Ivina and Ma
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Stability assessment of railway trackwork scheduling in Sweden

Daria Ivina[1,2*] and Zhenliang Ma[3]

Abstract

Ensuring the reliability of railway transportation is heavily dependent on the quality of its infrastructure. In this regard, renewal and maintenance of the railway track infrastructure, referred to as trackwork, play a vital role. However, trackwork execution requires temporary capacity restrictions for train traffic. Therefore, harmonising the train and maintenance schedules is critical but challenging to accomplish when one is frequently changing. This paper explores and models the nature of trackwork schedule instability at the tactical level of the scheduling process. We analyse data from one year of trackwork rolling horizon plans, focusing on weekly changes at eight key trackwork locations across Sweden's railway network. Our study considers various factors that may affect schedule stability, such as track type, location, time of day, train traffic intensity, and the type of prevailing traffic. We find that schedule instability increases as the rolling horizon plan approaches its end. The regression analysis reveals that the most significant predictors of changes in trackwork schedules include previous changes, track type (single vs. double), work location (at station vs. between stations), and the timing of trackwork (daytime vs. nighttime and month). These provide insights to trackwork planners in making informed and proactive decisions about trackwork timeslot allocation.

Keywords Railway, Trackwork, Schedule nervousness, Plan instability, Modelling analysis

1 Introduction

Freight and passenger train traffic in Sweden has grown over the past two decades by 30% and is expected to grow further, given the increasing recognition of railway transportation as an environmentally sustainable option [9, 41]. However, railway capacity is limited, and there is a decreasing amount of available time on track for trackwork. The time for performing essential trackwork must be well managed and decided well in advance to ensure that train traffic is not interrupted and to avoid further capacity restrictions. Therefore, the proper scheduling of railway maintenance activities is critical. In Sweden, the process must start three years before the operating period, as trackwork creates operational restrictions for train traffic. Coordinating time on track for maintenance between train traffic is crucial and challenging [24].

Scheduling is the process of developing a detailed plan to allocate resources to specific tasks to maximise service productivity and efficiency. The primary objective is to create a production schedule that optimises the use of available resources for a given set of assignments in an allocated time. In the scheduling process, three main variables are considered: the available resources, the tasks, and the time constraints within which these tasks must be completed [33]. As in other projects, the available resources, tasks, and time in railway maintenance can change over time due to the project environment. In other words, a constantly changing environment provokes disruptions, making trackwork scheduling an ongoing reactive process [31]. As revealed by [17], the compiled schedule can be modified repeatedly due to

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*Correspondence:
Daria Ivina
daria.ivina@tft.lth.se
[1] Department of Technology and Society, Lund University, P. O. Box 118, 22100 Lund, Sweden
[2] K2 Swedish Knowledge Centre for Public Transport, Bruksgatan 8, 222 36 Lund, Sweden
[3] Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

project uncertainties. The main project-related uncertainties discovered were rejection of modification of the contractor's application for time on track, modifications in the contract, and infrastructure failure notification. Understanding the factors contributing to schedule stability could contribute to the proactive responsiveness of trackwork schedule changes.

The frequent changes to service schedules caused by uncertainties are known as schedule instability or nervousness [35]. Such factors triggering instability are classified as uncertainties in the project management literature. Preparing extra resources in case of uncertainty is a common strategy in production planning to mitigate the risk of short supply [3]. Although the maintenance resources are organised similarly to production planning, reserving extra time for trackwork is not a practical strategy due to limited railway capacity. Regarding railway maintenance, rescheduling trackwork is the primary way that the maintenance contractors in Sweden respond to uncertainties [17]. Rescheduling entails either modifying the length of the trackwork or completing the planned maintenance at a different time slot from the intended one. Despite its significant impact on project performance and its stress on contractors, trackwork rescheduling remains an understudied issue [24, 39].

Trackwork scheduling complexity arises from the need to create a schedule that considers not only the resources available to the maintenance company but also the time slots when tracks are free from train operations. Extensive research has addressed the optimisation of trackwork schedules, considering various constraints [8, 13, 26, 27, 45, 50, 54, 56]. A principal objective within this field has been to create maintenance schedules that simultaneously minimise disruptions to train services and lower the costs associated with maintenance [27]. Initiatives, such as those by [7], have specifically targeted the minimisation of schedule deviations while maximising maintenance activities. More recent studies by [29, 50] have developed models aimed at establishing an optimal, regular maintenance schedule that minimally affects train traffic. While some case studies have demonstrated the potential efficacy of these models, the practical application of such schedules frequently deviates from theoretical designs. Ivina and Palmqvist [18] observed that a considerable portion of maintenance work in Southern Sweden was conducted outside the pre-arranged maintenance windows, underscoring the need for further investigation into the practical challenges and realities of maintenance scheduling in the railway sector.

In this study, we apply the concept of schedule instability traditionally associated with production planning to the operational management of trackwork. Utilising a unique set of empirical data, this study aims to understand the impact of factors on the trackwork plan stability, such as traffic volume, traffic type, track type, month, weekday, and daytime, on the trackwork plan stability. This study answers the following research questions: (1) How stable is the trackwork schedule in Sweden at the tactical and operational planning levels? (2) What factors affect the modification of the booked time on track in the track utilisation plan?

This study contributes to understanding factors leading to changes in booked time for trackwork over a planning cycle. Specifically, we developed a logistic regression model based on nine months of trackwork plan weekly update data to understand the effect of factors like track type, traffic intensity, location, month, and weekday on the plan change. These provide insights that will support trackwork planners in making informed and proactive decisions about timeslot allocation.

The remaining paper is structured as follows. Section 2 provides the background information related to schedule stability, rescheduling, and railway maintenance in Sweden. In Section 3, the research methodology employed in the study is described. Section 4 presents the research results, while Section 5 discusses the major findings. Finally, a summary of this study's major contributions and limitations is provided, followed by suggestions for future research directions.

2 Background

2.1 Schedule stability and rescheduling

Scheduling is a fundamental aspect of production management aimed at maximising the efficient use of time and resources. A well-constructed schedule should specify the start and end dates of each activity, as well as its duration. In manufacturing management, schedule stability is a critical consideration, referring to the consistency of production plans and material management practices across multiple scheduling cycles [21]. Schedule stability is achieved when the estimated demands for a particular planning period remain constant and correspond with the actual production requirements [34]. Similarly, [14] suggest that schedule stability can be attained if the number of planned activities within a certain time interval is performed according to the forecast without changes. This condition is highly desirable, as it reduces the need for emergency measures, simplifies communication and coordination between different departments, and improves the ability to achieve production goals.

Rescheduling is revising an existing production schedule in response to unexpected events, such as unscheduled tasks, machine breakdowns, or repairs [47]. Two types of rescheduling exist: schedule repair and complete rescheduling [31]. Schedule repair involves making local adjustments to the existing schedule to conserve production resources or reduce time. In contrast, complete rescheduling entails the creation of a new schedule from scratch.

Rescheduling the production plans that became unfeasible due to unforeseen disturbances is a key characteristic of project flexibility. Project flexibility is the ability to modify a project in response to uncertain circumstances that may arise within the project context [30]. Maintaining a certain degree of flexibility in the schedule is essential to enable adjustments in response to uncertainties, which is critical for efficient production planning. At the same time, there is a debate within the research community on whether frequent rescheduling is advantageous. Several studies suggest that frequent schedule changes threaten project success, as they can lead to reduced staff productivity, increased inventory, and higher production costs [34, 38, 47]. In order to avoid such cost losses for a project, flexibility must be strategised at the earlier stages of the project. Olsson [30] proposes three strategies to achieve flexibility in decision-making processes that can benefit the project: locking the plan closer to the project's completion, making continuous and reasonable plan adjustments, and preparing alternative plans in case the primary plan cannot be executed.

Flexibility in the decision-making process requires continuous and reasonable plan adjustments, which can be achieved through the utilisation of the rolling horizon plan technique. The rolling horizon plan (Fig. 1) is used to schedule and manage production activities over a fixed time horizon to meet the forecasted demands, minimise cost and meet the delivery dates [12]. Specifically in railway operations research, in [51] a rolling horizon approach was employed to reschedule train traffic in response to disruptions. Similarly, in [32] a rolling horizon framework was applied to enhance train routing and scheduling. The schedule is continually updated and revised on a rolling basis to ensure project activities are aligned with demand, resource availability, and other key factors that can impact production efficiency and effectiveness [6, 28]. Figure 1 illustrates different components of the rolling horizon plan, including the rolling horizon length (the time period that the planner focuses on at the time), the free interval (the period when modifications to the plan are allowed), the frozen interval (the period when modifications to the plan are not allowed), and the cycle (a set of replanning activity withing one planning horizon and comes periodically).

2.2 Schedule instability

Uncontrollable and continuous rescheduling of orders in production planning leads to schedule nervousness, which can negatively impact management's confidence in the system, resulting in disruptions in production or delivery systems. Schedule nervousness, also known as schedule instability, is a term describing the fluctuation in the supply and demand of the components in the master production schedule system [22, 34] due to inaccurate forecasts, supplier relationships or other reasons [14, 35].

Many methods to measure schedule instability have been developed since the concept was first introduced. One of the most straightforward ways is to measure instability by counting unplanned and changed orders in the first period of the planning horizon when the schedule is rolled forward [20]. The instability of scheduling activities can be measured as the sum of changes that a schedule undergoes during execution or the percentage of deviations from the initial schedule [15, 21, 38, 47], where fewer changes (lower instability index) represent greater stability in the schedule. Zhao et al. [58] measured schedule instability as the average differences per order between the scheduled order quantity for an item in the period during a planning cycle and the scheduled order quantity for that item in one earlier planning

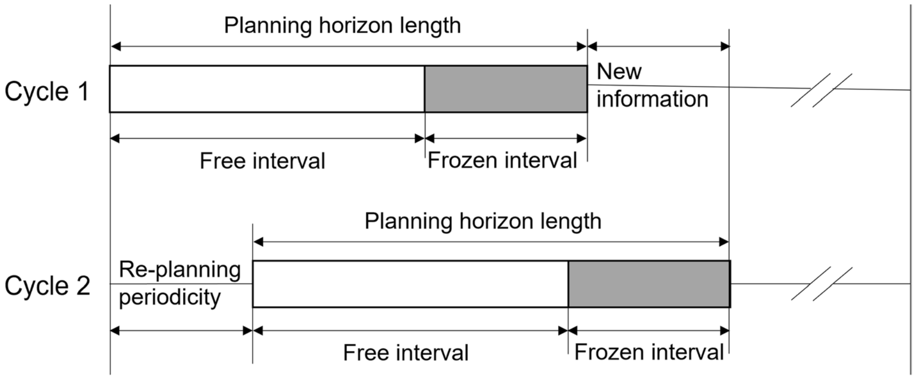

Fig. 1 Rolling horizon plan (adapted from [28])

cycle. The model developed by [34] enables the weighing of each change with a corresponding order quantity and type of change. It considers various factors, including the type of changes, period in the planning horizon, planning cycle, length of planning horizon and weight of change. In this study, we adapted the model from [34] to account for the trackwork-related factors that might be linked to each specific plan change in the rolling horizon plan.

Several strategies are outlined in the literature to minimise planning instability and its adverse impact on production. The most common are accumulating safety stock, forecasting beyond the planning horizon, and freezing the schedule within the planning horizon [3]. Safety stock refers to a surplus inventory, acting as a buffer in case of emergencies. In trackwork scheduling, this would translate to booking more track time for maintenance than necessary. Forecasting beyond a planning horizon involves predicting future demand beyond the established planning period. Meanwhile, freezing the production schedule, in other words, establishing the frozen interval, implies restricting changes in the master production plan for a defined period before production [40].

2.3 Train rescheduling

Train scheduling complexity is amplified by uncertainties such as passenger demand, platform crowding, train delays, and unexpected disruptions [23, 46, 49]. Rescheduling in case of disruptions demands immediate actions from dispatchers, including train cancellations, rerouting, and retiming, leading to subsequent crew and rolling stock rescheduling challenges [5, 53]. The primary aim in such situations is to restore normal operations as fast as possible, minimising delays and disruptions to passengers and freight, while considering the limited flexibility and time constraints of real-time operations.

Over the past decades, the challenge of train rescheduling has become a crucial concern for railway management, capturing the interest of researchers globally and resulting in a variety of solutions [53]. The employed methods aimed at minimising train disruptions, train delays, travel demand and passenger inconvenience, and operational costs, while also enhancing energy efficiency [4, 10, 11, 36, 46, 48, 57]. Notable contributions include the development of models that not only aim to optimise timetables during disruptions but also take into account the dynamic nature of passenger demand and system resilience. For example, [4, 10, 23, 46, 52] demonstrate approaches to integrating passenger routing with train rescheduling, and integrate the dynamic information of fault handling. Xu et al., Zhao et al., Li et al. and Han et al. [11, 23, 49, 57] focus on network-level optimisation of train schedules under emergencies and enhancing system resilience. Reynolds et al. and Xiu et al. [36, 48] provide insights into the fairness of optimisation models for train rescheduling and strategies to handle rescheduling uncertainties. Furthermore, [2, 19, 55] introduced a timetabling optimisation approach to manage the uncertainty in maintenance plans.

2.4 Trackwork rescheduling

Trackwork scheduling is a complex process that involves multiple actors and requires close coordination with train operations. The rescheduling of trackwork, despite the considerable focus on train rescheduling in response to disruptions, remains a relatively underexplored area [24, 39]. Referring to the aircraft maintenance rescheduling [44] applies a mathematical optimisation model for the efficient maintenance tasks rescheduling problem in a disruptive environment. Ruiz-Rodríguez et al. [37] analyse the maintenance scheduling problem with a focus on the impact of uncertainty on the failure distribution and time to repair.

According to [17], it is relatively common to reschedule trackwork in response to disruptions or unexpected events. Unexpected events and disruptions that can affect trackwork scheduling include equipment unavailability, staff shortages, changes in work priorities, and changes in work order. According to [37], uncertainty in maintenance is also linked to maintenance type, maintenance duration, technician availability, machine availability, failure distribution and joint schedule.

3 Method

3.1 Case study

This study aims to bridge the gap in existing research by exploring the trackwork rescheduling, particularly within a Swedish context. Similar to practices in other European countries, trackwork in Sweden is managed as a series of projects under the supervision of the Swedish Transport Administration, the main infrastructure manager [1]. This actor is responsible for developing the maintenance strategy, planning and scheduling railway maintenance, assigning train routes and scheduling major infrastructure repairs. Every year, the infrastructure manager must issue a trackwork plan outlining capacity restrictions for train traffic during the upcoming year. Basic maintenance work is typically delegated to private railway maintenance companies via regional contracts, and these companies must schedule their work within their designated areas of responsibility [16, 25]. Contractors must prepare the trackwork schedule and submit requests for time on track during a specified application period, usually four to twelve weeks before the work [42]. Time on track booked for railway maintenance is referred to as "possession". The infrastructure manager's planning departments review these requests and record the approved times in a track utilisation plan.

Trackwork is planned across three levels: strategic, tactical, and operational [16, 24]. The strategic level implies creating long-term maintenance plans and predicting necessary volumes of work. During this planning stage, freight corridors and international traffic are also considered. Since trackwork and train operations cannot happen simultaneously on the same track, it is crucial to make reliable forecasts regarding capacity restrictions for the train traffic in relation to the trackwork. At the tactical level, more detailed forecasts about capacity usage are prepared and shared with train operators, which allows them to adjust their schedules accordingly [1]. Finally, at the operational level, which starts two weeks before that trackwork, the last preparations for trackwork are made, such as obtaining security clearance for train paths and organising personnel and equipment [42]. Changes are prohibited once the schedule is set at the operational level, except for urgent repairs.

The application for possession process in Sweden is regulated by guidelines issued by the Swedish Transport Administration [42, 43]. The temporary capacity restrictions are documented in two primary documents: the trackwork plan and the track utilisation plan. The trackwork plan is created from 24 months to 13 weeks before operation and contains all information about major engineering works. The track utilisation plan gathers updated information from the trackwork plan and, thus, contains more detailed and optimal schedules based on accumulated information. The track utilisation plan is designed in a 'rolling horizon', from 12 to 4 weeks before trackwork operation week (Fig. 1). Contractors can change the track utilisation time up to four weeks before the scheduled trackwork execution [42]. The schedule becomes 'frozen' during the last four weeks before the trackwork execution, with the only exception being urgent repairs that cannot be postponed for more than four weeks. Late applications for capacity restrictions during this period can result in train rerouting or cancellations.

In our research, we selected eight railway lines across Sweden for detailed analysis (Table 1, Fig. 2). These lines encompass the country's northern and southern regions, providing a diverse range of single and double-track lines that accommodate different volumes of freight and passenger traffic (Table 1). We measured traffic volume and freight share on the stretches where trackwork was scheduled rather than for the whole line. Traffic volume was calculated as a weekly average of trains passing through stations where the trackwork was scheduled divided by the total length of the railway line. The maintenance of the selected track lines was under the responsibility of four maintenance companies.

3.2 Data

The study uses two datasets: the track utilisation plan and train operation data provided by the Swedish Transport Administration. The track utilisation plan contains information about temporary capacity restrictions for train traffic (Table 2), such as when and where the trackwork is planned. The train operation dataset contains information on scheduled train departures and arrivals; our interest in this dataset was the train traffic intensity and the type of trains passing the analysed lines.

Maintenance contractor companies in Sweden have a weekly production cycle, meaning there are 52 planning periods in a year. The track utilisation plan is updated

Table 1 Analysed lines

Code	Rail line	Length (km)	Track type	Traffic volume (1000 train km)	Share of freight trains
South					
S02	Southern Main Line (Södra Stambanan)	483	Double	16,597	26%
S03	West Coast Line (Västkustbanan)	283	Double	6635	9%
S11	Norway/Vanern Line with Northern Link (Norge/Vänerbanan med Nordlänken)	300	Single[a]	3613	26%
S12	Varmland Line (Värmlandsbanan)	202	Single[b]	2134	38%
S70	Fryksdal Line (Fryksdalsbanan)	82	Single	406	10%
North					
S07	Main Line Through Upper Norrland (Stambanan genom Övre Norrland)	626	Single[c]	5314	76%
S21	Iron Ore Line (Malmbanan)	398	Single	2779	73%
S29	Haparanda Line (Haparandabanan)	159	Single	53	86%

Single tracks except between [a]Göteborg and Öxnered, [b]Kil and Karlstad, and [c]Mellansel and Vännäs

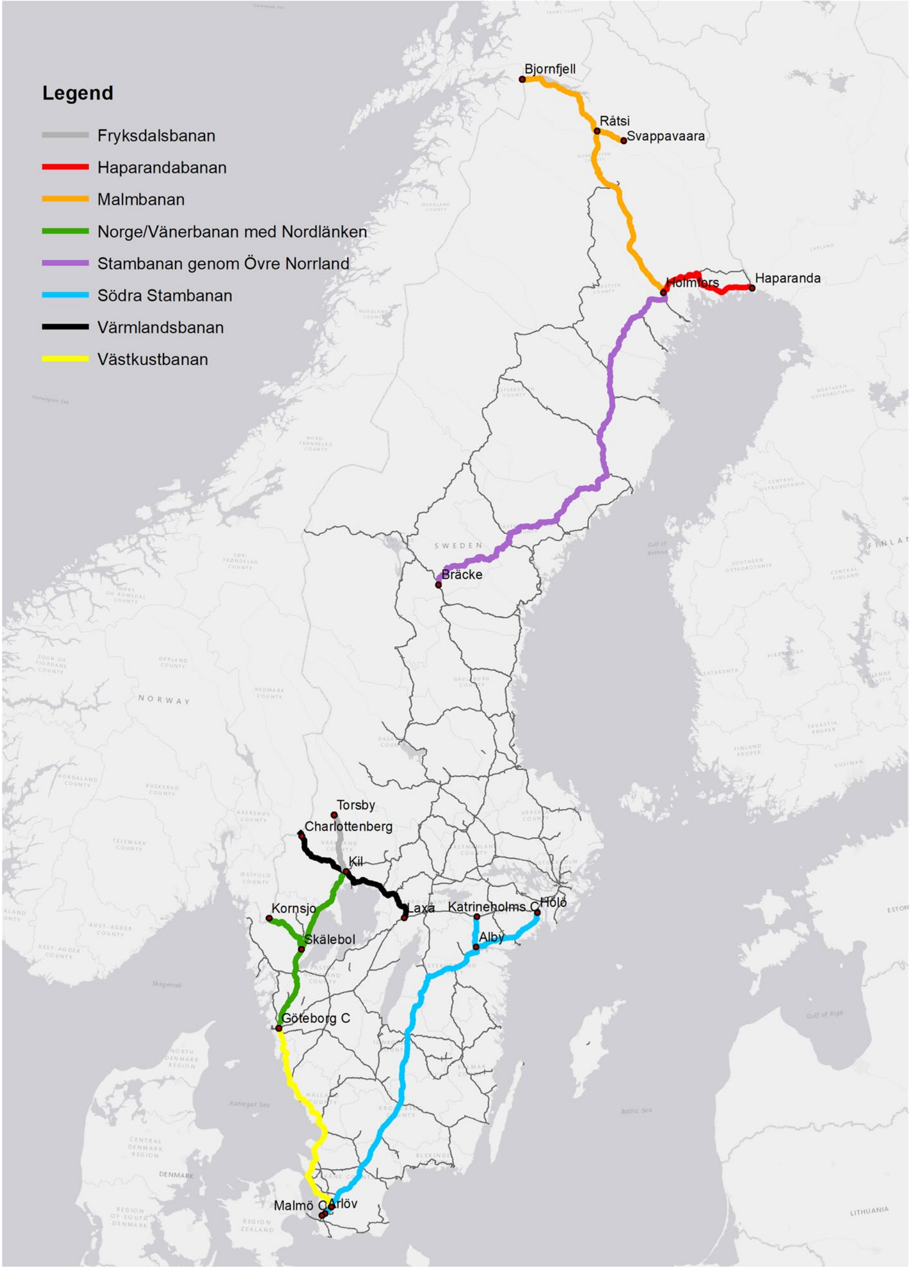

Fig. 2 The analysed railway lines in Sweden (own map produced using ArcGIS® software based on data from the Swedish Transport Administration, canvas map source: HERE)

weekly, but changes were frequently made due to the nature of day-to-day operations. However, the track utilisation plan does not explicitly keep track of changes. Therefore, we had to extract a version of an updated plan weekly for each analysed line. Each trackwork has an identification number, and two end stations and time define the location of the planned activity. The time of trackwork is specified as week number (from 1 to 52 according to the Swedish week numbering system), time and daytime (day or night).

We collected data on the trackwork plan from May to December 2020 to investigate changes in the timing of trackwork operations. We extracted the plan every Wednesday at 9 am to ensure consistency in the timing of updates. We obtained 32 weekly schedules for eight railway lines in Sweden. For the study purposes, we focused on an active period with a rolling horizon of 13 weeks. Therefore, we aggregated trackwork activities performed during the day or night over the 13-week cycle, resulting in a sample of 6646 trackwork activities.

Table 2 Track utilisation plan data description

Data field	Description
Object / Class	Identification number on trackwork
Station from / to	Trackwork area as the segment between two stations
Limitation point	Precise location of trackwork defined by signal points
Description	Nature and purpose of the trackwork
Track	Identifies the specific track(s) affected by the trackwork
Week from / to	The frame of trackwork expressed in calendar weeks
Days	Specific weekdays during which trackwork occurs
Time from / to	Start and end times for trackwork (in minutes)
Whole / Divided	Duration type of trackwork: continuous or intermittent
Details	Activity type description
Safety code	Full track closure or speed limit indication
Single track operation	Partial track closure indication
Voltage	The presence of zero voltage requirement in overhead lines
Special notes	Additional comments

3.3 Measure of plan instability

This study aims to detect and explain instability in the track utilisation plan, achievable by tracking changes in each trackwork record throughout the planning cycle. This approach is novel for railway operation systems; thus, we adopt the model proposed by [34] to identify trackwork schedule instability. In Pujawan's formulation, schedule instability is quantified by considering a detailed description of the nature of changes (i.e production start time, specification/design, quantity). However, this paper simplifies the model to quantify instability concerning change in the scheduled possession in each planning cycle. In this context, trackwork schedule change refers to the variation in the total weekly duration of scheduled trackwork activities between consecutive weeks in the planning cycle. The adaptation of the [34] model in this study is represented by the following equation:

$$I(t,j) = \sum_{x} Q^{t}(x,j,i), \tag{1}$$

where t is planning cycle; i is type of change in time in booked time on track (i.e., 1: increase; 2: decrease); j is period in the planning horizon (from 0 to 12 weeks); x is booked time on track for unique trackwork in the plan; $I(j)$ is total instability observed in period j in the planning horizon; $Q^{t}(x,j,i)$ is the length of x which experienced type i change in the observed planning cycle t.

According to regulations [43], the track utilisation plan allows modification starting 12 weeks before the trackwork execution. It is, however, also of interest to understand what happens within the period between 4 weeks and 0 weeks ahead of the execution of the trackwork because no changes are allowed during this planning period. Therefore, we set our timeframe to include the period from 12 weeks ahead of execution up to 0 weeks before the execution of the trackwork. Presenting data in this way helps to investigate the changes in the plan in the timeframe of the allowed changes and in the horizon of the frozen plan (4-0 weeks).

We identified three possible scenarios of how each trackwork duration gets modified over the planning cycle. These are the planned time for trackwork during the week: 1) increases in the following week of the planning cycle; 2) decreases in the following week of the planning cycle; 3) stays the same in the following week of the planning cycle. To explain the schedule instability for each trackwork, we gathered a set of characteristics such as location, track type, daytime, month, weekday, work length, train traffic intensity, and the share of the freight trains.

3.4 Regression model

We use multiple logistic regression to model the weekly change in track utilisation plan as a function of a set of explanatory variables. The multiple logistic regression predicts the logit of outcome Y (change/no change):

$$\log\left(\frac{P(Y=1)}{P(Y=0)}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{10} x_{10}, \tag{2}$$

where Y is a binomial variable indicating the presence of change in the trackwork length compared with the previous week in the trackwork planning cycle ($Y = 1$, if change), $\beta_{0\ldots10}$ are the logistic regression coefficients associated with the reference group, and $x_{1\ldots10}$ are the explanatory variables selected in our study.

As shown in Table 3, the 'change' is a binary explanatory variable for which 1 is assigned to cases where any change in the trackwork time had happened over the planning cycle (increase, decrease, cancellation or new work). The explanatory variables include both categorical and continuous factors.

4 Results

4.1 Descriptive statistical analysis of trackwork plan stability

Table 4 provides an overview of the characteristics of the analysed track utilisation plan data, broken down into several variables and categories. The study presents an analysis of the trackwork plan on eight railway lines in Sweden, with the share of observations with changes

Table 3 Regression model's variables description

Variable	Description
Categorical	
Change (response variable)	Alterations in scheduled trackwork timing
Previous change	Adjustment in previous week's trackwork duration
Location (line)	Railway line designated for trackwork
Track type	Type of track (single or double) for trackwork
Daytime	Trackwork scheduled during day or night
Month	Month of scheduled trackwork
Weeks ahead	Number of weeks before trackwork execution (0-12)
Work is at a station	Trackwork at a station or along a line segment
Continuous	
Count of previous changes	Count of trackwork duration changes in preceding weeks for each trackwork event
Train traffic intensity	Train frequency per km over 8 months (04/2020 - 12/2020)
Freight share	Ratio of freight to other trains per week at a location
Trackwork duration	Planned duration of trackwork in days

ranging from 10% for the Southern Main Line to 16% for the Iron Ore Line. A higher occurrence of changes was on single tracks (15%) compared to double tracks (11%). More changes were recorded for the trackwork planned during the day (14%) than at night (10%). The total observation period was seven months. The highest percentage of trackwork plan changes occurs in September (15%), while the lowest is in May (9%). It is also noted that trackwork at stations is associated with a higher percentage of changes (13%) versus when there is no trackwork (11%). The total number of observations across all categories is 79,752.

Table 5 shows the characteristics of the continuous variables in the model. The count of previous changes in the trackwork duration ranged from 0 to 10, accounting for 32 cycles of 6646 trackwork. The freight share (presented in percentages of freight trains from the total number of trains) varied from 9% to 86%, which emphasise the difference in types of traffic across the analysed lines. The train traffic intensity (train km) ranged from 53,045 to 16,597,365. Finally, trackwork duration in days spanned from 1 to 7 days, longer trackwork durations were excluded from the analysis, as they are not related to basic maintenance.

Table 4 Characteristics of analysed data

Variable	Observations	Share of observations with changes
Location		
Southern Main Line (Södra Stambanan)	29,316	10%
West Coast Line (Västkustbanan)	6588	11%
Norway/Vanern Line with Northern Link (Norge/Vänerbanan med Nordlänken)	14,580	12%
Main Line Through Upper Norrland (Stambanan genom Övre Norrland)	7848	12%
Varmland Line (Värmlandsbanan)	3588	13%
Iron Ore Line (Malmbanan)	16,416	16%
Haparanda Line (Haparandabanan)	804	12%
Fryksdal Line (Fryksdalsbanan)	612	11%
Track type		
Single	21,252	15%
Double	58,500	11%
Daytime		
Day	44,652	14%
Night	35,100	10%
Month		
May	12,816	9%
June	12,972	13%
July	10,428	13%
August	10,284	10%
September	10,872	15%
October	10,212	13%
November	8976	13%
December	3192	10%
Trackwork is at a station		
Yes	47,940	13%
No	31,812	11%

Total number of observations for each variable: 79,752

Table 5 Characteristics of continuous variables

Variable	Min	Max	Mean	St. Dev.
Count of previous changes	0	10	0.44	0.80
Freight share (%)	9	86	44	25
Train traffic intensity (train km)	53,045	16,597,365	8,648,072	6,192,999
Trackwork duration (days)	1	7	1.59	1.31

Total number of observations for each variable: 79,752

Figure 3 illustrates the percentage of unmodified trackwork durations for each cycle (0-12), representing the level of plan stability. The stability was calculated for each planning cycle within the planning horizon as the ratio of unaltered trackwork to the total trackwork.

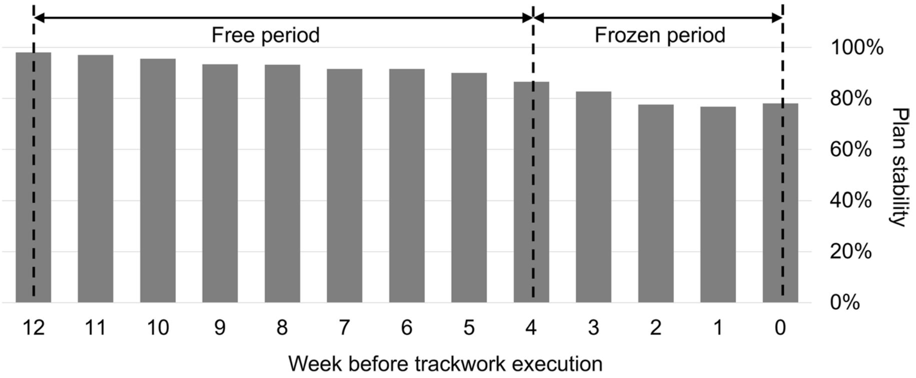

Fig. 3 Trackwork plan stability estimate for each analysed trackwork planning cycle

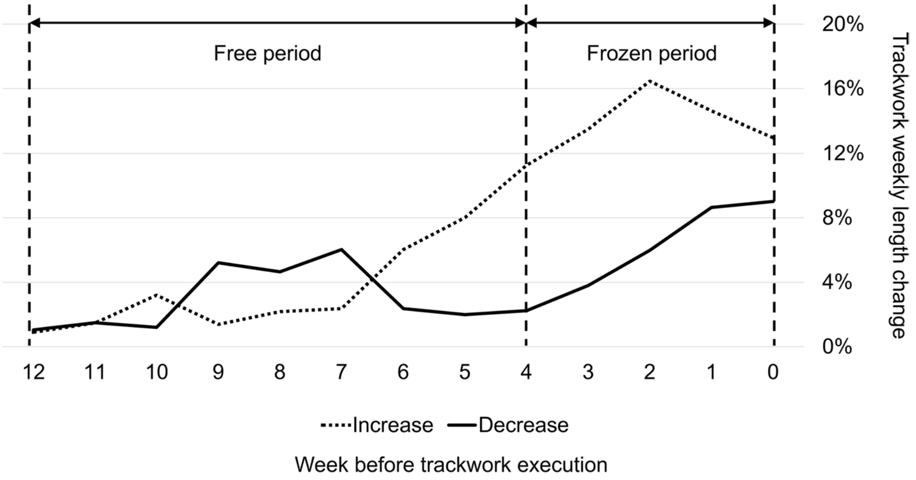

Fig. 4 Types of changes in each cycle (from 0 to 12 weeks) in the track utilisation plan

Figure 3 highlights the decreasing trend of plan stability towards the end of the planning horizon period, with the stability reaching 80% in the week before the operation week.

The number of changes in the track utilisation plan increases towards the end of the rolling horizon as the time approaches trackwork execution. Figure 4 illustrates the proportion of trackwork durations with observed changes in each planning cycle. Two types of changes are observed in the trackwork duration: an increase in the time on track for each unique trackwork and a decrease in time on track. According to the current regulations [43], all changes in the track utilisation plan are allowed to happen within the free interval - from 4 to 12 weeks before trackwork execution. However, the analysis reveals that the plan still changes the frozen interval. Notably, most of these changes are attributable to introducing new work activities, followed by cancellations and modifications to the trackwork duration.

4.2 Multiple logistic regression analysis

To analyse the effect of previous change, track type, time, traffic intensity and composition on the plan stability, we performed the multiple logistic regression. The regression coefficients were estimated using the maximum likelihood estimation method, the implementation of which was provided by the command GLM (Generalised Linear Model) in R, a free software environment for statistical computing. The statistical significance of each regression coefficient was tested using the Wald chi-square statistic test. The multiple logistic regression results are presented in Table 6.

Among the explanatory variables, the previous change, count of previous changes, trackwork at the station, daytime, trackwork duration, freight share and weeks

Table 6 Summary of the multiple logistic regression

Coefficients		Estimate	Std. Error	z Value
β_0	(Intercept)	-0.992	0.067	-14.898
β_1	Previous change (Yes)	0.188	0.036	5.159
β_2	Count of previous changes	-0.233	0.017	-13.967
β_3	Track type (Single)	0.259	0.032	7.968
β_4	Trackwork at the station (Yes)	0.147	0.024	6.038
β_5	Daytime (Night)	-0.306	0.025	-12.131
β_6	Train traffic volume	0.000^{ns}	0.000	-0.572
β_7	Freight share	0.331	0.059	5.609
β_8	Trackwork duration	-0.055	0.009	-5.800
β_9	Weeks ahead 1	0.022^{ns}	0.042	0.529
	Weeks ahead 2	-0.067^{ns}	0.043	-1.565
	Weeks ahead 3	-0.431	0.045	-9.506
	Weeks ahead 4	-0.743	0.048	-15.345
	Weeks ahead 5	-1.117	0.053	-21.267
	Weeks ahead 6	-1.330	0.055	-24.000
	Weeks ahead 7	-1.347	0.056	-24.168
	Weeks ahead 8	-1.588	0.060	-26.651
	Weeks ahead 9	-1.638	0.061	-27.060
	Weeks ahead 10	-2.073	0.069	-29.880
	Weeks ahead 11	-2.492	0.081	-30.927
β_{10}	Month (May)	-0.484	0.045	-10.832
	Month (June)	-0.117*	0.042	-2.827
	Month (July)	-0.080^{ns}	0.044	-1.832
	Month (August)	-0.343	0.045	-7.539
	Month (September)	0.180	0.042	4.324
	Month (November)	0.074^{ns}	0.045	1.661
	Month (December)	-0.290	0.067	-4.317

All coefficients are significant at the 0.1% level except for those marked with '*' (significant at the 1% level) and 'ns' (not significant)

ahead are statistically significant predictors of the weekly change in the track utilisation plan (Table 6). A positive estimate of the regression coefficient for the previous change variable (0.188) indicates that when there was a change in trackwork length in the previous week, the probability of a change in the current week's scheduled trackwork time increases. In contrast, the count of previous changes variable shows a significant negative effect on the likelihood of change in trackwork (β_2 = -0.233, $p < 0.001$). This indicates that the likelihood of a change decreases with an increase in the count of previous changes.

Regression analysis showed that the trackwork scheduled on a single track is more likely to experience changes compared to a double track ($\beta_3 = 0.259$, $p < 0.001$). Furthermore, the trackwork planned at stations has a higher probability of change than trackwork planned in a line between stations ($\beta_4 = 0.147$, $p < 0.001$). The nighttime trackwork is less likely to be rescheduled compared to the one scheduled for the daytime (β_5 = -0.306, $p < 0.001$). Interestingly, the train traffic intensity variable does not have a statistically significant effect on the likelihood of change in the trackwork schedule. However, an increase in the proportion of freight trains is associated with a higher likelihood of change in trackwork schedules ($\beta_7 = 0.331$, $p < 0.001$).

As the planned duration of trackwork increases, the probability of change in the scheduled trackwork time decreases. The weeks ahead variable reveals that change is more likely to happen as the time approaches operation week, compared to week twelve. Lastly, trackwork scheduled in May, June, and August is less likely to experience changes compared to other months.

5 Discussion

Planning and scheduling in railway maintenance is a complex process involving numerous actors and resources. Achieving an equilibrium between project flexibility and schedule stability presents a significant challenge. Typically, the trackwork schedule change is reasoned by contractors striving to optimise their work to save resources and create the most efficient maintenance solution. However, such efforts to enhance cost efficiency can unintentionally undermine the plan's stability.

Despite strict deadlines outlined in Swedish regulations for scheduling trackwork [43], alterations to the track utilisation plan occur even during the period where changes are typically restricted - the four weeks leading up to execution. This paper demonstrates that the current practices to mitigate schedule instability, precisely the restriction period within the 12-week planning horizon, are not effective. The stability of the trackwork schedule diminishes as the execution date approaches. This observation aligns with [17, 19], highlighting the impact of uncertainties on trackwork project performance, often resulting in frequent rescheduling, and requiring train timetable adjustments. One possible explanation for this issue might be the absence of incentives imposed by the Swedish Transport Administration on contractors to adhere to the schedule as the execution date draws near. Additionally, the necessity for urgent repairs due to the state of the infrastructure could also be a contributing factor, which requires further investigation.

Using a unique empirical data set of trackwork plans in Sweden, this paper sheds light on the elements that compromise the stability of trackwork scheduling. Insights derived from the multiple regression analysis suggest that any alteration in the duration of trackwork previously observed significantly heightens the probability of similar changes in the subsequent planning cycle. This pattern suggests that maintenance planners should pay close attention to the recent history of changes in trackwork length, as it may signal an increased probability of future changes. In contrast, the analysis also shows that the accumulated number of previous changes in each trackwork has a significant negative effect on the likelihood of changes. This finding implies that adjustments done earlier in the planning horizon might lead to stabilising the trackwork schedule during the frozen plan period. This finding highlights the importance of providing additional incentives to maintenance contractor companies to finalise their schedules earlier in the planning horizon.

The study's findings suggest a pronounced vulnerability in single-track sections to trackwork schedule adjustments, in contrast to double-track, potentially due to capacity constraints present in single-track. This necessitates that railway operators allocate additional resources and attention to single-track sections and stations, as they may require more frequent adjustments in trackwork schedules. Additionally, the regression analysis demonstrates that the likelihood of change in trackwork plans decreases as the planned trackwork duration increases, advocating for the initial planning of extended maintenance durations, similar to the safety stock strategy in production management [3].

Notably, the lower likelihood of trackwork duration change during night shifts could be linked to higher infrastructure availability and lower train traffic intensity during nighttime in Sweden. Nevertheless, the overall traffic intensity surprisingly does not significantly influence schedule stability. However, the significant positive effect of the freight train traffic share highlights the importance of considering the specific composition of train traffic when scheduling trackwork. This may be particularly relevant in areas with a high proportion of freight trains. Seasonal variations also emerge, with certain months more susceptible to schedule changes. For instance, railway maintenance companies may need to allocate additional resources to mitigate uncertainty during months with a higher likelihood of change, such as May and August, to ensure that trackwork is carried out effectively.

6 Conclusions

This study was conducted to identify the factors influencing the stability of trackwork schedules. Schedule stability was analysed from the perspective of production scheduling in manufacturing systems. To the authors' knowledge, there was no previous application of schedule stability estimates for trackwork schedules. The measurements obtained in this study are essential for getting a realistic picture of the trackwork utilisation plan functionality. The paper answered two research questions: (1) How stable is the trackwork schedule at the tactical and operational planning levels? (2) What factors affect the modification of the booked time on track in the track utilisation plan?

Descriptive statistical analysis and multiple regression were employed to detect and explain the patterns of trackwork plan stability. The findings indicate a progressive decline in plan stability as the time approaches the trackwork execution stage. Significant predictors of schedule changes were identified as previous modifications in the plan, trackwork being located on a single track or at a station, and the predominance of freight train operations in the area where trackwork is planned.

Comprehending the factors that lead to trackwork schedule changes can help planners refine their decision-making processes and adapt their schedules proactively. To mitigate trackwork schedule instability, authors suggest systematically evaluating schedule stability and implementing incentives to encourage contractors to complete their trackwork schedules earlier in the planning horizon. Moreover, future research should focus on examining the risks of updating schedules close to the execution stage and investigating strategies to manage schedule instability effectively.

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Authors' contributions

Ivina D.: Conceptualisation, Methodology, Formal analysis, Writing - Original draft preparation, Investigation, Visualisation, Writing - Review and Editing. Ma Z.: Data curation, Validation, Supervision, Review and Editing.

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Declarations

Competing interests

The authors declare that no known competing financial interests, personal relationships, affiliations, or funding sources could potentially influence the work reported in this paper.

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