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Railway Rescheduling Under Near-Operational Disruptions

Liyun Yu

LINKÖPING UNIVERSITY

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Department of Science and Technology
Linköping University, SE-601 74 Norrköping, Sweden

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Linköping University
Department of Science and Technology
SE-601 74 Norrköping

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Abstract

Railway is an environmentally sustainable mode of transportation, which offers convenience for passengers and provides a cost-effective and efficient solution for the movement of goods. However, railway transportation also has drawbacks, especially disruptions due to some incidents, which are difficult to accurately predict and prevent. Infrastructure failure, extreme weather, human error, and lack of staff are typical examples of such incidents. The disruptions cause different levels of train delays and even cancellations. Frequent delays and cancellations make the railway less competitive with other modes of transport. As a result, it is crucial to investigate the possible strategies for rapidly restoring railway traffic after disruptions. In this thesis, we focus on railway rescheduling after near-operational disruptions. We aim to achieve acceptable results within a short time and a small computational effort. This thesis introduces some fundamental concepts related to railway rescheduling, outlines the motivation and research questions of this thesis, discusses further concepts of railway rescheduling including timetable, rolling stock, and crew rescheduling, and displays the relevant methods used for rescheduling. In this thesis, we propose approaches for near-operational rescheduling of the timetable and crew schedules.

In Paper I, we focus on the problem of timetable rescheduling, which is the first step of railway rescheduling. We draw an overall picture of timetable rescheduling for freight trains including its different restrictions. The methodology involves an optimization model, which is aimed to be a baseline model of timetable rescheduling in substitute all this when a group of freight trains must be postponed due to an unexpected marshalling-yard closure and can be compared with other heuristic approaches in the future under similar scenarios.

Crew rescheduling is the last step of railway rescheduling. We discuss this problem in Papers II and III. The purpose of Paper II is to investigate the possibility of reducing the computational time for solving short-term crew rescheduling problems. We introduced a tabu-search-based approach and compared the results along with its computational time and space with a column-generation approach, which is a common method for crew rescheduling. The results show that our tabu-search-based approach can achieve similar results with significantly less computational time and space compared to the column-generation approach. In Paper III, we extend our tabu-search-based approach

from Paper II with more flexible options for what can be assigned to a crew member. By doing that, we significantly improved the assignment rate for the operating tasks. The results show that our tabu-search-based approach has a high potential to be applied in real-world scenarios.

Populärvetenskaplig sammanfattning

Järnväg är ett miljövänligt och hållbart transportsätt som erbjuder bekvämlighet för passagerare och en kostnadseffektiv samt effektiv lösning för godstransporter. Dock medför järnvägstransporter även utmaningar, särskilt i form av störningar till följd av händelser som är svåra att exakt förutse och förebygga. Exempel på sådana händelser inkluderar infrastrukturfel, extrema väderförhållanden, mänskliga misstag och personalbrist. Dessa störningar leder till olika nivåer av tågförseningar och till och med till inställda avgångar. Frekventa förseningar och inställda tåg minskar järnvägens konkurrenskraft i förhållande till andra transportsätt. Därför är det av stor vikt att strategier för att snabbt skapa återställa järnvägstrafiken efter störningar. Denna avhandling fokuserar på omplanering efter driftstörningar med målsättningen att uppnå acceptabla resultat inom kort tid och med begränsad beräkningskapacitet. Avhandlingen introducerar grundläggande koncept relaterade till omplanering inom järnvägen diskuterar viktiga delar såsom tidtabells-, fordons- och personalomplanering, samt presenterar relevanta metoder. Vidare föreslås metoder för omplanering av både tidtabeller och personalplanering vid driftstörningar nära realtid.

I Paper I behandlas problemet med tidtabellsomplanering, vilket är det första steget i omplaneringen. En övergripande bild ges av tidtabellsomplanering för godståg, inklusive dess olika begränsningar. Metodologin bygger på en optimeringsmodell som utgör en basmodell för tidtabellsomplanering när en grupp godståg måste försenas på grund av en oväntad stängning av en rangerbangård. Modellen kan i framtida studier jämföras med heuristiska metoder för liknande scenarier.

Personalomplanering utgör det sista steget i omplaneringen och behandlas i Paper II och III. Syftet med Paper II är att minska beräkningstiden för att lösa kortsiktiga personalomplaneringsproblem. En tabu-sökningsbaserad metod presenteras och dess resultat, beräkningstid och resursförbrukning jämförs med en kolumngenereringsmetod, som är en vanlig metod för personalomplanering. Resultaten visar att den tabu-sökningsbaserade metoden kan uppnå likvärdiga resultat med avsevärt kortare beräkningstid och mindre resursförbrukning än kolumngenereringsmetoden. I Paper III vidareutvecklas den tabu-sökningsbaserade metoden från Paper II genom att inkludera mer flexibla alternativ för hur arbetsuppgifter kan tilldelas personal.

Därigenom kan antalet icke bemannade arbetsuppgifts minskas avsevärt. Resultaten visar att den tabu-sökningsbaserade metoden har stor potential att tillämpas i verkliga scenarier.

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Finally, I would like to express my heartfelt thanks to all my friends and family, especially my grandmother Yayun Yang (杨雅云), for your love, encouragement, and support. Special thanks to Jonathan Lundgren, who always believed me when I doubted myself. Also, much love to our cat, Lulu. \(ˆ∀ˆ)/

Norrköping, 2025
Liyun Yu (俞李韵)

List of Publications

In this thesis, "Railway Rescheduling Under Near-Operational Disruptions", we introduce the overall railway background, discuss the relevant methodology, and summarize the three papers as the contributions. The following listed papers are the contributions of this thesis:

- Paper I: Häll, C.H., Peterson, A., Schmidt, C. & Yu, L., 2024. A Mixed-Integer-Linear-Programming Model for Rescheduling Freight Trains under an Unexpected Marshalling-Yard Closure, in *Ingegneria Ferroviaria*, (6), pp.463-482.

- Paper II: Yu, L., Häll, C.H., Peterson, A. & Schmidt, C., 2025. A Time-and Space-Efficient Heuristic Approach for Late Train-Crew Rescheduling, Submitted for journal publication.

- Paper III: Yu, L., Häll, C.H., Peterson, A. & Schmidt, C., 2025. Short-Term Crew Rescheduling: Extending the Scheduling Options in a Tabu-Search-Based Approach, in *11th International Conference on Railway Operations Modelling and Analysis.*

The authors' contributions to all three papers are listed as follows:

- **Yu, L.**: Literature review, conceptualization, modeling, implementation, visualization, and writing.
- **Peterson, A.**: Problem idea, conceptualization, supervision, modeling, reviewing, and editing.
- **Schmidt, C.**: Problem idea, conceptualization, supervision, modeling, reviewing, and editing.
- **Häll, C.H.**: Problem idea, conceptualization, supervision, modeling, reviewing, and editing.

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Chapter 1

Introduction

RAILWAY plays an important role in transportation, ensuring the efficient movement of both passengers and goods on both short-distance and long-distance trips. It is a mode of transportation that offers a cost-effective and environmentally friendly alternative to road and air transport at regional, national, and even international levels. However, the railway operation is very complicated, especially, for heterogeneous trains, which run at different speeds and have varying stopping patterns. Severe delays can easily spread in the railway system and are usually caused by operational changes and disruptions.

Although some patterns of common disruptions are easy to spot, it is still difficult to predict exactly when and where the disruptions will occur. Most of the disruptions are near-operational and have various causes, including infrastructure failure, extreme weather, staff shortage, and so on. These disruptions can lead to significant delays, congestion, and even cancellations. As a result, overall network performance is impacted, and public trust in the railway system's reliability declines. In this thesis, we explore the methods for railway rescheduling to tackle problems caused by near-operational disruptions.

1.1 Near-Operational Disruptions

Usually, disruptions can be distinguished into two groups, including minor disturbances and major disruptions, depending on how severe the consequences are to the railway system. Minor disturbances are caused by minor delays in some trains and can be solved by handling some operational deviations. Major disruptions are the ones that cause severe delays and the need for rescheduling timetables, rolling stock, and staff. The near-operational disruptions that we consider are a common type of major disruption. In this thesis, we focus on near-operational disruptions that occur within a relatively short timeframe, typically within a day or less, before or during railway operations.

Near-operational disruptions can arise from various causes, including infrastructure failures, nature-related accidents, rolling-stock issues, and human-related factors. Infrastructure failures affect railway assets such as signals, tracks, overhead wires, power systems, and so on. The nature-related accidents can be caused by extreme weather events such as wildfires, flooding, heavy snow, and others. They can also result from other natural occurrences, such as landslides. Rolling-stock issues primarily include the technical failures of rolling stock and accidents related to trains, for example, derailments. Human-related factors include incidents involving the public, such as trespassing, as well as issues with crew members, such as the shortage of train drivers. On the opposite, a non-near-operational disruption example could be pre-scheduled maintenance. The difference between near-operational disruptions and other major disruptions lies in the time point at which their existence becomes known. Near-operational disruptions arise close to the execution of the scheduled timetable and require quick responses to minimize their impact.

1.2 Motivation and Scope

Disruptions in railway operations occur occasionally worldwide due to various issues, often resulting in severe delays and cancellations. Sweden is one of many countries facing these challenges, which negatively affect railway reliability. As passengers, the reliability of different transportation modes plays a key role in our choice of travel. Thus, enhancing reliability is essential to encourage more passengers to choose this environmentally friendly mode of transportation. One key aspect is improving the ability of railway operators to manage near-operational disruptions effectively. The work in this thesis has also been motivated by the current situation in Sweden (Nelldal, 2014).

In this thesis, we focus on railway rescheduling in the context of near-operational disruptions. The definition of near-operational disruptions can be found in Subchapter 1.1. Our work involves exploring various methods for railway rescheduling, examining their effectiveness from different perspectives, evaluating their strengths and limitations, and assessing the results.

1.3 Objectives and Research Questions

Near-operational disruptions occur close to the time of operation, leaving little room for proactive adjustments. The main goal of this thesis is to develop optimization models and approaches for efficiently rescheduling railways due to near-operational disruptions. There are four Research Questions (RQs) relating to the research purpose.

RQ1: How can we replan the schedules of trains and crew to deal with a near-operational disruption?
RQ2: What should be considered as the criteria of results being good enough?
RQ3: How can optimization models or other approaches solve the issues caused by near-operational disruption?
RQ4: How can approaches achieve good-enough results within an acceptable time?

1.4 Structure

The rest of this thesis is structured into four chapters. In Chapter 2, we introduce the concepts related to railway rescheduling and identify gaps by reviewing the existing literature. In Chapter 3, we outline the methodology related to our contributions. In Chapter 4, we present the summary of our included papers and our contributions to these papers. In Chapter 5, we conclude the thesis and discuss the directions of future research. After the bibliography, we present the papers included in this thesis.

Chapter 2

Railway Rescheduling

In Figure 2.1, we display the railway planning process. The strategic level involves network planning and line planning, where the overall railway structure and traveling routes of trains are designed. At the tactical level, the railway timetables, rolling-stock schedules, and crew schedules are finalized. Once these schedules are established, they can be adjusted through the rescheduling process to cope with disruptions and operational changes.

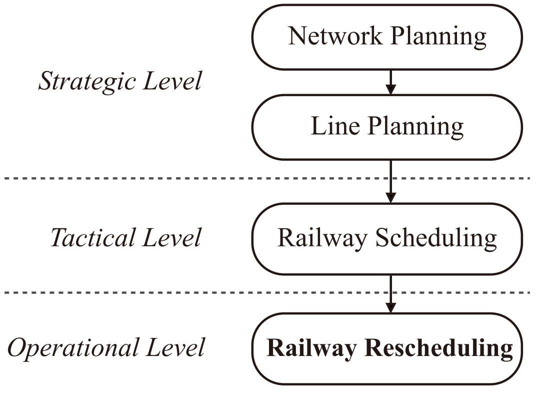

Figure 2.1: Railway Planning Process (Lusby et al., 2011)

In this chapter, we introduce the railway rescheduling process in Subchapter 2.1. Then, we describe the restrictions and review the existing research on rescheduling timetables and crew schedules in Subchapters 2.2 and 2.3, respectively.

2.1 Railway Rescheduling Process

One of the primary reasons for railway rescheduling is the occurrence of near-operational disruptions. Railway rescheduling involves adjustments to the timetable, rolling-stock, and crew schedules. One common goal is to offer different solutions close to the original schedule.

Railway rescheduling is essential for maintaining the stability and reliability of the railway system. Frequent train cancellations and severe delays not only disrupt the passengers' trips but also cause negative effects on freight transportation. Moreover, several stakeholders are affected. One possible consequence is a negative reputation for the railway system. As a result, passengers might tend to seek alternatives, for example, cars and airplanes, to secure the stability of traveling.

To be able to further describe the steps in railway rescheduling, we define some related concepts of railway timetable, rolling-stock schedule, and crew schedule. A **railway timetable** is a schedule of trains and specifies the locations and associated times for each train. Typically, a railway timetable includes the following key elements:

- Geographic locations along the train path
- Departure time at a geographic location
- Arrival time at a geographic location

In the railway industry, rolling stock refers to locomotives, wagons, etc. A **rolling-stock schedule** outlines the allocation, movement, and maintenance of rolling stock with respect to time. A **crew schedule** is a plan for organizing the shifts of railway crews. In crew rescheduling, we typically consider crew members who have home stations but do not have a fixed place of work, for example, train drivers and conductors.

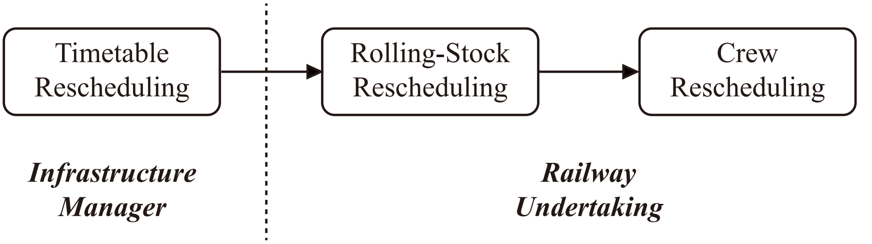

Figure 2.2: Rescheduling with stakeholders (Yu et al., 2025)

The process of railway rescheduling starts with timetable rescheduling, continues with the rolling-stock rescheduling, and ends with crew rescheduling. Figure 2.2 illustrates this sequential process, which must be coordinated and aligned to ensure the overall operational feasibility. In the step of rolling-stock rescheduling, we need to match the rolling-stock schedule with the updated railway timetable generated from timetable rescheduling. In crew rescheduling, we require the crews' schedule to be coordinated with both the updated timetable and rolling-stock schedule. Moreover, the process of rescheduling does not always start with timetable rescheduling. It can start from rolling-stock or crew rescheduling, depending on which schedule is affected by the disruption. In this thesis, we focus on timetable and crew rescheduling.

The **infrastructure manager** (IM) is responsible for the construction, maintenance, and operation of railway infrastructure, as well as the development of the timetable. **Railway undertakings** (RUs) are responsible for the transport services, including managing rolling stocks and crew members. In Sweden, there is only one IM, which is Trafikverket. Moreover, the railway market for RUs is deregulated in Sweden with examples including SJ, Mälartåg, and Snälltåget. In the process of railway rescheduling, the IM is responsible for timetable rescheduling, and the RUs reschedule the rolling stock and crews according to the updated railway timetable.

2.2 Timetabling Rescheduling

Near-operational disruptions create problems in the railway system and can result in significant delays. To prevent these delays from spreading across the network and affecting other lines, rescheduling the train timetable is essential in most cases.

Timetable rescheduling is the process of adjusting a railway timetable to deal with disruptions and operational changes. Cacchiani et al. (2014) pointed out that the components that can be changed include the trains' departure and arrival times at the stations, the routing of trains, and the order of trains on different tracks.

To reschedule the timetable, it is crucial to define the criteria for an acceptable revision. **Feasibility** is one important aspect while rescheduling timetables. Here, we outline some fundamental restrictions that must be taken into account while rescheduling to ensure a feasible timetable. These restrictions can be classified into capacity-related and time-related restrictions. Capacity-related restrictions involve the limited capacity of stations and track segments. One track can accommodate only one train at a time, making it essential to include this restriction during rescheduling. This applies to both segment and station capacity. Time-related restrictions include the restrictions on headway time and running speed. **Headway time** is the minimum time difference between two consecutive trains at one railway infrastructure, for example, stations and railway segments. Headway time involves both the technical headway time and the buffer time, where minimum buffer time is often considered according to the IM's policy. Restrictions related to headway time ensure a safe time gap between consecutive trains to prevent collisions. **Run time** refers to the duration that a train needs to cover the physical distance between two consecutive stations. Restrictions related to running speed limit the running time on railway tracks due to safety and efficiency.

In most studies, authors focus on passenger train rescheduling, considering primarily the perspectives of passengers and railway operators (Sharma et al., 2023; Leutwiler and Corman, 2023; Kang et al., 2024). A key reason for this prioritization is that passenger trains require higher punctuality to maintain reliable service (Binder et al., 2017), ensure smooth transfers (Zhu and Goverde, 2020; Hong et al., 2021), and meet passenger expectations (Zhu and Goverde, 2019; Zhan et al., 2021).

In contrast, freight trains are typically considered to have more flexibility in rescheduling, as delays of several hours generally do not significantly affect logistics and supply chains. Schneider and Nießen (2016) also pointed out that passenger dissatisfaction and economic losses due to delays make rescheduling more critical for passenger trains, whereas freight transport focuses more on cost optimization over strict operating based on schedules.

Freight trains have a higher tolerance towards delays to some degree compared to passenger trains. However, freight trains play a vital role in logistics and supply chain management. Bai et al. (2023) explored the freight train rescheduling problem, emphasizing both efficiency and equity by introducing dynamic priorities for freight trains during rescheduling. But, to the best of our knowledge, there are still very few studies on rescheduling freight trains under disruptions, let alone large-scale ones.

2.3 Crew Rescheduling

Due to disruptions, the schedule of crew members might become infeasible. In other words, some work in the original plan is uncovered because of the disruptions (Cacchiani et al., 2014). This is mainly because there are regulations to follow, for example, legal regulations and union agreements. Moreover, the crew members might not be located in the right place at the right time after disruptions.

Railway crew rescheduling is a process of reassigning operation-related work to different crew members (drivers, conductors, maintenance staff, and so on) in response to these operational changes (Potthoff et al., 2010). There are two levels of crew rescheduling: duty and roster levels. At the duty level, we reassign the tasks to duties that correspond to the crew members. A **task** is a basic element of the crew schedule. It mainly has five attributes: start time, end time, start location, end location, and activity. The attribute activity describes the work that needs to be completed in a task, including driving vehicles, operating maintenance, and so on. A **duty** consists of a sequence of tasks, which lasts up to one working day. A **roster** is a crew schedule covering a minimum of one week. It is composed of several duties assigned to different crew members. At the roster level, we can also reschedule the duties to change the crews' schedule for a longer time horizon.

Before digging into the methodology of crew rescheduling, we introduce one vital aspect of crew rescheduling, which is feasibility. **Feasibility** is an important indicator in judging whether crew rescheduling is executable at all. Other than the operational restrictions, e.g., each task/duty should be at least covered once, we further introduce basic regulations related to time, geographical location, and certificate for constructing a feasible schedule. The time-related regulations include avoiding time conflicts among the tasks assigned to one crew member, restricting working hours below the maximum limit, and ensuring rest time between duties. The regulations related to geographical location involve holding the geographical consistency between any consecutive tasks and fixing the crews' home depot as the start and end location of their duties. The certificate regulation limits that any task/duty assigned to a crew should fit the working certificate of the crew.

As the final step in railway rescheduling, for crew rescheduling, most researchers focus on disruptions that directly cause problems in railway timetables. Thus, they study scenarios where the modified railway timetable and rolling stock schedule are already rescheduled before adjusting the crew schedule (Potthoff, 2010). Since such disruptions often result in large-scale challenges, crew rescheduling typically focuses on those fundamental constraints to simplify the problem. Therefore, a gap exists in addressing near-operational crew rescheduling with more complex constraints on a smaller scale, and the core challenge to fill this gap is the computational time. Furthermore, there is also a gap in considering disruptions that only affect some of the crew members' schedules without making the timetable and rolling-stock schedule infeasible. Thus, we only need to reschedule crew members' schedules based on the original timetable and rolling-stock schedule.

To further identify the research gap, we discuss the existing methods for crew rescheduling. One classic method is to build mathematical models, and then solve them by commercial solvers (Cacchiani et al., 2014). The mathematical models are integer programming (IP) formulations, including formulations for set covering problems, set partitioning problems, and network flow problems (Heil et al., 2020). However, solving IP models by commercial solvers is not suitable for near-operational rescheduling due to the long computational times needed.

Column generation is a common option for replacing commercial solvers (Huisman, 2007; Potthoff et al., 2010; Dollevoet and Huisman, 2024). It is an optimization technique for solving large-scale IP problems efficiently. Desaulniers et al. (2006) mentioned that column generation consists of two main components. First, a restricted master problem (RMP) is solved by only including a limited set of variables. Second, a pricing problem (subproblem) identifies new variables that can enhance the solution and then those selected variables are added to the RMP, see the application of column generation on crew rescheduling in Breugem et al. (2022). However, Heil et al. (2020) mentioned that the computational time required for column generation can be significant due to problem size and slow convergence.

To further decrease the computational time, researchers have also incorporated heuristic approaches into this field. Verhaegh et al. (2017) pointed out that with heuristic approaches the computational time can be notably reduced, but the optimality of the results cannot be guaranteed. This is acceptable for rescheduling under near-operational disruptions, as reducing computational time to obtain a feasible schedule is more crucial than achieving optimal results. Depth-First Search

(DFS), as an exact method, is an algorithm that explores the tree as deep as possible before backtracking (Cormen et al., 2022). A variant of DFS, where the tree's growth is limited, is a heuristic method. See Verhaegh et al. (2017) and Yuan et al. (2022) as examples. A metaheuristic approach, which is Tabu Search (TS), has also been commonly used. Kokubo and Fukuyama (2017) adapted TS for crew rescheduling. We further introduce the concept of TS in Subchapter 3.2. The core idea of both TS and the variant of DFS is to try putting unassigned tasks back into the schedule with different rules and searching structures.

Chapter 3

Methods

METHODS used in our papers are presented in this chapter. In Subchapter 3.1, we introduce mathematical optimization models, including Integer Linear Programming (ILP) and Mixed Integer Linear Programming (MILP). In Subchapter 3.2, we give an overview of the solution approaches used in this thesis, with a focus on Column Generation and Tabu Search.

		Paper		
		I	**II**	**III**
Mathematical Optimization Model	**MILP**	✓		
	ILP		✓	
Exact Method	**Commercial Solver**	✓		
	Column Generation		✓	
Metaheuristic	**Tabu Search**		✓	✓

Table 3.1: Methods and Papers

In Table 3.1, we mark the methods for all papers correspondingly. In Paper I, we built a MILP model and solved it with a commercial solver. In Paper II, we introduced an approach based on Tabu Search. We also built an ILP model solved by Column Generation and compared it to the results from Tabu Search to show the results' quality and computing performance of Tabu Search. In Paper III, we used Tabu Search as our method.

3.1 Mathematical Optimization Models

A mathematical optimization model is a model that represents a real-world problem using mathematical formulations. The common components of a mathematical optimization model include variables, objective functions, and constraints. A Linear Programming (LP) problem is a type of problem that involves the mathematical optimization model with only linear objective functions, linear constraints, and continuous variables (Lundgren et al., 2010). Here, we present the mathematical optimization models utilized in our papers, including **Integer Linear Programming** (ILP) and **Mixed Integer Linear Programming** (MILP). Both of them fall under the category of LP. As a specialized type of LP problem, the ILP problem restricts that all variables must take integer values. Meanwhile, the MILP problem must contain both integer variables and continuous variables.

3.2 Approaches

Column Generation
Column Generation (CG) is an exact method for solving large-scale mathematical optimization models (Desaulniers et al., 2006). In Figure 3.1, we show the general process of CG, which iterates between solving the Restricted Master Problem (RMP) and Pricing Problem (PP).

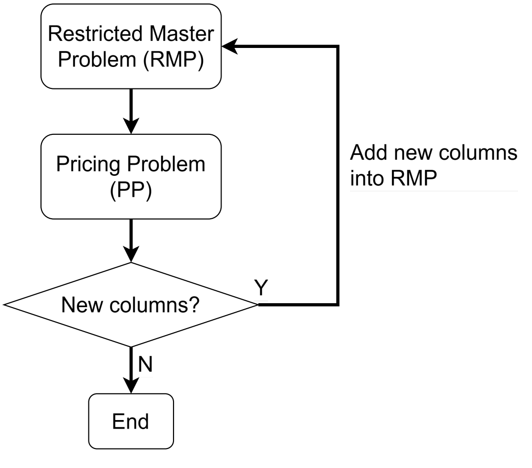

Figure 3.1: General process of column generation

The algorithm iterates until no new variables can be identified in the PP, indicating that the optimal solution is reached. The RMP is the simplified version of the original model, containing only a subset of variables (columns). The PP is typically formulated as a dual model of the RMP. By checking the reduced cost of variables not included in the RMP so far, the goal is to identify the new variables to include in the RMP, which will potentially improve the objective value. For the application of CG in crew rescheduling, we refer to the example in Breugem et al. (2022).

Tabu Search

Tabu Search (TS) is a metaheuristic approach for efficiently exploring complex search spaces and avoiding being trapped in a local optimum (Pham and Karaboga, 2012). In Algorithm 1, we display the pseudocode of the fundamental structure of Tabu Search, where we start with a given feasible solution s_0.

Algorithm 1 Tabu Search Structure

Initialize: a feasible solution s_0
Current solution $s \leftarrow s_0$
Historical best solution $s^* \leftarrow s_0$
while ***Stopping Criteria*** not met **do**
    Generate ***Neighboring Solutions*** $N(s)$
    Evaluate each $s \in N(s)$ based on ***Objective Function*** $f(s)$
    Select the best candidate $s' \in N(s)$ not in ***Tabu List*** T or satisfying ***Aspiration Criterion***
    Update Tabu List with s'
    if Tabu List T exceeds maximum length **then**
        Remove the oldest entry from the Tabu List T
    end if
    Update $s \leftarrow s'$
    if $f(s')$ is better than $f(s^*)$ **then**
        Update $s^* \leftarrow s'$
    end if
end while
Return: s^*

This algorithm stops based on some predefined conditions, which are called stopping criteria. Common criteria to use include setting a maximum number of iterations, limiting the runtime, and determining whether an optimal solution has been achieved. For each iteration, we generate the neighboring solutions $N(s)$, which include the ones that can be reached by making small adjustments to the current solution s. Then we evaluate the solutions in $N(s)$ by calculating their objective function $f(s)$, which is a mathematical formulation for evaluating and comparing the candidate solutions. Thus, the next step is to find the best candidate based on the value of $f(s)$ and the selected candidate should not appear in the tabu list T unless it satisfies the aspiration criterion. The tabu list T is a short-term memory that stores recently visited solutions, and the aspiration criterion is a group of conditions that allows a visited solution in the tabu list to be revisited as the newly selected candidate. After selecting the best candidate, we update the tabu list T, the current solution s, and the historical best solution s^* accordingly. In the end, the algorithm returns the historical best solution s^*.

Chapter 4

Contributions

In this thesis, we aim to explore the possibility of rescheduling railway schedules efficiently under near-operational disruptions. To achieve this goal, we present the research findings from three papers as contributions to this thesis. We illustrate which Research Question is addressed by each paper in Table 4.1. Paper I covers RQ1 and RQ3. Paper II covers all the Research Questions, but mainly RQ4. Paper III addresses RQ3. Overall, all three papers highlight the different aspects of railway rescheduling to address near-operational disruptions. In Subchapter 4.1, we summarize the research in each paper, state the highlights, and specify the connections with the Research Questions. We further describe our contributions in each paper in Subchapter 4.2.

	Paper		
	I	**II**	**III**
RQ1: rescheduling strategies	✓	✓	
RQ2: evaluation criteria		✓	
RQ3: solution approaches	✓	✓	✓
RQ4: computational efficiency		✓	

Table 4.1: Research Questions and Papers

4.1 Summary of the Papers

Paper I: A Mixed-Integer-Linear-Programming Model for Rescheduling Freight Trains under an Unexpected Marshalling-Yard Closure

In Paper I, we concentrate on the challenge of timetable rescheduling, with a particular emphasis on freight train rescheduling. We consider the situation that a marshalling yard faces an unexpected closure. To reduce the negative impacts of this near-operational disruption, we need to reschedule the timetable for the surrounding railway lines to avoid cancellations. We build a macroscopic MILP model and solve it with a commercial solver. We simultaneously reschedule multiple freight trains, instead of individually. We explore allowing trains to wait along the route during disruptions, implementing strategies such as extending station stopping times for temporary parking and delaying departure times at the originating yard in the MILP model. The goal of this paper is to present a comprehensive mathematical model that serves as a standardized framework for timetable rescheduling in similar disruption scenarios. Thus, we solve the model under three different cases with artificial data to show the feasibility and performance of our MILP model.

In this paper, we reschedule the railway timetable with a MILP model to deal with a near-operational disruption in a marshalling yard, which partly blocks the surrounding railway lines. Thus, this paper addresses the Research Questions 1 and 3. A previous version of this paper was presented at the 10th International Conference on Railway Operations Modeling and Analysis (ICROMA) in Belgrade 2023.

Paper II: A Time-and Space-Efficient Heuristic Approach for Late Train-Crew Rescheduling

In Paper II, we focus on the rescheduling problem that occurs one day before the operation. Because of sick leave and other reasons, train drivers will be absent the next day. Thus, their tasks need to be rescheduled. We aim to re-assign the uncovered tasks to achieve few cancellations and few changes from the original schedule to other on-duty drivers. We propose a tabu-search-based approach for crew rescheduling and compare it to a column-generation method, both handling the same constraints. In this paper, we introduce different types of operations for searching for neighbourhood solutions.

The data used in this paper is provided by a Swedish railway undertaking called Mälartåg, which runs regional passenger trains. In the case study, the results show that the tabu-search approach outperforms the column-generation method in computational time and space while providing comparable assignment rates of tasks to train drivers. Our approach is scalable, with performance remaining non-exponential even when the number of absent drivers increases. It provides a feasible solution for rescheduling crew members' schedules for a one-day shift in real-world scenarios, offering a practical and computationally efficient alternative to column-generation methods. Although this paper addresses all the Research Questions, the main focus is on RQ4. The work in Paper II has also been presented at:

- The 33rd of European Conference on Operational Research (EURO), Copenhagen, 2024
- The 26th of Euro Working Group Transportation conference (EWGT), Lund, 2024

Paper III: Short-Term Crew Rescheduling: Extending the Scheduling Options in a Tabu-Search-Based Approach

Paper III is an extension of Paper II. In Paper III, we also focus on the short-term crew rescheduling problem, specifically addressing near-operational drivers' absences due to sickness or other unforeseen issues. Building on the tabu-search-based approach introduced in Paper II, we enhance the options for the neighborhood-search strategies by adding taxi trips and combinations with other options, such as deadheading one or multiple consecutive tasks, as connecting options. Additionally, we incorporate various relaxation strategies, including extending the maximum duty hours, increasing the allowable taxi travel duration, and adjusting duties' start and end times. These enhancements provide better performance of our approach, for example, more accurately reflecting real-world operational constraints and improving the quality of the results. On the other hand, we observe a strong trade-off between the length of taxi trips and the assignment rate. The results indicate that achieving a higher assignment rate comes at the cost of longer taxi trips. In this paper, we run the approach on three data sets from Mälartåg. Each data set is a one-day schedule of all drivers. We test the performance of our improved approach and the trade-offs between different parameters. Thus, this paper addresses the Research Question 3. We have presented this paper at the 11th International

Conference on Railway Operations Modelling and Analysis (ICROMA), Dresden 2025.

4.2 Research Contributions

The main contribution of this thesis is the advancement of mathematical optimization models and approaches to enhance the railway system's capability to deal with disruptions, particularly those occurring near-operationally.

Our contributions can be categorized into two key aspects. The first aspect focuses on timetable rescheduling for freight trains, as explored in Paper I, where we address disruptions in railway operations by optimizing the timetable adjustments. The second aspect pertains to crew rescheduling, covered in Papers II and III, where we build a heuristics approach by adapting tabu search to improve computational efficiency and solution quality. Beyond these technical improvements, our work provides a broader framework for handling near-operational disruptions in railway systems by offering practical solutions. Through these contributions, we aim to support infrastructure managers and railway undertakings in making more informed, data-driven decisions to mitigate the impact of near-operational disruptions.

Chapter 5

Conclusions and Future Work

In this thesis, we address the challenge of railway rescheduling in the face of near-operational disruptions, aiming to enhance the railway system's ability to adapt to near-operational disruptions and recover efficiently. The work is divided into three papers, which tackle two different aspects of the problem. In Paper I, we focus on timetable rescheduling, developing a mathematical model to adjust train schedules in response to disruptions in a marshalling yard. In Papers II and III, we concentrate on crew rescheduling. With an emphasis on developing efficient approaches for reassigning uncovered tasks shortly before operations. This might be caused by drivers taking leave on short notice due to unforeseen circumstances, such as sickness. In this thesis, we not only develop methodological solutions for rescheduling but also, from the output solutions, provide decision support for real-world railway operations in handling unexpected disruptions more effectively.

For the continuation of the work, several research directions can be explored. From the perspective of timetable rescheduling, a potential extension of Paper I involves exploring methods to enhance computational efficiency, as the commercial solver suffered from long computational time when solving the mathematical model in Paper I. Possible methods may include exact algorithms tailored for solving the presented MILP model. Additionally, we can also investigate heuristic approaches as alternatives to achieve acceptable solutions within a short computational timeframe.

From the perspective of rolling-stock rescheduling, there are two initial steps of research directions. One direction involves examining existing studies on rolling-stock rescheduling under near-operational disruptions and identifying suitable methodologies for addressing these challenges. Another direction relates to integrating rolling-stock and crew rescheduling, as both processes fall under the responsibility of the same stakeholder. A common scenario arises when, following timetable rescheduling, railway undertakings must adjust both rolling-stock and crew schedules. Addressing these two rescheduling processes simultaneously may mitigate infeasibilities that could emerge from treating them as separate processes.

For crew rescheduling, we can continue the research in four possible future directions. Firstly, it can be an extension of Paper III by extending crew rescheduling from individual duty-level adjustments to shift-level rescheduling, enabling the management of near-operational disruptions on a larger scale. A straightforward example of such a scenario is when train drivers take leave for multiple consecutive days, necessitating more comprehensive rescheduling strategies. Secondly, we could integrate multimodal transport options into the crew rescheduling process. Currently, deadheading is primarily managed using taxis in real-world operations, but adapting other transportation modes, such as metro systems, buses, or even trains from other railway undertakings, could offer more flexible options to replace long taxi journeys for repositioning crew members. Thirdly, in the domain of crew rescheduling, further efforts can be made to quantify the optimality gap and enhance computational efficiency while maintaining or improving the solution quality. One potential approach to addressing this challenge is the integration of AI-driven methods into crew rescheduling. For instance, a comparative analysis could be conducted to evaluate the solutions generated by AI-based approaches against those obtained through heuristic methods. Fourthly, we can further identify and include more aspects from the employee's perspective, aiming for the benefits of their work-life balance and overall job satisfaction. This direction might lead to a more sustainable working environment.

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Papers

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Department of Science and Technology

Linköping University
SE-581 83 Linköping, Sweden

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