using an approximation of the probability that a schedule finishes on time is highly correlated with schedule robustness. This was the only study using such an objective, so this poses an interesting direction forward, while the buffer time remains the easiest to implement, which is also close to the railway operations in practice.

Table 6: Solution methods for the 43 Recovery methods, showing the number of approaches that were classified as providing realistic runtime.

Problem	**Method**	**Realistic runtime**	**Unrealistic runtime**
RHP	Simulation	[56]	-
	State-Based	[16] [56]	-
TRPP	Evolutionary	[57] [63]	-
	Mathematical Optimization	[58] [59] [63]	[62]
	Meta-Heuristic	[61]	[60]
TUSP	Other	[64]	-
TUSPwSS	Mathematical Optimization	[65]	-
TUSPwSPS	-	-	-
RTM	Alternative Graph	[72]	-
	Evolutionary	[85]	-
	Mathematical Optimization	[76]	[83]
	Meta-Heuristic	[66] [69] [21] [90] [11] [79] [80] [81] [82] [92] [84]	[91]
	Simulation	[86] [89] [72] [74] [75] [78] [81] [82]	[77]
	State-Based	[22] [86] [87] [67] [68] [88] [69] [70] [71] [21] [89] [73] [74] [81]	[83]
RSPH	Mathematical Optimization	[5]	-
	Simulation	[93]	-

9.3. Algorithmic Approaches for Recovery

Table 6 shows the different methods used by recovery approaches, grouped by the main problem solved, and we determine whether each approach has a realistic runtime.

The runtime is deemed realistic if it can be employed in an online setting, thus running in seconds to minutes at most. From Table 6, we see a larger variety in the solution methods, also including evolutionary methods and many alternative graph formulations. The Alternative Graph formulation uses a job-shop scheduling approach where each block section of infrastructure is a machine, and we need a conflict-free schedule assigning trains to blocks. This formulation is used exclusively for Railway Traffic Management, which imposes the most restrictive signaling constraints. We see that the alternative graph offers a realistic runtime in almost all cases. Most problems in RHP, in general, are solved with realistic runtimes, except for the RSPH. Meta-heuristic models are also not always solved in realistic runtimes. In the table, we also see that two solution methods do not fall within the earlier-presented algorithm classification. The first of these is the one TUSP approach with recovery, which used an Affected Operation Rescheduling approach. This is a different formulation, also based on job-shop scheduling, similar to the Alternative Graph approach. The 'other' category for the RTM problem used so-called 'disruption programs', which form a set of dispatching rules that can be used by train dispatchers and take into account capacity consumption.

From our analysis, we see that a variety of approaches achieved realistic runtimes for recovery problems. Although many methods could obtain exact solutions within a reasonable running time, this was not always possible. Often, exact methods had to be augmented with heuristics to obtain more realistic runtimes. In general, a combination of exact methods and heuristics seems most effective at obtaining high-quality solutions within reasonable running times. This is especially true when considering larger instances with more disturbances and disruptions.

9.4. Useful Solution Methods for the RHP problem

In practice, the problems studied seldom appear in isolation, but rather are combined into a single problem, identified in this work as the RHP. The main question here is whether and how the solution methods for the subproblems can be applied to the RHP in the complex real world. This section shows which methods have been shown useful for both robustness and recovery and are thus an interesting direction forward for the RHP. Mathematical optimization methods using Mixed Integer Linear Programming have been very successful at solving the TRPP. This method is very versatile, as it can be applied to many different versions of this problem. Moreover, these formulations can often be extended to create more robust solutions. Also, for recovery, these methods are frequently used, providing reasonable runtimes in many cases when combined with heuristics. However, it must also be noted that, although these methods are successful on realistic instances, their scalability remains quite poor. Therefore, these methods may not be feasible for some larger railway hubs.

Another method that has been very useful for railway hub planning is local search. Local search has proven to be a very useful tool for solving the TUSP(wSS). This is likely due to this problem's similarity to job shop scheduling, where local search has also been very successful at producing good solutions. Moreover, local search methods can be extended with, for instance, MILP algorithms to also include and solve other subproblems. Local search generally provides faster solutions than mathematical optimization, and is thus very suitable for recovery approaches in an online setting. While not used for the TUSP(wSS), this proved useful for the TRPP and the RTM. While local search is here listed as a meta-heuristic (Table 4), it is closely related to evolutionary algorithms, which are also used in these categories.

Lastly, we want to note that in general, methods that work well for job shop scheduling also seem to work well for most RHP problems. General methods like the previously mentioned mathematical optimization and local search, as well as more specialized methods like alternative graph, all saw great success in solving RHP problems. By comparing different variations of the job shop scheduling problem with different RHP problems, it might be possible to find other solution methods to solve any remaining open problems in the Railway Hub Planning.

10. Discussion

After discussing the individual papers resulting from our survey, we present the overall findings and identify gaps in the current literature. We also connect the robustness findings with those of the recovery.

10.1. State of the Different Railway Hub Subproblems

Looking at railway hub problems from both robustness and recovery perspectives, we first note that, from a robustness perspective, the main shortcoming of the current literature is that not all problems have been fully investigated. Specifically for the RTM and RSPH problems, next to no literature considers robust planning. Moreover, operations for integrating personnel scheduling have only received limited consideration. Due to the many constraints imposed by collective labor agreements, it is often difficult to align yard personnel schedules with operational schedules. We therefore think that this is one subproblem that is very interesting for future research.

Furthermore, no papers were found that address a fully integrated railway hub planning problem, both in terms of robustness and recovery approaches. Since all components of the railway hub plan affect each other, it is important that they work well together. Some work for the RTM problem coordinates different parts of the network during large disruptions. However, this work did not include operations on the shunting yard. We think that, to make these algorithms more useful in real-world practice, it is vital that these different parts can all work together simultaneously. Although a completely integrated solution might not be attainable in the near future, we believe it is possible to combine multiple methods for the different subproblems to obtain a complete railway hub schedule. The question remains how to combine algorithms to account for all details arising from integrating the different subproblems, such that, together, they solve the Railway Hub Planning problem.

Finally, we discuss the different signaling constraints used in the current literature. Although many papers use a microscopic viewpoint for the signaling system, we found no papers that consider all the details of interlocking, including flanking constraints and route dependencies (see Pachl [94]). Not taking these details into account can lead to an overestimation of the capacity in a station area. Thus, to make an accurate plan, these extra signaling constraints also need to be added to current methods.

10.2. Types of Disturbances and Disruptions

Next, we turn to the gaps identified in the literature with respect to the types of disturbances and disruptions. We start with the work on disturbances, for which we concluded that considerable work has been done for the TRPP, TUSP(wSS) and RTM. For the RSPH problem, we found only very little work focusing on disturbances, with no work that focuses on robustness for the RSPH problem. Looking back at Table 2 and Table 3, we see that most papers that investigated disturbances focused only on delays. For robustness, only two papers considered disturbances other than temporal delays. Of course, for problems like the TRPP and the RTM, these are also the most common types of disturbances. However, many other types of disturbances should be considered. For instance, during daily operation, trains often arrive in different compositions than planned. Another example is that the set of train units that require a service task can change between planning and execution. Moreover, it might even happen that trains arrive that were never planned to arrive at that railway hub. Although these changes may seem like major disruptions, they occur daily as a result of earlier schedule changes. These types of disturbances may require major rescheduling, especially at shunting yards. To develop algorithms for railway hub problems that are applicable in practice, they must handle these variations.

This also ties in with what we mentioned in Section 10.1 about aligning the algorithms for the different parts of the railway hub. For instance, when an extra train arrives at a station, it may not always be possible to simply drive that train to the shunting yard, even though that would fix the plan for the platforming problem. By not aligning the procedures for the different parts of the railway hub, these types of disturbances will only occur more frequently and become more difficult to solve.

Next, we discuss the disruptions, for which we have found far fewer papers that considered robustness or recovery methods (Table 2 and Table 3). For robustness, no papers were found that dealt with disruptions, while quite a few recovery papers addressed them. This is not entirely unexpected, as it is often better to solve these in the recovery phase than to try to prevent them using robustness due to the size of the disruptions. Nevertheless, disruptions such as unavailable pieces of infrastructure occur frequently enough to at least try to incorporate those in a robust plan. These might, for instance, be accounted for by recoverable robust methods. Although more literature is available on recovery methods for disruptions, quite a few problem areas, such as the TUSP(wSPS), need more research on this.

Finally, we want to mention one underrepresented aspect in the literature, which is the passenger perspective. The RTM problem and the TRPP are two problems where the passengers experience the most impact from operational decisions. Passenger transfers are rarely considered, even though these can play an important role in determining the quality of the schedule. We therefore believe that this is another important aspect that may be included in future research on the railway hub problem.

11. Conclusion

In this paper, we formally establish the Railway Hub Planning problem, in which all operations at a railway hub are planned to realize the timetable and ensure smooth passenger transportation. As different lines and operators intersect in these railway hubs, the operations are prone to disturbances and disruptions. Therefore, creating a robust plan to address such uncertainties and having suitable recovery methods to deal with unexpected events is crucial. While robust planning approaches prevent delays, additional recovery methods are also necessary to address unforeseen events, and both approaches should thus be considered for any railway hub system. This paper explicitly defines the Railway Hub Planning problem and presents a taxonomy of the associated subproblems in the literature. We review the current state of the art in the literature on the different subproblems that cover a subset of railway hub operations. We analyze 57 papers addressing the robustness or recovery of related problems, such as Railway Traffic Management, the Train Unit Shunting Problem (with Service and Personnel Scheduling), the Train Routing and Platforming Problem, and the Rolling Stock Planning in the Hub problem. We find that while each of these problems has been studied extensively on its own, the combination of them as a complete railway hub remains incomplete. Our survey shows that about three times as many papers focused on recovery approaches versus robustness. Moreover, disturbances were more often addressed than disruptions, and most papers considered only delay-related uncertainties rather than resource unavailability. Finally, we conclude that hybrid methods seem to be most promising for making a plan of all the interconnected components and processes of the railway hub, taking inspiration from job-shop scheduling approaches to combine heuristics with optimization methods.

11.1. Limitations of the study

We define the railway hub study area and the railway hub planning problem based on the literature and combined insights from different papers. This scope was also verified with the operations as planned in the Netherlands, and while we cross-checked against papers based on operations in other countries, our definition might be slightly tailored to the Dutch railway network. Nevertheless, we believe our conclusions remain relevant for railway hubs in any country.

Our literature selection focused only on the Scopus database, which is very extensive, but we did not consider any other databases. The selected papers had to meet several criteria, resulting in only 57 out of the 308 papers being selected for our survey. While this resulted in a feasible study that really focused on the railway hub, this may have been slightly constricting, for example, when considering the specific impact on passengers and transfers. Moreover, the papers that were not available as open-source or in English were not considered in this study, even though they may offer interesting insights into railway hub planning.

11.2. Directions for Future Research

The main gap identified in our survey is the lack of integration between the different subproblems of the Railway Hub Planning problem. Although the different subproblems have been studied individually, more research is needed to develop a planning approach for the entire railway hub that accounts for robustness and provides recovery measures for events previously unaccounted for. Additionally, we found a gap in the literature on the scheduling of yard personnel, as very few studies have integrated this subproblem into their approach, and robustness or recovery is not even considered. Finally, we also found a gap in the types of delay sources studied, particularly the lack of accounting for resource constraints in disruption management. Currently, no research considers changes in the arriving composition types of rolling stock arriving at the railway hub or variations in the required service tasks. These changes can have a drastic impact on the shunting schedule, making it an important direction for future research.

In terms of solution methods for resilience in the railway hub, this remains an open problem. While we identified several promising methods for solving the railway hub entirely, such as local search and alternative graph, the main road forward seems to be a hybrid approach. Especially, combining heuristics with optimization can account for the scaling factor of the problem complexity, as well as the many interdependent components of the planning process.

References

[1] Y. Wang, R. Song, S. He, Z. Song, Train routing and track allocation optimization model of multi-station high-speed railway hub, Sustainability 14 (2022). doi:10.3390/su14127292.

[2] R. W. van den Broek, Towards a Robust Planning of Train Shunting and Servicing, phdthesis, Utrecht University, 2022. doi:10.33540/1301.

[3] J. Shi, H. Li, P. Vansteenwegen, Joint optimization of train platforming and shunting with service scheduling at a railway hub, Computers & Industrial Engineering 197 (2024) 110544. doi:10.1016/j.cie.2024.110544.

[4] R. van den Broek, H. Hoogeveen, M. van den Akker, Personnel Scheduling on Railway Yards, in: D. Huisman, C. D. Zaroliagis (Eds.), 20th Symposium on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS 2020), volume 85 of *Open Access Series in Informatics (OASIcs)*, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl, Germany, 2020, pp. 12:1–12:15. doi:10.4230/OASIcs.ATMOS.2020.12.

[5] R. van Lieshout, J. van den Akker, R. Mendes Borges, T. Druijf, E. Quaglietta, Microscopic simulation of decentralized dispatching strategies in railways, Journal of Rail Transport Planning & Management 23 (2022) 100335. doi:10.1016/j.jrtpm.2022.100335.

[6] T. Dewilde, P. Sels, D. Cattrysse, P. Vansteenwegen, Robust railway station planning: An interaction between routing, timetabling and platforming, Journal of Rail Transport Planning & Management 3 (2013) 68–77. doi:10.1016/j.jrtpm.2013.11.002, robust Rescheduling and Capacity Use.

[7] R. M. Lentink, P.-J. Fioole, L. G. Kroon, C. van't Woudt, Applying operations research techniques to planning of train shunting, Planning in Intelligent Systems: Aspects, Motivations, and Methods (2006) 415–436.

[8] P. Thorlacius, J. Larsen, M. Laumanns, An integrated rolling stock planning model for the copenhagen suburban passenger railway, Journal of Rail Transport Planning & Management 5 (2015) 240–262. doi:10.1016/j.jrtpm.2015.11.001.

[9] A. D'Ariano, M. Pranzo, An advanced real-time train dispatching system for minimizing the propagation of delays in a dispatching area under severe disturbances, Networks and Spatial Economics 9 (2009) 63–84. doi:10.1007/s11067-008-9088-1.

[10] P. J. Zwaneveld, L. G. Kroon, H. E. Romeijn, M. Salomon, S. Dauzère-Pérès, S. P. van Hoessel, H. W. Ambergen, Routing trains through railway stations: Model formulation and algorithms, Transportation Science 30 (1996) 181–194. doi:10.1287/trsc.30.3.181.

[11] R. M. Lusby, J. Larsen, M. Ehrgott, D. M. Ryan, A set packing inspired method for real-time junction train routing, Computers & Operations Research 40 (2013) 713–724. doi:10.1016/j.cor.2011.12.004, transport Scheduling.

[12] M. Carey, S. Carville, Testing schedule performance and reliability for train stations, The Journal of the Operational Research Society 51 (2000) 666–682. doi:10.2307/254010.

[13] V. Cacchiani, D. Huisman, M. Kidd, L. Kroon, P. Toth, L. Veelenturf, J. Wagenaar, An overview of recovery models and algorithms for real-time railway rescheduling, Transportation Research Part B: Methodological 63 (2014) 15–37. doi:10.1016/j.trb.2014.01.009.

[14] F. Kamenga, Combinatorial optimization for integrating rolling stock management and railway track scheduling in passenger stations, phdthesis, l'Université de Lille, 2020. arXiv:https://theses.hal.science/tel-03169424/.

[15] M. He, Q. Tang, J. N. D. Gupta, D. Yin, Z. Zhang, The shunting scheduling of emu first-level maintenance in a stub-end depot, Flexible Services and Manufacturing Journal 35 (2023) 754–796. doi:10.1007/s10696-022-09459-6.

[16] I. K. Hanou, D. W. Thomas, W. Ruml, M. de Weerdt, Replanning in advance for instant delay recovery in multi-agent applications: Rerouting trains in a railway hub, Proceedings of the International Conference on Automated Planning and Scheduling 34 (2024) 258–266. doi:10.1609/icaps.v34i1.31483.

[17] B. Yan, L. Huang, C. Wan, S. Qu, X. Fan, X. Zou, Stochastic multi-objective optimization for dynamic timetable and track allocation at high-speed railway hubs, International Journal of Transportation Science and Technology (2025). doi:10.1016/j.ijtst.2025.02.011.

[18] P. Pellegrini, G. Marliere, R. Pesenti, J. Rodriguez, Recife-milp: An effective milp-based heuristic for the real-time railway traffic management problem, IEEE Transactions on Intelligent Transportation Systems 16 (2015) 2609–2619. doi:10.1109/tits.2015.2414294.

[19] V. Cacchiani, F. Furini, M. P. Kidd, Approaches to a real-world train timetabling problem in a railway node, Omega 58 (2016) 97–110. doi:10.1016/j.omega.2015.04.006.

[20] L. Wang, X. Zhu, Z. Xie, Modeling and analyzing of railway container hub scheduling system based on multi-agent system, Journal of System and Management Sciences 2 (2012) 31–39. doi:10.1007/978-3-642-32054-5_71.

[21] F. Corman, A. D'Ariano, Assessment of advanced dispatching measures for recovering disrupted railway traffic situations, Transportation Research Record 2289 (2012) 1–9. doi:10.3141/2289-01.

[22] F. Corman, R. M. P. Goverde, A. D'Ariano, Rescheduling Dense Train Traffic over Complex Station Interlocking Areas, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 369–386. doi:10.1007/978-3-642-05465-5_16.

[23] B. Su, F. Wang, S. Su, Z. Wang, T. Tang, A two-step optimization framework for real-time train rescheduling in an urban rail transit line, IEEE Transactions on Intelligent Transportation Systems 26 (2025) 9065–9079. doi:10.1109/TITS.2025.3541275.

[24] G. Theeg, S. Vlasenko, Railway Signaling and Interlocking, 3rd ed., PMC Media House GmbH, 2020. Eurail Press.

[25] P. Liu, B. Han, Optimizing the train timetable with consideration of different kinds of headway time, Journal of Algorithms & Computational Technology 11 (2017) 148–162. doi:10.1177/1748301816689685.

[26] R. van den Broek, H. Hoogeveen, M. van den Akker, B. Huisman, A local search algorithm for train unit shunting with service scheduling, Transportation Science 56 (2021) 141–161. doi:10.1287/trsc.2021.1090.

[27] R. Freling, R. M. Lentink, L. G. Kroon, D. Huisman, Shunting of passenger train units in a railway station, Transportation Science 39 (2005) 261–272. doi:10.1287/trsc.1030.0076.

[28] I. K. Hanou, M. M. de Weerdt, J. Mulderij, Moving trains like pebbles: A feasibility study on tree yards, in: Proceedings of the International Conference on Automated Planning and Scheduling, volume 33 of *Industry and Applications Track*, 2023, pp. 482–490. URL: 10.1609/icaps.v33i1.27228.

[29] S. Dauzère-Pérès, J. Ding, L. Shen, K. Tamssaouet, The flexible job shop scheduling problem: A review, European Journal of Operational Research 314 (2024) 409–432. doi:10.1016/j.ejor.2023.05.017.

[30] C. Goodman, R. Takagi, Dynamic re-scheduling of trains after disruption, Advances in Transport 15 (2004) 765–774.

[31] S. Cicerone, G. D'Angelo, G. Di Stefano, D. Frigioni, A. Navarra, M. Schachtebeck, A. Schöbel, Recoverable Robustness in Shunting and Timetabling, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 28–60. doi:10.1007/978-3-642-05465-5_2.

[32] I. Hansen, Railway network timetabling and dynamic traffic management, 2nd International Conference on Recent Advances in Railway Engineering, ICRARE-2009, Tehran, I.R. Iran, Sept. 27-28, 2009 8 (2010).

[33] F. Corman, L. Meng, A review of online dynamic models and algorithms for railway traffic control, in: 2013 IEEE International Conference on Intelligent Rail Transportation Proceedings, 2013, pp. 128–133. doi:10.1109/ICIRT.2013.6696281.

[34] X. Dai, H. Zhao, S. Yu, D. Cui, Q. Zhang, H. Dong, T. Chai, Dynamic scheduling, operation control and their integration in high-speed railways: A review of recent research, IEEE Transactions on Intelligent Transportation Systems 23 (2022) 13994–14010. doi:10.1109/TITS.2021.3131202.

[35] L. Lamorgese, C. Mannino, D. Pacciarelli, J. T. Krasemann, Train Dispatching, Springer International Publishing, Cham, 2018, pp. 265–283. doi:10.1007/978-3-319-72153-8_12.

[36] N. D. Versluis, E. Quaglietta, R. M. Goverde, P. Pellegrini, J. Rodriguez, Real-time railway traffic management under moving-block signalling: A literature review and research agenda, Transportation Research Part C: Emerging Technologies 158 (2024) 104438. doi:10.1016/j.trc.2023.104438.

[37] S. Zhan, J. Xie, S. Wong, Y. Zhu, F. Corman, Handling uncertainty in train timetable rescheduling: A review of the literature and future research directions, Transportation Research Part E: Logistics and Transportation Review 183 (2024) 103429. doi:10.1016/j.tre.2024.103429.

[38] C. Wen, P. Huang, Z. Li, J. Lessan, L. Fu, C. Jiang, X. Xu, Train dispatching management with data- driven approaches: A comprehensive review and appraisal, IEEE Access 7 (2019) 114547–114571. doi:10.1109/ACCESS.2019.2935106.

[39] N. Bešinović, Resilience in railway transport systems: a literature review and research agenda, Transport Reviews 40 (2020) 457–478. doi:10.1080/01441647.2020.1728419.

[40] R. M. Lusby, J. Larsen, S. Bull, A survey on robustness in railway planning, European Journal of Operational Research 266 (2018) 1–15. doi:10.1016/j.ejor.2017.07.044.

[41] F. Kamenga, P. Pellegrini, J. Rodriguez, B. Merabet, Solution algorithms for the generalized train unit shunting problem, EURO Journal on Transportation and Logistics 10 (2021) 100042. doi:10.1016/j.ejtl.2021.100042.

[42] B. Zhang, Y. Zhang, A. D'Ariano, T. Bosi, G. Lu, Q. Peng, Optimal platforming, routing, and scheduling of trains and locomotives in a rail passenger station yard, Transportation Research Part C: Emerging Technologies 152 (2023) 104160. doi:10.1016/j.trc.2023.104160.

[43] E. Dahlhaus, P. Horak, M. Miller, J. Ryan, The train marshalling problem, in: Discrete Applied Mathematics, volume 103, 2000, pp. 41–45. doi:10.1016/S0166-218X(99)00219-X.

[44] N. Bešinović, R. M. Goverde, Stable and robust train routing in station areas with balanced infrastructure capacity occupation, Public Transport 11 (2019) 211–236.

[45] A. Caprara, L. Galli, L. Kroon, G. Maróti, P. Toth, Robust Train Routing and Online Re-scheduling, in: T. Erlebach, M. Lübbecke (Eds.), 10th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS'10), volume 14 of *Open Access Series in Informatics (OASIcs)*, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl, Germany, 2010, pp. 24–33. doi:10.4230/OASIcs.ATMOS.2010.24.

[46] A. Caprara, L. Galli, S. Stiller, P. Toth, Delay-robust event scheduling, Operations Research 62 (2014) 274–283. doi:10.1287/opre.2014.1259.

[47] T. Dewilde, P. Sels, D. Cattrysse, P. Vansteenwegen, Improving the robustness in railway station areas, European Journal of Operational Research 235 (2014) 276–286. doi:10.1016/j.ejor.2013.10.062.

[48] C. Liebchen, M. Lübbecke, R. Möhring, S. Stiller, The Concept of Recoverable Robustness, Linear Programming Recovery, and Railway Applications, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 1–27. doi:10.1007/978-3-642-05465-5_1.

[49] Q. Zeng, Y. Zhang, H. Su, R. Hu, Robustness-oriented optimization of train platforming problem in busy complex railway station, Mathematical Problems in Engineering 2022 (2022) 5922653. doi:10.1155/2022/5922653.

[50] B. Gilg, T. Klug, R. Martienssen, J. Paat, T. Schlechte, C. Schulz, S. Seymen, A. Tesch, Conflict-free railway track assignment at depots, Journal of Rail Transport Planning & Management 8 (2018) 16–28. doi:10.1016/j.jrtpm.2017.12.004.

[51] E. Peer, V. Menkovski, Y. Zhang, W.-J. Lee, Shunting trains with deep reinforcement learning, in: 2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC), 2018, pp. 3063–3068. doi:10.1109/SMC.2018.00520.

[52] R. van den Broek, H. Hoogeveen, M. van den Akker, How to Measure the Robustness of Shunting Plans, in: R. Borndörfer, S. Storandt (Eds.), 18th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS 2018), volume 65 of *Open Access Series in Informatics (OASIcs)*, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl, Germany, 2018, pp. 3:1–3:13. doi:10.4230/OASIcs.ATMOS.2018.3.

[53] M. He, Q. Tang, J. N. Gupta, Z. Zhang, J. Cao, Robust scheduling of emu first-level maintenance in a stub-end depot under stochastic uncertainties, Engineering Applications of Artificial Intelligence 123 (2023) 106398. doi:10.1016/j.engappai.2023.106398.

[54] E. Quaglietta, F. Corman, R. M. Goverde, Stability analysis of railway dispatching plans in a stochastic and dynamic environment, Journal of Rail Transport Planning & Management 3 (2013) 137–149. doi:10.1016/j.jrtpm.2013.10.009.

[55] W. van den Broek, Roel, Train Shunting and Service Scheduling: an integrated local search approach, Msc thesis, Universiteit Utrecht, 2016.

[56] B. He, P. Chen, A. D'Ariano, L. Chen, H. Zhang, G. Lu, A microscopic agent-based simulation for real-time dispatching problem of a busy railway passenger station, in: 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), 2020, pp. 1–7. doi:10.1109/ITSC45102.2020.9294651.

[57] S. Ding, T. Zhang, Z. Yuan, Y. Sun, Q. Fu, P. Hu, Efficient multi-objective evolutionary algorithms for railway train platforming rescheduling under arrival delays, in: 2024 China Automation Congress (CAC), 2024, pp. 6076–6082. doi:10.1109/CAC63892.2024.10865226.

[58] R. García-Ródenas, M. L. López-García, L. Cadarso, E. Codina, An efficient greedy heuristic for the real-time train platforming problem, Computers & Operations Research 164 (2024) 106525. doi:10.1016/j.cor.2023.106525.

[59] G. Lu, J. Ning, X. Liu, Y. M. Nie, Train platforming and rescheduling with flexible interlocking mechanisms: An aggregate approach, Transportation Research Part E: Logistics and Transportation Review 159 (2022) 102622. doi:10.1016/j.tre.2022.102622.

[60] X. Meng, Y. Wang, W. Xiang, L. Jia, An integrated model for train rescheduling and station track assignment, IET Intelligent Transport Systems 15 (2021) 17–30. doi:10.1049/itr2.12001.

[61] B. Pascariu, M. Samà, P. Pellegrini, A. D'Ariano, J. Rodriguez, D. Pacciarelli, Performance evaluation of a parallel ant colony optimization for the real-time train routing selection problem in large instances, in: L. Pérez Cáceres, S. Verel (Eds.), Evolutionary Computation in Combinatorial Optimization, Springer International Publishing, Cham, 2022, pp. 46–61.

[62] J. Teng, J. Gao, P. Wang, S. Qu, Train rescheduling and platforming in large high-speed railway stations, International Journal of Transportation Science and Technology 16 (2024) 100–118. doi:10.1016/j.ijtst.2023.11.001.

[63] Q. Zeng, R. Hu, Y. Zhang, H. Su, Y. Liu, A genetic simulated annealing algorithm for real-time track reallocation in busy complex railway station, Mathematical Problems in Engineering 2022 (2022) 7706556. doi:10.1155/2022/7706556.

[64] M. Sugi, H. Nagai, M. Yamamoto, Y. Shiomi, J. Ota, Rescheduling of train shunting in railway stations, International Journal of Automation Technology 4 (2010). doi:10.20965/ijat.2010.p0495.

[65] J. Shi, H. Li, D. Wang, P. Vansteenwegen, Reschedule the shunting and service scheduling plan after disturbances at a chinese high-speed railway depot, IEEE Access 12 (2024) 38615–38630. doi:10.1109/ACCESS.2024.3368807.

[66] G. Caimi, M. Fuchsberger, M. Laumanns, M. Lüthi, A model predictive control approach for discrete-time rescheduling in complex central railway station areas, Computers & Operations Research 39 (2012) 2578–2593. doi:10.1016/j.cor.2012.01.003.

[67] F. Corman, A. D'Ariano, M. Pranzo, I. Hansen, Effectiveness of dynamic reordering and rerouting of trains in a complicated and densely occupied station area, Transportation Planning and Technology 34 (2011) 341–362. doi:10.1080/03081060.2011.577152.

[68] F. Corman, A. D'Ariano, D. Pacciarelli, M. Pranzo, A bilevel rescheduling framework for optimal inter-area train coordination, in: A. Caprara, S. Kontogiannis (Eds.), 11th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems, volume 20 of *Open Access Series in Informatics (OASIcs)*, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl, Germany, 2011, pp. 15–26. doi:10.4230/OASIcs.ATMOS.2011.15.

[69] F. Corman, A. D'Ariano, I. A. Hansen, D. Pacciarelli, Optimal multi-class rescheduling of railway traffic, Journal of Rail Transport Planning & Management 1 (2011) 14–24. doi:10.1016/j.jrtpm.2011.06.001, robust Modelling of Capacity, Delays and Rescheduling in Regional Networks.

[70] F. Corman, A. D'Ariano, D. Pacciarelli, M. Pranzo, Optimal inter-area coordination of train rescheduling decisions, Procedia - Social and Behavioral Sciences 17 (2011) 58–81. doi:10.1016/j.sbspro.2011.04.508, papers selected for the 19th International Symposium on Transportation and Traffic Theory.

[71] F. Corman, A. D'Ariano, D. Pacciarelli, M. Pranzo, Optimal inter-area coordination of train rescheduling decisions, Procedia - Social and Behavioral Sciences 17 (2011) 58–81. doi:10.1016/j.sbspro.2011.04.508, papers selected for the 19th International Symposium on Transportation and Traffic Theory.

[72] F. Corman, E. Quaglietta, R. M. P. Goverde, Automated real-time railway traffic control: an experimental analysis of reliability, resilience and robustness, Transportation Planning and Technology 41 (2018) 421–447. doi:10.1080/03081060.2018.1453916.

[73] A. D'Ariano, I. A. Hansen, R. Hemelrijk, Railway dynamic traffic management: Application of a train rescheduling system reducing delays, IFAC Proceedings Volumes 39 (2006) 337–342. doi:10.3182/20060829-3-NL-2908.00059, 11th IFAC Symposium on Control in Transportation Systems.

[74] A. D'Ariano, M. Pranzo, I. A. Hansen, Conflict resolution and train speed coordination for solving real-time timetable perturbations, IEEE Transactions on Intelligent Transportation Systems 8 (2007) 208–222. doi:10.1109/TITS.2006.888605.

[75] Z. HongTao, W. Tao, Z. Qi, A heuristic algorithm for dispatching policy based on vague set's evaluation and optimization, in: 2013 Fourth International Conference on Intelligent Control and Information Processing (ICICIP), 2013, pp. 19–24. doi:10.1109/ICICIP.2013.6568032.

[76] J. Liu, L. Chen, C. Roberts, G. Nicholson, B. Ai, Algorithm and peer-to-peer negotiation strategies for train dispatching problems in railway bottleneck sections, IET Intelligent Transport Systems 13 (2019) 1717–1725. doi:10.1049/iet-its.2019.0020.

[77] U. Martin, M. Tideman, W. Zhao, Generation of Dispatching Solutions in a Rolling Time Horizon Framework with the Aid of Tabu Search, volume 199, WIT Press, 2020, pp. 97–106. doi:10.2495/CR200091, wIT Transactions on The Built Environment.

[78] S. Mladenovic, S. Veskovic, I. Branovic, S. Jankovic, S. Acimovic, Heuristic based real-time train rescheduling system, Networks 67 (2016) 32–48. doi:10.1002/net.21625.

[79] P. Pellegrini, G. Marlière, J. Rodriguez, Real Time Railway Traffic Management Modeling Track-Circuits, in: D. Delling, L. Liberti (Eds.), 12th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems, volume 25 of *Open Access Series in Informatics (OASIcs)*, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl, Germany, 2012, pp. 23–34. doi:10.4230/OASIcs.ATMOS.2012.23.

[80] P. Pellegrini, G. Marlière, R. Pesenti, J. Rodriguez, A milp reformulation for train routing and scheduling in case of perturbation, in: A. Sforza, C. Sterle (Eds.), Optimization and Decision Science: Methodologies and Applications, Springer International Publishing, 2017, pp. 495–503. doi:10.1007/978-3-319-67308-0_50.

[81] M. Samà, A. D'Ariano, D. Pacciarelli, P. Pellegrini, J. Rodriguez, Applications of train routing selection methods for real-time railway traffic management, in: 2018 21st International Conference on Intelligent Transportation Systems (ITSC), 2018, pp. 72–77. doi:10.1109/ITSC.2018.8569555.

[82] B. Sharma, B. Pascariu, P. Pellegrini, J. Rodriguez, N. Chaudhary, A real-time railway traffic management approach preserving passenger connections, IEEE Access 12 (2024) 79066–79081. doi:10.1109/ACCESS.2024.3409183.

[83] S. Wegele, F. Corman, A. D'Ariano, Comparing the effectiveness of two real-time train rescheduling systems in case of perturbed traffic conditions, WIT Transactions on The Built Environment 103 (2008) 535–544.

[84] X. Yi, G. Marlière, P. Pellegrini, J. Rodriguez, R. Pesenti, Coordinated train rerouting and rescheduling in large infrastructures, Transportation Research Procedia 72 (2023) 319–326. doi:10.1016/j.trpro.2023.11.410, tRA Lisbon 2022 Conference Proceedings Transport Research Arena (TRA Lisbon 2022),14th-17th November 2022, Lisboa, Portugal.

[85] Y. Zhu, H. Wang, R. M. Goverde, Reinforcement learning in railway timetable rescheduling, in: 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), 2020, pp. 1–6. doi:10.1109/ITSC45102.2020.9294188.

[86] F. Corman, A. D'Ariano, D. Pacciarelli, M. Pranzo, A tabu search algorithm for rerouting trains during rail operations, Transportation Research Part B: Methodological 44 (2010) 175–192. doi:10.1016/j.trb.2009.05.004.

[87] F. Corman, A. D'Ariano, D. Pacciarelli, M. Pranzo, Centralized versus distributed systems to reschedule trains in two dispatching areas, Public Transport 2 (2010) 219–247. doi:10.1007/s12469-010-0032-7.

[88] F. Corman, A. D'Ariano, I. A. Hansen, D. Pacciarelli, M. Pranzo, Dispatching trains during seriously disrupted traffic situations, in: 2011 International Conference on Networking, Sensing and Control, 2011, pp. 323–328. doi:10.1109/ICNSC.2011.5874901.

[89] F. Corman, A. D'Ariano, D. Pacciarelli, M. Pranzo, Dispatching and coordination in multi-area railway traffic management, Computers & Operations Research 44 (2014) 146–160. doi:10.1016/j.cor.2013.11.011.

[90] X. Liu, M. Zhou, H. Dong, X. Wu, Y. Li, F.-Y. Wang, Admm-based joint rescheduling method for high-speed railway timetabling and platforming in case of uncertain perturbation, Transportation Research Part C: Emerging Technologies 152 (2023) 104150. doi:10.1016/j.trc.2023.104150.

[91] Z. Liao, Rescheduling out-of-gauge trains with speed restrictions and temporal blockades on the opposite-direction track, Mathematics 11 (2023). doi:10.3390/math11122659.

[92] P. Vansteenwegen, T. Dewilde, S. Burggraeve, D. Cattrysse, An iterative approach for reducing the impact of infrastructure maintenance on the performance of railway systems, European Journal of Operational Research 252 (2016) 39–53. doi:10.1016/j.ejor.2015.12.037.

[93] J. H. Zhu, T. Dollevoet, D. Huisman, An exact and heuristic framework for rolling stock rescheduling with railway infrastructure availability constraints, Transportation Research Part B: Methodological 195 (2025) 103189. doi:10.1016/j.trb.2025.103189.

[94] J. Pachl, Railway signalling principles, Technische Universität Braunschweig (2020) 1–83.

Appendix A. Complete Table

Table A.7 categorizes all papers according to the main problem they solve, and whether it addresses robustness (Robus) or recovery (Recov). Then, for each cited paper, we report the

1. RHP operations (Definition 3.2) that are addressed, these are abbreviated Operation(s): Parking (P), Platform Allocation (Pl), Routing (R), Matching (M), Servicing Tasks (ST), Yard Personnel (YP), and Signal Constraints (SC),
2. the solution Method(s) used (Table 4), abbreviated: State-based (State), Simulation (Sim), Mathematical Optimization (OR), Alternative Graph (AG), Meta-heuristic (Meta), Evolutionary (Evo),
3. whether the approach combines (Comb) operations planning integrally (Int) or handles them sequentially (Seq),
4. the resilience scale (disturbance (Turb) or disruption (Rupt) and the type (e.g., delay or resource dependency) considered: Track Unavailable (TU), Temporal Delays (TD), Block Section Unavailable (BSU), Other Resource Dependency (ORD),
5. the type of signaling constraint (Signal) accounted for: Macroscopic headway (MacH), Microscopic route-based (MicR), Microscopic signal-based (MicS), and signal-free areas (NoS),
6. the planning horizon (Hor), how much time is planned for,
7. the abstraction (Abstr) level, whether it is simplified (Simpl) or realistic (Real), and
8. the runtime (Time), whether it is fast enough to provide solutions in practice (Real) or infeasible (Infeas).

Table A.7: Complete results for all 57 papers included in this survey.

Problem	Type	Paper	Operation	Method	Comb	Delays	Signal	Hor	Time
RHP	Recov	Hanou et al. [16]	R, SC	State	Seq	Both (TD)	Mic	Hours	Real
RHP	Recov	He et al. [56]	R, P	State, Sim	Int	Turb (TD)	Mac	Day	Real
TRPP	Recov	Ding et al. [57]	R, Pl	Evo	Int	Turb (TD)	Mac	Day	Real
TRPP	Recov	García-Ródenas et al. [58]	Pl, R	OR	Int	Turb (TD)	Mic	Hours	Real
TRPP	Recov	Lu et al. [59]	Pl, SC, R	OR	Int	Both (TD)	Mic	Hours	Real
TRPP	Recov	Meng et al. [60]	R, Pl	Meta	Int	Rupt (TD)	Mac	Hours	Infeas
TRPP	Recov	Pascariu et al. [61]	R, SC	Meta	Int	Turb (TD)	Mic	Hours	Real
TRPP	Recov	Teng et al. [62]	Pl, R	OR	Seq	Turb (TD)	Mic	Day	Infeas
TRPP	Recov	Zeng et al. [63]	Pl	Evo, OR	Seq	Both (TU)	Mac	Hours	Real
TRPP	Robus	Bešinović and Goverde [44]	R, Pl	Meta	Int	Turb (TD)	Mic	Hours	Real

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Table A.7: Complete results for all 57 papers included in this survey.

Problem	**Type**	**Paper**	**Operation**	**Method**	**Comb**	**Delays**	**Signal**	**Hor**	**Time**
TRPP	Robus	Caprara et al. [45]	R, Pl	OR	Int	Turb (TD)	Mac	Day	Real
TRPP	Robus	Caprara et al. [46]	R, Pl	OR	Int	Turb (TD)	Mac	Hours	Real
TRPP	Robus	Dewilde et al. [6]	R, Pl	Meta, OR	Seq	Turb (TD)	Mac	Hours	Infeas
TRPP	Robus	Dewilde et al. [47]	R	OR	Int	Turb (TD)	Mac	Hours	Real
TRPP	Robus	Liebchen et al. [48]	R, Pl	OR	Int	Turb (TD)	Mac	Hours	Real
TRPP	Robus	Yan et al. [17]	Pl	OR	Int	Turb (TD)	Mac	Hours	Infeas
TRPP	Robus	Zeng et al. [49]	Pl, R	Meta	Seq	Turb (TD)	Mic	Day	Real
TUSP	Recov	Sugi et al. [64]	P, R	Other	Int	Both (TU)	Mac	Hours	Real
TUSP	Robus	Gilg et al. [50]	P	OR	Int	Turb (TD)	Mic	Week	Infeas
TUSP	Robus	Peer et al. [51]	P, R, M	State	Seq	Turb (TD)	NoS	Hours	Infeas
TUSPwSS	Recov	Shi et al. [65]	ST, R, M	OR	Int	Rupt (TD)	NoS	Day	Real
TUSPwSS	Robus	van den Broek et al. [52]	ST, P, M, R	Meta	Int	Turb (TD)	NoS	Hours	Infeas
TUSPwSS	Robus	He et al. [53]	R, P, ST	Meta, OR	Int	Turb (TD)	Mic	Day	Infeas
TUSPwSPS	Robus	van den Broek et al. [4]	YP	OR	Int	Turb (TD)	NoS	Hours	Real
RTM	Recov	Caimi et al. [66]	SC, R, Pl	OR	Int	Turb (TD)	Mic	Day	Real
RTM	Recov	Corman et al. [22]	SC	AG	Seq	Turb (TD)	Mic	Hours	Real
RTM	Recov	Corman et al. [86]	R	AG, Meta	Int	Rupt (TU)	Mic	Hours	Real
RTM	Recov	Corman et al. [87]	R, SC	AG	Int	Both (TU)	Mic	Hours	Real
RTM	Recov	Corman et al. [67]	R, SC	AG	Int	Rupt (TD)	Mic	Hours	Real
RTM	Recov	Corman et al. [68]	SC	AG	Int	Turb (TD)	Mic	Hours	Real
RTM	Recov	Corman et al. [88]	R, SC	AG	Int	Both (TU)	Mic	Hours	Real
RTM	Recov	Corman et al. [69]	R	AG, OR	Seq	Turb (TD)	Mic	Hours	Real
RTM	Recov	Corman et al. [70]	R, SC	AG	Seq	Turb (TD)	Mic	Hours	Real
RTM	Recov	Corman et al. [71]	SC	AG	Seq	Both (TD)	Mic	Hours	Real
RTM	Recov	Corman and D'Ariano [21]	R, SC	AG, OR	Seq	Both (TU)	Mic	Hours	Real
RTM	Recov	Corman et al. [89]	R, SC	AG, Meta	Int	Rupt (TU)	Mic	Hours	Real

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Table A.7: Complete results for all 57 papers included in this survey.

Problem	Type	Paper	Operation	Method	Comb	Delays	Signal	Hor	Time
RTM	Recov	Corman et al. [72]	SC	Meta, Sim	Seq	Turb (TD)	Mic	Hours	Real
RTM	Recov	D'Ariano et al. [73]	R, SC	AG	Seq	Turb (TD)	Mic	Hours	Real
RTM	Recov	D'Ariano et al. [74]	SC, R	AG, Meta	Int	Turb (TD)	Mic	Hours	Real
RTM	Recov	HongTao et al. [75]	SC	Meta	Seq	Turb (TD)	Mac	Hours	Real
RTM	Recov	Liao [91]	Pl, R	OR	Seq	Both (ORD)	Mac	Hours	Infeas
RTM	Recov	Liu et al. [76]	R, SC	Evo	Int	Turb (TD)	Mic	Hours	Real
RTM	Recov	Liu et al. [90]	Pl, R	OR	Int	Both (TU)	Mac	Hours	Real
RTM	Recov	Lusby et al. [11]	R	OR	Int	Both (TD)	Mac	Hours	Real
RTM	Recov	Martin et al. [77]	SC	Meta	Seq	Turb (TD)	Mic	Hours	Infeas
RTM	Recov	Mladenovic et al. [78]	SC	Meta	Int	Turb (TD)	Mic	Hours	Real
RTM	Recov	Pellegrini et al. [79]	R, SC	OR	Int	Turb (TD)	Mac	Hours	Real
RTM	Recov	Pellegrini et al. [80]	R	OR	Int	Turb (TD)	Mic	Hours	Real
RTM	Recov	Samà et al. [81]	R, SC	AG, Meta, OR	Int	Turb (TD)	Mic	Hours	Real
RTM	Recov	Sharma et al. [82]	R, SC	Meta, OR	Int	Turb (TD)	Mic	Hours	Real
RTM	Recov	Vansteenwegen et al. [92]	R, SC	OR	Seq	Both (ORD)	Mac	Hours	Real
RTM	Recov	Wegele et al. [83]	R, SC	AG, Evo	Int	Turb (TD)	Mic	Hours	Infeas
RTM	Recov	Yi et al. [84]	R, SC	OR	Int	Turb (TD)	Mic	Day	Real
RTM	Recov	Zhu et al. [85]	SC	State	Seq	Turb (TD)	Mic	Hours	Real
RTM	Robus	Quaglietta et al. [54]	R, SC, Pl	Sim	Int	Turb (TD)	Mic	Hours	Real
RSPH	Recov	van Lieshout et al. [5]	YP, M	Sim	Int	Both (ORD)	Mic	Hours	Real
RSPH	Recov	Zhu et al. [93]	M, R, P, Pl	OR	Int	Both (TU)	Mac	Hours	Real