Efficiency of the trackwork scheduling process in Sweden

Ivina, Daria

2024

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Ivina, D. (2024). *Efficiency of the trackwork scheduling process in Sweden*. Department of Technology and Society, Lund University.

Total number of authors:
1

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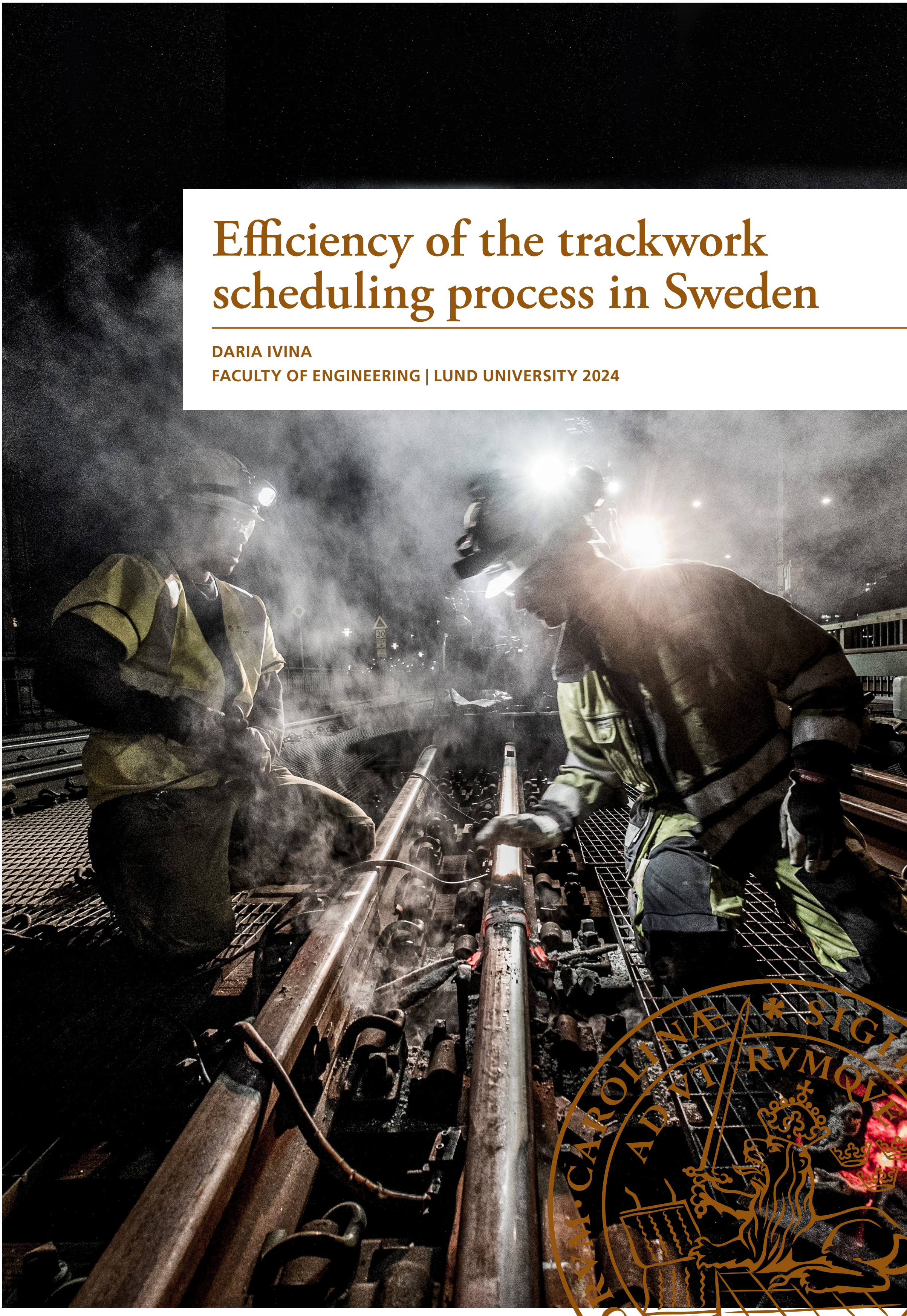
FACULTY OF ENGINEERING | LUND UNIVERSITY 2024



Printed by Media-Tryck, Lund 2024 NORDIC SWAN ECOLABEL 3041 0903

RAILWAYS require regular maintenance to ensure smooth and punctual train operations. However, if this maintenance is not properly planned and executed, it can inadvertently lead to the very delays it aims to prevent. This thesis dives into the intricate world of trackwork scheduling within the Swedish railway system, identifying the main factors that affect scheduling efficiency and discussing potential strategies to evaluate and improve efficiency.

LUND UNIVERSITY

Department of Technology and Society
Faculty of Engineering

ISBN 978-91-8039-964-7
ISSN 1653-1930

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Efficiency of the trackwork scheduling process in Sweden

Daria Ivina

DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University to be publicly defended on 20 of March at 09:00 in V:A hall, V-House, Department of Technology and Society, John Ericssons väg 1, Lund

Faculty opponent
Dr. John Armstrong, University of Southampton

Organisation: LUND UNIVERSITY

Document name: Doctoral dissertation **Date of issue:** 20 March 2024

Author: Daria Ivina **Sponsoring organisation:** Lund University

Title and subtitle Efficiency of the trackwork scheduling process in Sweden

Abstract

Efficient scheduling is vital for railway maintenance, which is increasingly challenged by rising train traffic and infrastructure wear. Trackwork often necessitates the reduction of train speeds and the partial or complete closure of tracks. Despite advancements in maintenance technology, the efficiency of planning processes, especially the repetitive tasks of planners and the adaptation to unforeseen events, have been under-addressed.

This thesis delves into the topic of trackwork scheduling efficiency in Sweden and analyses the current process through the lens of Lean philosophy. In this thesis, 'trackwork' specifically denotes preventive maintenance of railway infrastructure requiring temporary capacity restrictions, excluding renewal works that also fall under this definition but are outside the scope of this thesis. The goal of this research is to identify the main factors that affect scheduling efficiency in trackwork management and discuss potential strategies to evaluate and improve efficiency. In assessing scheduling efficiency, the focus is on the time dimension, where an efficient trackwork schedule involves utilising 100% of the booked time on the track, with waste defined as trackwork rescheduling or any avoidable disruption to train operations. In the context of trackwork scheduling, this might be caused by overscheduled possession time, where trackwork takes significantly less time than allocated, or underestimated maintenance duration, where trackwork completion exceeds the allocated on-track time.

Following the Lean framework, the five papers comprising this thesis correspond to the six practices of Lean production: elimination of waste, pursuit of zero defects, pull instead of push, decentralisation of responsibilities, a vertical information system, and continuous improvement. All six practices are emphasised in the aims and contributions of each of the five papers. Paper 1 describes the trackwork planning and scheduling process in the context of the Lean framework. Papers 2 and 4 are designed to explain the factors influencing changes in the trackwork schedule, drawing on empirical evidence from an interview study and logistic regression modelling. Papers 1, 3, and 4 suggest percent plan complete and schedule instability as methods of evaluating trackwork scheduling efficiency.

The qualitative and quantitative analyses of the trackwork scheduling and execution process reveal the nature of schedule changes and demonstrate how trackwork affects train traffic. The results indicate that the efficiency of trackwork scheduling is influenced by external and internal railway maintenance project uncertainties, a lack of trust between project managers and contractors, and poor knowledge transfer within contracting companies. Schedule changes may also derive from changes in contract terms, additional maintenance project requests from the Swedish Transport Administration, or shortages of specialists in specific technical areas, infrastructure failures, or urgent repair needs. Additionally, the consequences of inefficient scheduling are quantified: trains passing scheduled trackwork 1.43 times are more likely to experience delays of least one minute, and the risk of delay is higher for trains scheduled on double-track railway segments.

This thesis recommends the implementation of consistent measures to assess trackwork scheduling efficiency, applicable across strategic, tactical, and operational levels. These include regular assessments of maintenance window utilisation, estimation of trackwork schedule stability, and analysis of the impact on train traffic. This approach aims to provide a clear understanding of the scheduling's effectiveness in railway operations.

Key words: Railways, Maintenance Management, Trackwork, Project Uncertainties, Lean, Efficiency

Classification system and/or index terms (if any) Supplementary bibliographical information

Language English **ISSN**: 978-91-8039-964-7 (print); 978-91-8039-965-4 (electronic)

ISBN: 1653-1930

Bulletin – Lund University, Faculty of Engineering, Department of

Technology and Society **Number of pages**: 182

Price Security classification

Signature Date 2022-01-24

Efficiency of the trackwork scheduling process in Sweden

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LUND UNIVERSITY

Front cover photo by Magnus Neideman

Back cover photo by Ricardo Alonso Gonzales Vera

Faculty of Engineering

Department of Technology and Society

ISBN 1653-1930

ISSN 978-91-8039-964-7 (print); 978-91-8039-965-4 (electronic)

Nr 332

Printed in Sweden by Media-Tryck, Lund University

Lund 2024

Populärvetenskaplig sammanfattning

Järnvägar kräver regelbundet underhåll för att tågen ska gå säkert och i tid. Tyvärr kan banarbeten ibland leda till just de förseningar och trafikstörningar som de syftar till att förhindra. Min avhandling fördjupar sig därför i den mycket komplicerade banarbetsplaneringsprocessen, och granskar processen ur olika synvinklar för att kunna göra den mer effektivit.

Konceptuellt tar avhandlingen avstamp i 'lean', en metodologi och ett ramverk som fokuserar på att maximera värde genom att minimera slöseri. Här handlar det om att optimera den tid som tilldelas för banarbeten, förebyggande åtgärder som behöver göras men tillfälligt begränsar kapaciteten för tågtrafik, och minimera eventuella störningar och omplaneringar som kan påverka trafiken negativt. Forskningen kretsade främst kring att:

1. Identifiera faktorer som påverkar hur väl vi kan planera banarbeten. Att förstå komplexiteten och de oväntade problem som kan uppstå, såsom oförutsedda skador på spåren eller kommunikationsluckor mellan planerare och arbetare.
2. Att undersöka hur och varför banarbetsplaner så ofta behöver justeras när de planerade starterna närmar sig. Detta är avgörande eftersom ändringar i sista minuten kan orsaka betydande störningar i trafiken.
3. Att uppskatta hur banarbeten påverkar tågens punktlighet. Har ett tåg som passerar igenom ett banarbete större risk att bli försenat?
4. Förslag på hur banarbetsplaneringsprocessen kan förbättras för att bli mer effektiv och ha mindre påverkan på trafiken.

Kortfattat visar avhandlingen att planeringens påverkas av flera oförutsedda interna och externa faktorer. Det finns stora osäkerheter i form av oväntade infrastrukturfel och akuta reparationsbehov som stör planerna, och bristen på förtroende och effektiv kommunikation mellan projektledare och entreprenörer är anmärkningsvärd. Ändringar av planerna blir vanligare allteftersom man närmar sig startdatumen, och de planerade underhållsfönstren är ofta underutnyttjade. Vi ser också att tåg som passerar banarbeten oftare blir försenade, även om den totala effekten av detta inte är så stor. Avhandlingen föreslår några metoder för att mer noggrant övervaka och utvärdera förändringar i banarbetsplaner, vilket skulle öka förutsägbarheten och leda till en mer effektiv planering. Det är en fin balans som kräver noggrann planering, tydlig kommunikation och adaptiva strategier för att optimera användningen av tid och resurser vid banarbeten.

Sammanfattningsvis ger avhandlingen en fördjupad bild av hur man kan effektivisera banarbetsprocessen i Sverige, så att mer blir av i tid, och för effekterna på trafiken minskar.

To my family

Acknowledgements

Up to this point, a significant portion of my life has been devoted to Lund University, the division of Transport and Roads. I am deeply grateful for the person I have become thanks to this academic pursuit. My PhD journey has become a pivotal chapter of my life, largely shaped by the people I encountered along the way. I am endlessly grateful to my wonderful supervisors Lena Winslott Hiselius, Nils O.E. Olsson, and Carl-William Palmqvist for all your great support and academic guidance. They effectively guided my academic journey, helping me acquire the necessary skills and encouraging bravery in my research. My gratitude also extends to my first supervisor at Lund University, Aliaksei Laureshyn, who, during my time as a research assistant, revealed to me that research could be not only intellectually stimulating and scientific but also fun and linked to personal growth.

I wish to express special thanks to Lars Brunsson, Lars Johansson, and Peter Billsten, my mentors at the Swedish Transport Administration (Trafikverket) for the Bandat project, who always responded kindly to my countless requests. Bandat project, funded by Trafikverket, offered me a wonderful opportunity to be part of the Swedish railway community through KAJT. I always felt welcomed at KAJT, thanks to Martin Joborn, Sara Gestrelius, Jennifer Warg, and Abderrahman Ait Ali. I am particularly grateful to Emma Dyrssen and Ola Malmberg, for their interest in my research findings and for the stimulating discussions around them. My sincere thanks go to all at Trafikverket who engaged with my research, offering valuable feedback and sharing insights. A big thank you to everyone involved in interviews, phone calls, and those who helped with information and input: Peter Backman, Marie Schultz, Pernilla Merkenius, Jesper Andersson, Göran Lindberg, Erik Hellberg, Morgan Segerstrom, Patrick Huhtimo, Ludwig Appelblad, Jonas Bälter, Mathias Hofrén, Jonas Kjellgren, Kristian Ljunberg, Johan Holmdahl, and Sven-Bertil Jovald.

During the project, I received great help from the reference group members: Jonatan Gjerdrum, Kenneth Håkansson, Kristian Lorentzon, Ramin Karim, and Marie Dagerholm. Thank you, Tomas Lidén, for our productive discussions, your valuable advice, and inspiring ideas. It is always a pleasure to meet you at conferences. Anders Peterson, thank you for becoming my railway friend and sharing my interest in fun railway facts. A special thanks to Taku Fujiyama, for our discussions and your kind advice. Zhenliang Ma, I greatly appreciate our collaborative work. Thank you to Norman Weik, Albert Lau, and Bo-Lennart Nelldal for your insightful comments and constructive feedback, which significantly improved my work.

My former supervisors played a crucial role in guiding me towards the path of becoming a researcher. My dear Rūta Garuckienė, who became my "Lithuanian mom," has been the greatest mentor in the industry. The projects we worked on together were always fascinating. I am grateful to my master thesis supervisors:

Mykola Tregub in Ukraine, and Vytautas Palevičius in Lithuania, for encouraging me to pursue research.

I am immensely grateful for the community I was part of during my PhD studies at K2, the Swedish Knowledge Centre for Public Transport. It was a unique place to share new ideas, have the most inspiring conversations, and learn extensively about the topic I am passionate about – public transport. My thanks go to my fellow PhD students at K2 Emma, Sergei, Eva-Lena, Vendela, Jakob, Russell, Jessica, Gustav, and to the people from whom I learned a great deal about leadership, organisation, and expertise: Helena, John, Chiara, Ebba. Thank you, Lia, Chunli, Phil, and Michelle, for your friendship and the many wonderful moments we shared. I wish you all the best in your future endeavours.

My railway group provided me with countless positive experiences. I felt like part of a railway family, surrounded by people who shared the same goals and who were incredibly fun to be with. Thank you, Ruben, Kah Yong, Michelle, Grace, Joe and Frida, for your companionship. I will always cherish your friendship, wisdom and the reminder that "*there are so many things to be done that cannot be done*". Our extended railway family at KTH, including the most brilliant railway researchers in Sweden - Ingrid, Emil, Niloofar, and Elin, deserve thanks for our productive manuscript peer review meetings.

I am grateful to the former PhD students who inspired me and helped me understand the path to becoming a PhD: Erik, Alfred, Jean, Joel, Hampus, Azreena, Ulrik, and Pajtim. My fun colleagues, Hampus and Carl always made discussions about research ideas interesting. Thank you for always being cheerful, along with Janet, Carmelo, Joacim, Maya, Matilda, Zhankun, Kevin, and Sadegh, for the great conversations in the coffee room that always lifted my spirits. Thanks to all my colleagues at Transport and Roads, you are wonderful people! Thank you, Helena, Petra, Astrid, Thomas, Fredrik, Vanessa, Till, and Anders.

I will always be grateful to my wonderful friend, Oksana, who is intelligent, dedicated, and a very good person. Thank you very much for all our shared adventures and for being such a great friend. Thanks to my soul sisters, the "PhD-to-be" support group, and my best friends in Sweden, Kreema and Sakshi. I am forever grateful for your friendship and all our fun and endearing moments together. You always make me feel at home. Thank you to all my friends in Sweden; I am so grateful to have met such wonderful people like Agnieszka, Alan, Ilayda, and Rafsan. I am also thankful to my friends in the UK; without your kind support, this journey would not have been complete. Thank you all for being such wonderful people and so nice to be around.

This journey would not have been as joyful and adventurous without my beloved husband, Ricardo, whom I met at the very beginning of my PhD studies. Your love, support, and intellectual companionship have been the greatest blessings. You are the love of my life, the best partner in everything. Together, we are continually growing, achieving, and developing. Thank you for your passion, support, and always being there for me. I am forever grateful for your expert peer review of all my papers. The PhD journey marks the happiest moments of my life with you, and I am looking forward to living through all the adventures we will share.

I am grateful to my parents, Svitlana and Serhii, the most supportive people in the world. They provided a solid foundation of love for good stories and engineering and always encouraged me to forge my own path. Thanks to my new much-loved family, my parents-in-law, Rolando and Lida, thank you so much for your great unconditional love. Thanks to my brother, Andrey, who always ensures that I remember to have fun and live life beyond my studies. Thanks to my Cheli, Rolo, Alina, Natalia, Vova, Ira and all my extended family, thanks to you I never feel alone. To my beloved grandparents and godmother, who will forever be in my heart. A big thank you to my family in Ukraine for your support and prayers. We have persevered through the toughest times and remained strong. Slava Ukraini!

“Projects do not live in a world on their own;
they are influenced by changes around them.”

Nils O.E. Olsson

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Introduction

Train traffic and maintenance

To reduce emissions, the European Commission has set a target to develop a competitive and sustainable transport system by 2050 (European Commission, 2011). A key part of this initiative is improving railway infrastructure and technology to increase its competitiveness and market share in freight and passenger transport. In this context, one tangible objective is achieving a modal shift that would see 30% of road freight switched to rail and waterborne transport by 2030. Railway transport makes an important contribution to sustainable mobility, with 60% of Europe's Main Line rail networks electrified. In Sweden, the proportion is even higher, at 75% (Eurostat, 2023). Freight rail transport in Europe has been growing since 2011, with growth expected to continue (Eurostat, 2023; Islam et al., 2016; Sasidharan et al., 2020). Notably, in Sweden, over the past 20 years, both freight and passenger train traffic have seen a robust increase of 30% (Trafikanalys, 2022).

Recognising the need to meet future traffic demand, the existing infrastructure must adhere to quality requirements. In the sustainable transition to rail services, reliability, availability, and service safety play vital roles (Islam et al., 2016). Punctuality is crucial in maintaining the competitiveness of railway systems. However, train delays, which adversely affect both passenger and freight services, can arise from various factors, including mechanical and infrastructure failures, maintenance work, human errors, network control decisions, and unforeseen incidents (Olsson & Haugland, 2004; Palmqvist et al., 2017). Primary delays, often resulting from infrastructure failures or malfunctions, not only hinder the goal of achieving a 95% punctuality score in Sweden but also escalate operating costs (Palmqvist et al., 2023; Palmqvist et al., 2017; Sasidharan et al., 2020). Therefore, this thesis delves into the complex relationship between track maintenance and train delays, acknowledging that while track maintenance contributes to delays, it is not the sole cause. Delays often result from a combination of events, including maintenance, occurring simultaneously at the same location.

To ensure the reliability of the railway system and the efficiency of train services, maintaining the railway track in good condition is crucial (Khajehei, 2021). This recognition has guided Sweden's investment strategy, which prioritises railway infrastructure and maintenance projects, giving them the highest funding in the transport sector for the next decade (Trafikverket, 2021). Investment in railway infrastructure, specifically for renewal and maintenance, has seen a significant increase of 50%, reaching a considerable 30,769 million SEK in 2021 (Trafikanalys, 2022). This trend can be attributed to network expansion, increased traffic, and an ageing infrastructure that demands more investment for upkeep (Ait-Ali & Lidén, 2022). Beyond the direct costs of maintenance, like materials and labour, it is crucial to recognise the broader social costs associated with maintenance, including train cancellations or delays (Sasidharan et al., 2020).

Limited access to railway track gives rise to a unique challenge, which often results in competition between train operations and maintenance (Forsgren et al., 2013). Interestingly, while insufficient maintenance can lead to increased breakdowns and consequent delays, the execution of essential maintenance activities can also temporarily disrupt train schedules (Higgins, 1998; Olsson & Haugland, 2004). This is particularly true when maintenance demands an adaptation of train paths for trackwork, which requires train timetable rescheduling (Peterson et al., 2019). Furthermore, railway trackwork may lead to greater capacity restrictions for train traffic, such as track closures, speed restrictions, and single-track operation (Peterson et al., 2019; van der Kooij et al., 2017). Therefore, it is essential to achieve a balance between train operations and trackwork.

Effectively managing time on the track is a significant task in railway operations, where a balance must be struck between train operations and maintenance. This responsibility is guided by the European Union's SERA directive, as adhered to by the infrastructure manager (Council of European Union, 2012). In line with this, Sweden, with its vertically separated railway market, follows these regulations. Here, railway services are provided by various companies while the Swedish Transport Administration oversees infrastructure management (Ait-Ali & Eliasson, 2021). Although there has been extensive discussion on efficient railway capacity allocation in the Swedish context (Ait-Ali & Eliasson, 2021; Broman et al., 2022; Gibson, 2003), the specific aspect concerning the efficiency of the process for allocating capacity for railway track maintenance has not been thoroughly explored.

Efficient trackwork scheduling

Scheduling is an activity aiming to optimise the allocation of plans and available resources, manage workloads efficiently, and handle human resources effectively, with the ultimate goal of ensuring the most optimal use of time and resources in production (Palmer, 2013). Efficient scheduling is crucial for railway infrastructure maintenance, as access to the track is limited. More train traffic leads to increased wear on railway infrastructure, which in turn necessitates more maintenance. At the same time, maintaining railway track components requires time free from train operations. In other words, increased train traffic drives the need for more trackwork, which can affect train traffic (Budai-Balke, 2009; Stenström et al., 2016).

Performing repairs on the track while trains are operating poses a significant risk to the lives of maintenance workers. Therefore, track maintenance and train operations are mutually exclusive activities. Additionally, trains must slow down if work is being performed on a parallel track. While many studies have focused on optimising maintenance strategies and the technological aspects of maintenance (Sedghi et al., 2021), one crucial aspect has been overlooked. This aspect is related to waste in production, specifically the time wasted by trackwork planners who must repeatedly perform similar tasks. Planned maintenance can face uncertainties and significant challenges, necessitating continuous adjustments to the plan in real time. Therefore, it is essential to examine these aspects of planning and executing trackwork.

In Sweden, non-emergency railway maintenance requiring more than 15 minutes must be scheduled at least four weeks in advance (Trafikverket, 2015b). This necessitates a complex planning process that demands coordination among various stakeholders, balancing infrastructure needs, worker safety, and uninterrupted train traffic. Maintaining this equilibrium in a dynamic environment poses a significant challenge. Although Lean principles have never been used to manage projects in railway maintenance, we suggest that its application would present an effective solution. The Lean philosophy, centred on maximising customer value and minimising waste, advocates for continuous improvement of the process and respect for the individuals involved. Its primary goal in any process, including railway maintenance, is to enhance efficiency, which involves the wise use of resources including time, materials, and labour, while simultaneously reducing waste. As my research progressed, I sought to integrate maintenance management, operations research, and project management principles with train operations. I adopted this comprehensive approach to confront and remedy the existing inefficiencies in planning, ensuring a smoother, more effective maintenance schedule for railways.

Research gaps

This thesis aims to address significant research gaps in railway maintenance research, with a particular focus on understanding and enhancing the trackwork scheduling process in Sweden. Trackwork requires temporary capacity restrictions for train traffic. Therefore, central to this thesis is an in-depth analysis of decision-making regarding railway capacity allocation for trackwork and the trackwork schedule's resilience to external influences. While previous research has applied Lean principles to enhance railway operations and maintenance management, a gap exists in their specific application to railway maintenance scheduling. This thesis aims to bridge this gap, exploring the application of Lean principles in the context of time allocation for maintenance operations on tracks. While the focus of this research is Sweden, the challenges in railway maintenance observed here have global parallels, underscoring the broader relevance of this thesis to other countries and other industries.

No prior research has thoroughly examined the impact trackwork rescheduling on overall railway system efficiency. This thesis addresses the organisational aspects of trackwork processes, emphasising the importance of revealing project uncertainties and their effect on trackwork scheduling. Currently, trackwork scheduling relies predominantly on capacity allocation process timelines rather than information availability, resulting in operational unpredictability. This research views trackwork through the lens of Lean production, which has been successfully applied in construction, production, and maintenance to enhance project management and workflow reliability.

Additionally, existing studies on railway capacity allocation and timetable optimisation do not consider the capacity reserved for trackwork and the complexities involved in its scheduling. This oversight results in underestimating maintenance needs, leading to infrastructure failures. This thesis advocates for a well-coordinated capacity allocation process, integrating railway maintenance with train traffic. Furthermore, this research addresses the complex relationship between railway maintenance activities and train punctuality. Previous studies have identified various factors contributing to train delays, but the specific role of trackwork has been overlooked.

Scope and aim of the thesis

Scope

In the context of this thesis, ‘trackwork’ is defined as preventive maintenance activities related to railway infrastructure that require temporary capacity restrictions for train traffic. This thesis is particularly focused on planned preventive maintenance. It intentionally excludes reinvestments and corrective maintenance, which are beyond the scope of this investigation.

Trackwork scheduling efficiency can be analysed from different perspectives, focusing on the measures taken to maintain infrastructure, labour efficiency, choice of materials, or the use of time on track when trackwork is performed. Efficiency in trackwork scheduling, as explored in this thesis, signifies the optimisation of the possession allocation process while minimising the need for rescheduling. While it is important to address what happens at the execution stage, this study does not consider in detail how the time on track is used by contractors. Instead, it focuses primarily on the efficiency of trackwork from the standpoint of time management decisions, the time invested in these decisions, and their subsequent impacts.

This thesis adopts a unique perspective, focusing on historical data and analysing how the existing regulation of the trackwork scheduling process functions in practice. Rather than questioning the validity of the chosen maintenance strategy, the focus is on understanding how the existing strategy is implemented in real-world scenarios. This thesis examines the planning and scheduling processes of trackwork, conducted in accordance with Swedish regulations governing railway capacity allocation and regional contractual agreements. The focus is on the decisions and information surrounding the planning and implementation of trackwork and their subsequent impact on train operations. This approach aims to achieve an understanding of the dynamics of trackwork scheduling within the framework of Swedish railway operations.

Focusing on the trackwork scheduling aspect, the initial stage involves coordinating time slots for maintenance activities a year in advance, in alignment with the train schedule. This arrangement ensures that train operating companies experience minimal operational disturbances due to maintenance. However, while maintenance is inherently aimed at preventing operational issues, paradoxically, it can also lead to train delays. Understanding the various factors contributing to these delays is crucial, but this understanding is insufficient if we do not consider the broader context in which these factors manifest. Therefore, it is essential to investigate the trackwork scheduling system as a holistic process, considering each step in detail.

Aim

This thesis examines the efficiency of trackwork scheduling within the Swedish railway system. Focusing on the trackwork process, which is vital for railway infrastructure functioning, the thesis delves into the complexities and challenges posed by the necessity of conducting maintenance during periods free from train operations. The primary objective of this work is to unravel the complexities of the trackwork scheduling process and assess its efficiency. It *aims* to identify and analyse the factors that affect scheduling efficiency and the conditions under which they impact the process. The overarching goal is to enhance the efficiency of trackwork scheduling in the Swedish railway context.

Research questions

This thesis revolves around four complementary research questions that collectively contribute to a comprehensive understanding of the research problem. Research question (RQ) 1 serves as an exploratory inquiry designed to identify factors influencing the efficiency of the trackwork scheduling process. This question delves into the reasons for modifications to trackwork schedules. In this context, rescheduling is a consequence of inefficient scheduling practices. RQ2 and RQ3 focus on examining how and when trackwork schedules are adjusted, and how those adjustments influence train delays. These questions provide valuable insights into the repercussions of inefficiencies in scheduling. Finally, RQ4 is directly linked to the main goal of the thesis, which is to identify potential strategies for enhancing the efficiency of the scheduling process.

Research questions:

RQ1: What factors influence the efficiency of trackwork scheduling, and in what ways?

RQ2: How and to what extent are trackwork schedules adjusted over time?

RQ3: What impact does scheduled trackwork have on train operations?

RQ4: In what ways can the trackwork scheduling process be improved?

The motivation behind the first research question lies in understanding the complex nature of the planning process. To achieve this, we must first break down the process into distinct steps, delineating the boundaries between each level and structuring the process accordingly. In this thesis, changes in the trackwork schedule are seen as inefficiency. This leads to the second research question. By identifying when and what changes occur during the planning and scheduling process, we can undertake targeted actions towards enhancing efficiency.

The reasoning for the third question is that as the main goal of railway maintenance is to uphold operational standards and prevent disturbances, train delays caused by trackwork operations signal a problem in trackwork planning. This issue may arise from train paths not aligning well with trackwork schedules or trackwork contractors not adhering to the schedule, thus affecting train operations. The last question forms the foundational rationale across all the included papers, serving as the central justification for the comprehensive research compiled in this thesis.

Structure of the thesis

This thesis comprises a research summary and the five papers included in the appendix. First, the *Introduction* chapter outlines the research gaps addressed in this thesis, defines the scope and aim of the thesis, and then lists the research questions. Next, the *Background* chapter outlines the research context, including maintenance, maintenance management, the Lean philosophy, efficiency, and railway maintenance in Sweden. The subsequent chapter, *Methodology*, justifies the chosen framework and methods, provides an overview of the datasets, and describes the connections between papers. Then, the *Results* chapter provides the summary of papers and answers to the research questions. The second-to-last chapter, *Discussion*, discusses the main findings and summarises the contributions of this research and highlight the future research directions. The thesis concludes with the *Conclusions* chapter, which encapsulates the main findings of the research.

Background

Maintenance

European standards (British Standard Institution, 2010) define maintenance as a combination of actions during the life cycle of an item to retain it in, or restore it to, a state in which it can perform the required function. According to RailNetEurope (2022), maintenance is 'an activity aiming to maintain something in good working order, prevent operational disturbance and/or uphold a given technical standard'. It is evident from both definitions that the fundamental objective of maintenance is to safeguard the continuous, efficient, and safe operation of the designated infrastructure.

The railway infrastructure encompasses a range of technical subsystems, including track, electrical, signalling, and telecom systems, with rolling stock classified separately (Al-Douri et al., 2016). The railway infrastructure is a complex assembly crucial for train operations, featuring assets such as the railway (rails, sleepers, fastenings, ballast), switches and crossings, bridges and tunnels, catenary systems, and signalling systems (Budai-Balke, 2009). Railway infrastructure maintenance generally refers to regular and routine tasks including inspection, cleaning, lubrication, minor repairs, adjustments, and the replacement of parts expected to wear out over time.

There are two basic types of maintenance (Ben-Daya et al., 2016): corrective and preventive maintenance. Corrective maintenance, undertaken after an item has failed, involves repairing or replacing the damaged component. A key characteristic of this maintenance type is its unpredictability, as it typically cannot be scheduled in advance, unlike the planned nature of preventive maintenance (Budai-Balke, 2009; Deighton, 2016). Corrective maintenance aims to quickly restore a system to operational status, minimising additional costs incurred by the owner due to machinery failures. When an element has failed, corrective maintenance tends to be significantly more costly than preventive maintenance (Mostafa et al., 2015; Yile et al., 2008), and often requires that the track be completely closed to traffic until the fault is rectified (Trafikverket, 2015c).

Preventive maintenance

Only preventive maintenance can be planned in advance and scheduled (Al-Douri et al., 2016). This thesis focuses on this type of maintenance activity. The purpose of preventive maintenance is to reduce the probability of an item's failure. Preventive maintenance is conducted regularly and divided into subgroups (Ben-Daya et al., 2016): clock-based, age-based, and condition-based. Clock-based preventive maintenance is performed at a specific period, depending on the time since the last maintenance. A drawback of this method is that items are replaced at predetermined intervals without considering historical events. Consequently, the item might be changed due to failure shortly before the clock-based due date, and then changed again on the scheduled maintenance date. Age-based preventive maintenance is performed when an item has been in operation for a certain length of time. This type of maintenance is used when the cost of failure is higher than the cost of planned maintenance (Lidén, 2016). Condition-based preventive maintenance focuses on the condition of the item and predicts when a failure will occur.

Preventive railway maintenance includes visual inspections, replacing sleepers, re-railing, rail grinding, ballast cleaning, lubrication, grinding repairs, tamping maintenance and parts replacements (Lidén, 2016; Trafikverket, 2015c). These tasks can be categorised into two types (Budai et al., 2006). The first type includes regular, smaller tasks like inspecting rails, switches, and signalling systems, along with minor repairs like switch and track revisions or lubrication. According to (Lidén, 2016), this type of preventive maintenance requires a shorter planning horizon and takes less time to perform. The second type involves larger, less frequent activities such as ballast cleaning, tamping, and rail grinding, typically done every few years.

To enable a comprehensive understanding of the context of this thesis, it is essential to clearly delineate between the concepts of railway maintenance and trackwork. Trackwork incorporates both maintenance and renewal activities on railway infrastructure components, which necessitate planned temporary capacity restrictions on the track where the activity is taking place. Railway maintenance refers to activities that maintain railway infrastructure in a functional state, prevent operational disruptions, and adhere to technical standards. On the other hand, 'renewal' denotes substantial substitution work on a subsystem or subsystem part, which does not alter the subsystem's overall performance (RailNetEurope, 2022). In this thesis, we refer to both renewal and maintenance activities, provided they are planned well in advance and do not require a planned temporary capacity restriction for more than 24 hours.

When examining the capacity usage and planning timelines for railway infrastructure maintenance in Sweden, there are two maintenance types: basic maintenance and railway infrastructure reinvestments. The former refers to activities that maintain railway infrastructure in a functional state and are performed regularly, which could be corrective or preventive. Typically, basic maintenance activities require planned temporary capacity restrictions of less than 24 hours. More substantial maintenance undertakings – preventive and remedial measures not classified as basic maintenance – are referred to as reinvestments (Trafikverket, 2023b).

Possessions

To ensure an efficient capacity allocation and maintenance schedule, it is crucial to choose the optimal times for trackwork. This operational procedure is referred to as 'possession' booking in some literature (Forsgren et al., 2013; Lidén, 2015). In railway operations, possession refers to a period when the full use of a section of the rail network is restricted for train traffic to facilitate maintenance or construction works (RailNetEurope, 2022). This operational arrangement, which may be planned or unplanned, ensures the safety of work crews by prohibiting scheduled train movements. The need for possession arises from the necessity to disconnect or limit the use of signalling equipment during upgrades or repairs.

Planned possession requires temporary capacity restriction, including track closures, speed reductions, and single-track operation (RailNetEurope, 2022). In some cases, capacity restrictions necessitate adjustments to paths for trackwork through train timetable rescheduling. The topic of strategic and operational planning for maintenance activities and train operations in parallel has received some research attention (Budai-Balke, 2009; Buurman et al., 2023; Forsgren et al., 2013; Lidén, 2016).

The level of capacity utilisation affects the availability of track access for maintenance. In general, maintenance costs are higher in areas with greater capacity utilisation because the maintenance becomes more fragmented, significantly increasing maintenance costs. The cost of possession is defined by the time during which a railway track cannot be used for railway traffic (Budai et al., 2006). According to (Odolinski, 2019), the cost of maintenance time also depends on railway line capacity utilisation, with a higher capacity utilisation increasing the cost of possession.

Based on possession cost and the impact it might have on train traffic, (Budai-Balke, 2009) distinguished three types of possession relevant in the context of the Netherlands: overnight possessions, Sunday and full weekend possessions, and daytime possessions. While this classification is influenced by varying capacity allocation strategies unique to each country, it is applicable in the Swedish context. Overnight possessions occur for a few hours between the last and first trains of consecutive days, offering limited time for productive maintenance work due to the need to set up and clear the site. This reduces efficiency and necessitates multiple possessions. Sunday and weekend possessions, spanning entire weekends or Sundays, allow for continuous maintenance work and less passenger disruption, with train services either rescheduled, rerouted, or replaced with alternative transportation, like buses. Daytime possessions typically cause significant disruptions to passenger services. They are more feasible during low-traffic periods or on less frequently used tracks and tend to be associated with high costs, increased passenger inconvenience, and a greater risk of accidents.

Maintenance requires time on track, and several strategies are employed to ensure regular access to it. In Sweden, a concept called maintenance windows ensures that annual timetables allot enough time for trackwork. In the Netherlands, regular track access is ensured by maintenance schedules, which allocate regular train-free periods when trackwork can be conducted safely for maintenance workers. However, according to Nijland et al. (2021), these assigned time periods are not always utilised by contractors, which can cause unnecessary disruptions in train traffic (Budai-Balke, 2009; Nijland et al., 2021). In this thesis, we consider these unused maintenance windows inefficiencies.

Maintenance project management

Similar to other sectors, railway maintenance is structured in the form of projects. A project is a temporary and unique endeavour aimed at producing a specific result, such as a product, service, or capability (Project Management Institute, 2017). This definition highlights two key aspects: its finite nature, marked by a clear start and end, and its uniqueness, which often involves novel collaborations or characteristics specific to the project's output. In these projects, planning plays a pivotal role in ensuring that objectives related to time, cost, quality, and safety are met. Planning plays a critical role in the early phases of a project, when the proper allocation of time and resources to planning efforts increases the probability of success. Planning reliability and project performance are positively correlated. A reliable plan, dependent on many factors, minimises financial losses during project realisation if it undergoes fewer changes along the way.

Maintenance management involves maintenance-related decisions at the strategic, tactical, and operational levels (Ben-Daya et al., 2016; Budai-Balke, 2009; Lidén, 2015). The strategic level includes large-scale maintenance planning, including predicting future demand and contract design. The tactical level includes maintenance planning, scheduling, and rescheduling, as well as the routing of maintenance teams and vehicles. The operational level involves maintenance project implementation. As this thesis aims to investigate the factors affecting trackwork scheduling efficiency in Sweden, it focuses on the tactical and operational levels of railway maintenance management (Figure 1).

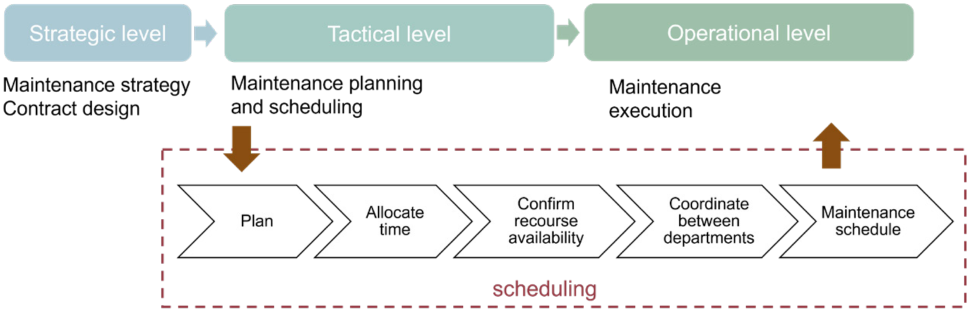

Figure 1.Levels of decision-making in maintenance management.

Planning and scheduling

Much like other maintenance projects, railway maintenance is performed following five main steps: recognising the tasks to be undertaken, creating a plan for the work, scheduling the related tasks, implementing the work, and finalising the work according to the plan. While the literature on production and maintenance management clearly differentiates between the planning and scheduling processes, railway maintenance research has yet to thoroughly examine this distinction (Sedghi et al., 2021). Maintenance planning involves preparing a plan for forthcoming works, managing resources, and prioritising repairs (Palmer, 2013). Maintenance scheduling involves allocating the plan and available resources, optimising the workload, and managing human resources (Palmer, 2013). The goal of scheduling is to ensure the most optimal use of time and resources in production.

In the planning and scheduling process, decisions regarding resource allocation and work prioritisation are based on the information available at the moment the decision must be made. In other words, trackwork planning and the scheduling process align with the information available. Currently, the decision-making process for scheduling trackwork largely depends on manual methods as well as the expertise and judgement of the professionals involved in the process (Peng & Ouyang, 2012). The railway maintenance planning process involves a complex, structured flow from the strategic planning stage to the execution stage. Scheduling is a critical process in the trackwork flow, as its efficiency directly impacts overall performance. The ultimate value of an efficient scheduling process is a reliable railway system with no delays or infrastructure failures, which benefits all stakeholders.

Optimal trackwork scheduling

Scheduling trackwork is a complicated task, as each activity on the track must receive a planned temporary capacity restriction (TCR). TCR, also known as possession, is a temporary operational arrangement that forbids or restricts train operation in the areas limited by the signal or the track section (RailNetEurope, 2022). The primary operational restrictions for train traffic are the closure of the work section, single-track operation, speed restrictions, and occupancy by engineering vehicles and work trains (Peterson et al., 2019).

Over the past 20 years, many automated solutions have been developed to simplify and optimise the decision-making process in maintenance and possession allocation (Lidén, 2015; Sedghi et al., 2021). Higgins (1998) developed a maintenance planning model that optimises the time on track for maintenance and available crews while simultaneously minimising disruptions to and from train services, emphasising that scheduling must become an integral part of the capacity allocation process. Armstrong and Preston (2020) emphasised the need to improve maintenance planning efficiency by employing predictive maintenance and optimising the balance between maintenance possession times and traffic flow. For contractors seeking to minimise maintenance costs and optimise work, Su et al. (2019) developed a model for optimal scheduling of track maintenance activities. Peng and Ouyang (2012); (2014), Siqueira Bueno et al. (2019), and Nijland et al. (2021), developed a mixed-integer linear programming model to optimise both maintenance schedules for varying maintenance needs and performance among train operators and contractors. Tezuka et al. (2015) proposed a maintenance schedule optimisation method based on failure probability distribution.

The scheduling process is typically structured with a rolling horizon (Wang et al., 2019). A rolling horizon plan is a planning technique used in railway maintenance projects to ensure efficient and effective railway infrastructure maintenance (Consilvio et al., 2021). It involves creating a long-term maintenance plan that is continuously updated as new information becomes available. The advantage of a rolling horizon plan is that it allows railway maintenance managers to be responsive to changing circumstances and uncertainty, such as unexpected failures or changes in capacity availability.

Project uncertainty

In project management, project uncertainty refers to unpredictability and a lack of definitive knowledge regarding events that may impact a project's outcome. It encompasses two main viewpoints: the first, following (Galbraith, 1974), perceives project uncertainty as the gap between the information needed and the information available, which impacts decision-making. The second view, aligned with risk management theories (Rolstadås & Johansen, 2008), considers uncertainty in terms of the probabilities and consequences of unforeseen events.

Managing project uncertainty involves identifying potential risks, assessing their likelihood and impact, and developing strategies to mitigate or adapt to these risks to ensure successful project completion (Perminova et al., 2008; Rolstadås & Johansen, 2008). Understanding and identifying project uncertainties, and identifying effective strategies to mitigate them, is crucial for trackwork process efficiency.

Schedule instability

Project uncertainties trigger schedule instability, which is characterised by fluctuations in the supply and demand of components in the master production schedule system caused by inaccurate forecasts or other factors (Pujawan, 2004). The instability of scheduling activities can be estimated as the sum of changes that a schedule undergoes during execution or the percentage of deviation from the initial schedule. A simple method of measuring instability is counting the unplanned and revised orders in the initial phase of the planning horizon as the schedule progresses (Kabak & Ornek, 2009).

In production management, schedule stability refers to the consistent execution of planned activities within a specified time frame. It involves aligning estimated demands with actual production needs, thus minimising alterations across scheduling cycles, streamlining coordination, and optimising resource use to enhance operational efficiency (Inman & Gonsalvez, 1997; LaForge et al., 2000; Pujawan et al., 2014). In railway maintenance scheduling, schedule stability means keeping maintenance plans and resource allocation consistent, thereby reducing changes in the schedule cycle. This approach enhances resource efficiency, improves team coordination, and increases the likelihood of meeting maintenance goals on time.

Rescheduling

Rescheduling involves updating a current production schedule to address unexpected disruptions, such as unplanned tasks or equipment breakdowns (Vieira et al., 2003). In possession planning, rescheduling entails either modifying the length of the trackwork or completing the planned maintenance at a different time than intended. Adapting production plans that become unfeasible due to unexpected disturbances is crucial for effective production planning, necessitating a balance between schedule stability and flexibility (Olsson, 2006). However, as identified by (Guenther Schuh, 2019; Pujawan, 2004; Vieira et al., 2003), regular alterations to schedules are considered detrimental to project success, as they may lead to reduced staff productivity and increased inventory and production costs.

Lean philosophy

Lean philosophy can help identify and eliminate non-value-added activities that result in waste and delays, such as inefficient resource utilisation, poor planning, and inadequate communication. Lean philosophy has been widely implemented in production management but has been overlooked in railway maintenance management. Lean aims to optimise flow, reduce uncertainty, and improve efficiency by continuously improving processes and eliminating activities that do not add value (Ballard, 1999; Parry & Turner, 2006; Womack & Jones, 1997). The concept aims to address project needs on two levels: external, where it focuses on the value for the customer, and internal, where it focuses on executing the delivery process with minimal waste (Hansen & Olsson, 2011). Research has demonstrated the positive effects of introducing Lean principles on customer satisfaction and operational efficiency in a range of industries (Aziz & Hafez, 2013).

Lean philosophy is driven by five key principles (Womack & Jones, 1997): (1) creating value for the customer, (2) mapping the value stream, (3) ensuring flow, (4) a pull or 'just in time' project delivery approach, and (5) perfection. To address and follow these five core principles, Lean practices were developed. Practices are the activities undertaken to change the organisation in pursuit of the desired performance (Åhlström, 2004). Lean practices include:

1. Elimination of waste. Everything that does not add value to the product is considered waste and must be eliminated. Use preventive maintenance to reduce downtime, optimise layout from safe transportation distances, and eliminate causes for rework.
2. Zero defects. Ensure product quality and provide fault-free components. Delegate the responsibility for quality assurance to all participants in the process. Prevent failure before it happens by ensuring the quality of the product from the early stages.
3. Pull instead of push. Production is based on demand from customers. Utilise the just-in-time principle of material control. A pull scheduling system provides each operation in the manufacturing process with the correct part in the appropriate quantity and at the right time.
4. Decentralisation of responsibilities. The responsibility for decisions in the process is pushed down to the lowest levels of the organisation, reducing hierarchical levels. People who know more about the task take leadership.
5. Vertical information system. Information flows directly to the relevant decision-makers to allow for rapid feedback. New, up-to-date information is available when it is needed most.
6. Continuous improvement. Learning from experience and applying knowledge in practice. The goal is to reach perfection.

According to Lean principles, it is essential to track completed work and compare it with the initial plan to improve the planning process. Percent plan complete (PPC) is metric that measures workflow reliability and helps identify reasons for plan failure so they can be addressed (Ballard, 1999).

Lean maintenance

Lean principles have been adapted into the field of maintenance management, giving rise to a new concept known as 'Lean maintenance' (Mostafa et al., 2015; Smith & Hawkins, 2004). Smith and Hawkins (2004) defined Lean maintenance as a 'proactive maintenance operation employing planned and scheduled maintenance activities through total productive maintenance practices'. The top priority for Lean maintenance is prevention measures, which means not letting the failure of an item influence production. Lean maintenance differs from Lean manufacturing in that it focuses on the planning stage. For Lean maintenance, 'waste' means inefficiently planned maintenance requiring repeated operations or inadequate track maintenance (Olofsson, 2019). According to Dirnberger and Barkan (2007), the inefficiently planned maintenance is linked to direct waste in the railway industry.

Efficiency

Efficiency is defined differently in various studies, reflecting the diverse perspectives and contexts in which it is used (Zidane & Olsson, 2017). In the context of project management, efficiency is often associated with the optimal use of resources to achieve specific goals. This encompasses not only economic aspects but also includes considerations of time, quality, and scope. Olsson (2008) emphasised the distinction between efficiency and effectiveness, where efficiency is about producing direct outputs and effectiveness involves adding value for owners and users. In other words, efficiency is an internal measurement focused on doing things in the right way, whereas effectiveness is externally oriented towards doing the right things. According to Zidane and Olsson (2017), efficient processes require continual evaluation and assessment in terms of meeting project objectives and the optimal use of resources.

In the context of a process or system, 'increasing efficiency' means finding ways to produce the desired output or outcome using fewer resources (such as time, money, or materials) or with less waste (Cooper, 2004). In the context of the trackwork process, increasing efficiency means finding ways to complete maintenance or renewal with minimal rescheduling and the shortest amount of time on track while simultaneously minimising the possibility of infrastructure failure.

Inefficient maintenance schedules are often characterised by fragmented periods on track, caused by limited track availability due to high traffic intensity. This inefficiency arises when maintenance windows are small and contractors are forced to adjust their plans to fit the limited time slots available, resulting in higher maintenance operation costs (Budai-Balke, 2009; Nijland et al., 2021; Odolinski, 2019). Odolinski et al. (2023) further illustrated this by linking maintenance costs to railway line capacity utilisation, suggesting that higher capacity utilisation often leads to increased maintenance costs, indicating greater inefficiency. Budai-Balke

(2009) suggested that scheduling multiple trackwork simultaneously or allowing longer possessions may enhance productivity. This approach is exemplified in high-speed railway networks as in China, where maintenance is a nightly routine (Zhang et al., 2019), highlighting the importance of efficient scheduling to minimise disruptions to train traffic and maximise productivity.

Additionally, railway maintenance performance efficiency can be evaluated using the RAMS (reliability, availability, maintainability, and safety) framework. Building on this, Nathanail (2014) introduced a framework for monitoring and assessing trackwork performance quality, comprising performance, speed, safety, comfort, maintenance cost, operability, reliability, and overall condition. This framework reflects the essence of efficient trackwork scheduling.

Railway maintenance in Sweden

The total length of railway infrastructure in Sweden is approximately 15,500 km (Figure 2). The Swedish Transport Administration manages the infrastructure and is responsible for around 14,200 kilometres of track, 4,000 railway bridges, 150 tunnels, and close to 11,500 switches. The predominant track type in the Swedish railway network is single track, with most of the lines being electrified (Trafikverket, 2020). The goal of the Swedish Transport Administration (Trafikverket, 2022) is to attain more effective utilisation of time on track for trackwork to cope with an increasing demand for railway capacity.

Contracts

The Swedish Transport Administration, the infrastructure manager, delegates railway maintenance to contractor companies (Trafikverket, 2023b). The contractor company is responsible for performing all required maintenance in the contract region and fulfilling all the requirements demanded by the contract (Trafikverket, 2015b). As time on track is limited, efficient maintenance management (the utilisation of track capacity with minimal traffic disturbances) is necessary. Currently, railway maintenance is delegated to five major contracting companies through 34 basic maintenance contracts.

In Sweden, there are three types of maintenance contracts (Lidén, 2016): renewal projects, national maintenance, and regional maintenance contracts. Renewal projects usually involve restorations of infrastructure parts. National maintenance contracts cover specific types of activities, typically requiring the use of expensive equipment. Regional maintenance contracts are utilised for the performance of regular maintenance, putting the contractor in charge of maintenance in one region of the infrastructure network.

Figure 2. Swedish railway network (own map produced using ArcGIS® software based on data from the Swedish Transport Administration, canvas map source: HERE).

For regional maintenance in Sweden, two contract types are used: ABT06 turnkey and AB04 execution contracts. With both contract types, the lowest bid typically wins the contract. While this maximises profit for the project, it also might affect the quality of the work. Ivina et al. (2021) demonstrated that contractors strategically seek ways to inflate prices over the life of the contract, such as purchasing expensive machinery and setting high prices for additional activities not included in the contract. These strategies cause conflicts between contractors and the Swedish Transport Administration, creating uncertainty and distrust between the two parties.

The Swedish Transport Administration evaluates contractor performance using the experience index and the maintenance index (Trafikverket, 2020). The experience index, assessed by an independent external company, subjectively measures the level of satisfaction with the collaboration between the client and the contractor. In contrast, the maintenance index gauges the contractor's work efficiency through diverse data inputs, such as traffic delays, maintenance delays, and infrastructure failures.

Possession allocation

Lidén (2015) defined possession planning at contracting companies as particularly challenging due to the complex coordination and foresight required for successful implementation. There are a multitude of factors involved in the planning process, including work time scheduling and coordinating teams or resources. Therefore, the planning process must start several years before trackwork begins. Timetables and trackwork are planned in a coordinated process called the annual capacity allocation process (Trafikverket, 2020).

The annually published Network Statement describes the conditions for running traffic on the tracks during the upcoming train schedule (Trafikverket, 2023a). The document also includes planned major engineering works, thus forming the basis for ongoing trackwork planning. Planned major engineering works are activities that cause traffic interruptions for more than three days, shut down traffic for part of the day for at least five days in a row, or require single-track operation for at least 10 days (Lidén, 2016; Thorsén et al., 2018). Information about these works is collected 1.5 years before the timetable is implemented. The work is prioritised based on its duration and how it affects the timetable.

Trackwork planning and scheduling fall under the responsibility of maintenance contractors on the tactical and operational levels. To prepare the trackwork schedule, contractors rely on a variety of information sources, primarily maintenance contracts and inspections (Trafikverket, 2020). Inspections can be performed internally by a contracted company or externally by the Swedish Transport Administration (this is agreed upon before signing the maintenance contract). In both cases, the document (known as an 'inspection plan') contains schedules for all inspections and is under the constant supervision of the Swedish Transport Administration.

Contractors are responsible for determining the time required for each trackwork project and applying for temporary capacity restrictions following the regulated process. In the scheduling process, three primary documents are created: the major engineering works plan, the trackwork plan, the track utilisation plan (Figure 3). The major engineering works plan comprises the list of all major traffic impact trackwork and serves as an input for the Network Statement. The Network Statement serves as the basis for continuous trackwork scheduling, as these activities must be planned for hours with less traffic on the tracks or within predetermined time slots in the schedule known as maintenance windows (Lidén, 2016).

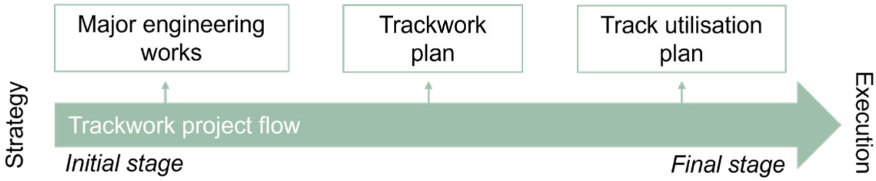

Figure 3. Trackwork flow in the context of Swedish trackwork time allocation.

The trackwork plan describes when and where tracks are reserved for traffic, influencing trackwork. All possible adjustments to the trackwork plan that are preferable from a production point of view, as well as entirely new works, are documented in the track utilisation plan. The track utilisation plan is updated every week and contains a detailed description of capacity needs (Trafikverket, 2015a, 2015b). Four weeks before the activity commences is the final date for application to the track utilisation plan. Before production day, all required documents – such as time-out descriptions (safety and contact information) and daily graphs – must be submitted to the traffic control centres that handle train clearance. Contractors can also authorise unplanned possessions on the day of the operation, using a manual procedure called direct planning.

Maintenance windows

Since 2015, according to a new planning regime, contractors receive prearranged 'maintenance windows' (Lidén, 2016; Trafikverket, 2015b). Maintenance windows guarantee access to the railway track for performing essential maintenance during the contract period and are intended to increase trackwork scheduling efficiency at contracting companies. Railway maintenance contractors are obliged to perform trackwork during train free periods, therefore the Swedish Transport Administration is suggesting using maintenance windows for all types of preventive maintenance. Figure 4 illustrates the simplified version of the decision-making process regarding the possession requests in relation to traffic impact, where the maintenance windows have the highest priority.

Maintenance windows are defined by the Swedish Transport Administration based on capacity evaluations and are discussed and adjusted annually before the Network Statement is published. They are designed for each specific region covered by a maintenance contract for the period of the contract. The size and location of maintenance windows are stated in the maintenance contract. These reserved times in track for maintenance intended primarily for so-called 'basic maintenance', activities that must be performed frequently to preserve the condition of the infrastructure. Such activities, which do not exceed the duration of the maintenance window, include inspections, snow removal, signal repair, tamping of tracks, and turnouts. Two weeks before the day on which maintenance windows are reserved, those without scheduled trackwork are opened up for train operation.

On double-track sections, maintenance windows imply partial track closure, with operation at reduced speed on the opposite track. On single-track sections, maintenance windows lead to complete track closure. Trackwork is allowed to occupy a maximum of two segments, as delimited by the nearest stations, within one maintenance window at a time – this is done to minimise train delays.

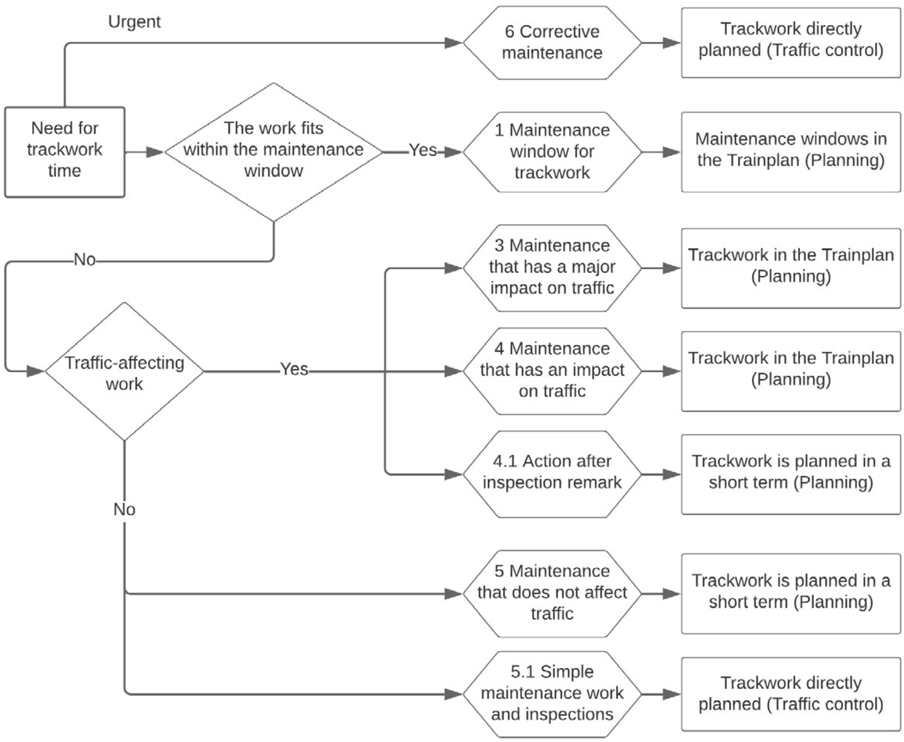

Figure 4. Step-by-step decision-making process for scheduling track maintenance time, as regulated by the Swedish Transport Administration (Trafikverket, 2015b).

Rolling horizon plan

The track utilisation plan is designed within the rolling horizon plan. With a rolling horizon, the schedule is continuously updated and revised on a rolling basis to ensure trackwork activities are aligned with demand, resource availability, and other key factors impacting production efficiency and effectiveness (Campbell, 1992; Narayanan & Robinson, 2010). Figure 5 illustrates the different components of the rolling horizon plan, including the rolling horizon length (the time period on which the planner is focused), 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 (periodical replanning activity within one planning horizon). For this specific plan, the cycle for updating, reflecting the latest decisions for the most optimal trackwork, occurs weekly. Contractors are allowed to make changes to track utilisation time up to four weeks before the scheduled trackwork execution (Trafikverket, 2015a). 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.

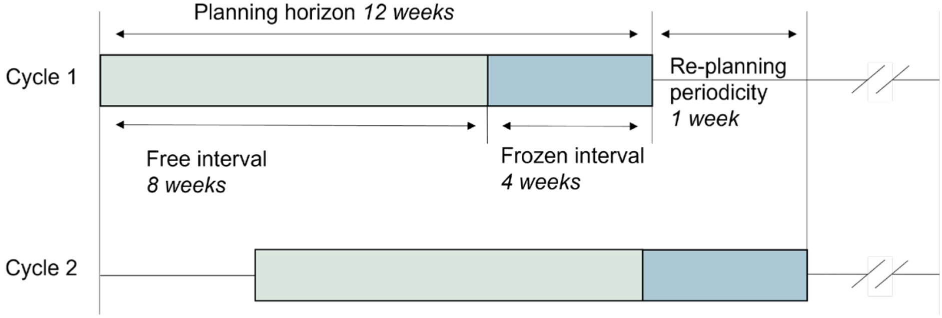

Figure 5. Track utilisation plan in the rolling horizon.

Methodology

This thesis investigates the underlying mechanisms in the trackwork planning and scheduling process, delving into the subjective understanding of the existing mechanisms. Trackwork planning and scheduling is a complex process involving various elements and actors. Influences on this process can include human errors, infrastructure failures, environmental conditions, and policy guideline updates. Firstly, the interaction between key stakeholders in the trackwork planning and scheduling process in Sweden is governed by contractual obligations and regulations. Secondly, it is influenced by the individuals involved, who bring their subjective interpretations to their respective responsibilities. Ultimately, these complex interdependencies culminate in the final product – a fully functioning railway infrastructure.

In this thesis, I focus on specific aspects, such as scheduling, possession planning and application, to gain a more comprehensive understanding of how the current system is functioning in relation to the capacity allocation process. This thesis employs a unique approach in focusing on the efficiency of the regulated process in practical scenarios. It investigates the current maintenance management process and its resilience to disruptions and develops an understanding of the complexity of railway maintenance planning, considering both human and technical aspects. Causality is an integral aspect of this research, as it influences each step in the process. Given that plan changes inevitably occur during execution, interactions between participants in the maintenance process are a crucial element of the process.

In this thesis, Lean philosophy was chosen as a theoretical framework for analysing the trackwork process. The core concept of Lean philosophy is minimising waste and maximising efficiency, which aligns with the overarching goal of this research – to improve the efficiency of trackwork scheduling. Lean is a suitable theoretical framework for analysing the trackwork process, as it aligns well with the purpose of improving efficiency and reducing waste. Another argument is that ‘scheduling is the heart of Lean’ (Bicheno and Holweg, 2009 p.137). While scheduling might be overlooked, it is a crucial task, as it emphasises the efficient use of time and the on-time performance of all activities.

Methods

To establish a holistic picture of the decision chain in the trackwork planning and scheduling process, this research employs a mixed-methods design. The mixed-methods approach is linked to the pragmatic philosophical worldview (Mason, 2017). Pragmatism emphasises practicality over abstract theories and is focused on solving real-world problems, which is also the purpose of Lean philosophy in the context of project management (Creswell & Creswell, 2022). The mixed-methods approach involves collecting and analysing both qualitative and quantitative data to address complex research questions and produce practical knowledge that can be applied in the real world.

The utilisation of qualitative and quantitative methods is evenly spread in this research. An overview of the methods employed is presented in Table 1. Papers 1 and 2 utilise qualitative research methods, combining interviews with maintenance contractors, project managers, and planners at contractor companies and document study. Papers 3, 4, and 5 are the product of quantitative research methods, combining logistic and negative binomial regression analyses and visual data analysis. The selection of research methods used in this thesis was determined by the research objectives.

Table 1 Overview of methods used in this thesis

Paper	Aim	Method
1	Study maintenance planning processes based on the Last Planner framework and explore possibilities for the adaptation of Lean construction principles	Qualitative Semi-structured interviews, document study
2	Identify and classify uncertainties and the strategies applied to manage those uncertainties in contractors' everyday planning and trackwork scheduling	Qualitative Semi-structured interviews
3	Explore the patterns of trackwork execution and maintenance window utilisation	Quantitative Logistic regression analysis
4	Investigate the actual use of reserved capacity inside maintenance windows to perform trackwork in Sweden using the Southern Main Line during 2019–2020	Quantitative Graphical visual analysis
5	Investigate the effect of trackwork on train delays in Sweden	Quantitative Logistic regression analysis Negative binomial regression analysis

Paper 1 was focused on gaining a deeper understanding of the processes and decisions involved in maintenance planning, as well as their impact on the efficiency of trackwork scheduling. To achieve this, the study employed a combination of literature and document review, data analysis, and semi-structured interviews with project and site managers. Recognising that unused booked time on track is considered wasteful, we applied the PPC metric to assess the contractors' use of this time.

Paper 2 employed the interview method to gain a clearer insight into the existing problems within the trackwork scheduling process. This involved conducting semi-structured interviews with key professionals, notably planners and foremen, from leading railway maintenance contracting companies in Sweden. Through thematic analysis of the interview transcripts, we were able to conduct an in-depth exploration of the participants' experiences, perceptions, and strategies for managing uncertainties in trackwork planning and scheduling.

In Paper 3, our analysis centred on data from a year's worth of trackwork rolling horizon plans, examining weekly changes in track utilisation plans across eight railway lines in Sweden. A multiple logistic regression model was utilised to understand the likelihood of alterations in the trackwork plan, taking into account variables such as track type, location, time of day, train traffic intensity, and the predominant type of traffic.

Paper 4 presents an analysis of the railway line between Arlöv and Nässjö in Sweden, drawing on two datasets from the Swedish Transport Administration. These datasets, covering July 2019 to December 2020, provided insights into planned maintenance windows and detailed records of completed trackwork activities on the Southern Main Line. We calculated the maintenance window utilisation rate as the proportion of active trackwork time within these windows relative to the total time allocated for them.

Finally, Paper 5 offered an analysis of over 225,000 scheduled trackwork events and approximately 32.6 million train passage records. This study utilised two statistical models: multiple logistic regression to evaluate the probability of train delays in relation to trackwork and other factors, and negative binomial regression to assess the frequency of these delays.

Qualitative methods

In this thesis, the research has been structured using an exploratory sequential design. This approach first involves collecting and analysing qualitative data to attain a more comprehensive understanding of the studied phenomenon from the point of view of the study participants, followed by quantitative data analysis of variables that arise in the qualitative analysis step (Creswell & Creswell, 2022). The qualitative data analysis involved document study and semi-structured interview analysis.

Document analysis

The document analysis conducted in this research is situated within the social setting of the trackwork planning process. This approach, rooted in the framework set out by Prior (2003) delves into the functional aspects of documents, including their design and utility within the planning context rather than solely their content. The emphasis is placed on understanding documents as active components that influence and are influenced by the social dynamics of planning and execution in maintenance work.

This methodological choice acknowledges that documents do not exist in a vacuum; they are integral to, and reflective of, organisational culture and practices. As such, the analysis of documents in this thesis is not an isolated method but is integrated with interviews to provide a holistic view of the interaction between planning regulations and human agency. This approach uncovers the experiences of those engaged with the planning and execution processes. For instance, in Paper 1, the process of maintenance planning in Sweden is examined through the lens of Lean principles. This analysis aims to reveal the relationship between the regulated and the actual trackwork processes, shedding light on scheduling efficiency.

Interviews

To investigate the subjective perception of trackwork planning and scheduling complexity, we supplemented the document study with interviews, following the methodological framework suggested by Prior (2003). In Paper 2, semi-structured interviews helped uncover key problems at the tactical and operational levels of trackwork management.

The selection of interviewees for Papers 1 and 2 aimed at capturing a wide spectrum of perspectives. We interviewed maintenance company personnel across various Swedish regions to ensure diversity. We focused on those directly involved in the planning and scheduling processes, examining how their experiences correspond with the established regulatory framework. The first interviewed group comprised project leaders tasked with devising long-term plans, while the second included foremen responsible for managerial decisions at the tactical and operational levels as well as the execution of trackwork. The interviewed foremen are responsible for planning in specific technical areas, such as track, signals, telecommunication, and electricity.

Utilising the ‘snowballing’ sampling technique, as outlined by Harrell and Bradley (2009), we were able to identify interview candidates effectively, with project leaders recommending various foremen for the interviews. The semi-structured interviews were designed to delve into the experiences, attitudes, and perceptions of these key participants. This interview approach usually involves a conversation between the researcher and the participant, guided by a customisable interview procedure and reinforced by follow-up questions and comments (Harrell & Bradley, 2009). After the interviews, the responses were transcribed, coded, and analysed using the thematic interview analysis method in Paper 2.

Quantitative methods

The selection of quantitative data analysis methods to assess trackwork scheduling efficiency was based on the insights and understanding gained from the document study and the interviews conducted. In this thesis, efficiency refers to Lean principles, where all possible waste (anything not adding value for customers or to the final product) must be identified. We address waste from four different perspectives at different levels of maintenance planning. First, at the operational level, the assessment focused on the utilisation of booked possession time using criteria based on one of the tools in Lean, the PPC (Paper 1). Second, the efficiency metric involves trackwork schedule stability, as constant rescheduling consumes time and resources, which is considered a form of waste (Paper 3). Following the same principle but targeting the efficiency of maintenance-related decisions on the strategic level, the suggested measure pertains to the utilisation of maintenance windows (Paper 4). Train delays caused by trackwork are another measure related to waste in Lean, as they do not add value for the customer (Paper 5).

PPC

PPC is a metric commonly used to evaluate team performance. It is calculated as the ratio of work performed to work planned. In Paper 1, PPC was calculated by comparing the percentage of time used by the contractor based on the total allocated possession time in the track utilisation plan. The discrepancy between the booked time on track and the actual time used for the trackwork is considered waste. Paper 1 introduced PPC metrics for the evaluation of contractor performance.

Schedule stability

Paper 3 presents a metric to evaluate schedule performance – the schedule stability estimate. Stability for each planning cycle was calculated as the ratio of the number of unmodified possessions to the total number of planned works within the planning cycle. This study investigated track utilisation plan stability by examining changes in trackwork records throughout the planning cycle. We focused on variations in the total weekly length of scheduled trackwork, comparing consecutive weeks.

In Paper 3, the schedule instability measure was suggested based on the model proposed by (Pujawan, 2004). We quantified schedule instability based on changes in planned times, regardless of the nature of these changes. We categorised trackwork duration modifications into three scenarios: increase, decrease, or no change in the following week. Factors such as location, track type, time of day, month, day of the week, work duration, train traffic volume, and freight train proportion were analysed using multiple logistic regression analyses to explain these changes.

Maintenance window utilisation rate

The maintenance window utilisation rate was calculated as the ratio of active trackwork time within maintenance windows to the total time reserved for planned maintenance windows. Active hours inside maintenance windows are defined as at least one trackwork activity being performed within a planned maintenance window. To attain the highest maintenance window utilisation rate, all booked capacity for trackwork inside maintenance windows would have to be used 100% of the time in 100% of allowed locations (two segments per maintenance window).

Multiple logistic regression analysis

This thesis utilised multiple logistic regression to analyse the functional relationships in two scenarios: the occurrence of track utilisation plan changes in Paper 3 and the fluctuation of train delays in Paper 5. The dependent variables were categorical, and we investigated their relationships with a combination of categorical and continuous independent variables. Initially, Pearson's chi-squared test was employed to assess the independence of the qualitative variables in our models. This test confirmed that all variables were independent. Subsequently, we selected the most pertinent variables for our models by examining their significance across various logistic regression configurations. The aim of this analysis was to identify variables that significantly influenced our response variables and to understand these influences through the estimated coefficients of the regression. The statistical significance of these coefficients was tested using Welch's t-test.

Multiple logistic regression was used to understand the nature of schedule instability in Paper 3. This model predicted the likelihood of changes in trackwork length compared to the previous week. The response variable here was a binomial indicator of change (1 for change, 0 for no change). Explanatory variables included categorical factors such as track type, location, and time of day, and continuous variables such as the number of previous changes and train traffic intensity.

Two multiple logistic regressions were used to analyse the likelihood of train running time delays and recovery in relation to scheduled trackwork in Paper 5. The first model assessed the probability of train running time delays, with factors including trackwork, train type, subtype, train entry status, track type, and time of day. It treated delay increase as binary outcomes (1 for delay, 0 for no delay) and included sensitivity thresholds for delays (five or 10 minutes). The second model evaluated the probability of train delay recovery, using the same set of independent variables. Here, the dependent variable was coded as 1 for an increase in delay and 0 for no increase in delay.

Negative binomial regression analysis

The negative binomial regression was used to analyse the likelihood of train running time delay frequency in relation to scheduled trackwork occurrences in Paper 5. This type of regression was chosen due to its effectiveness in managing count data with over-dispersion. Paper 5 presents summary of two negative binomial regressions that quantifies the instances of train running time delay (1) increases or (2) decreases, offering insights into the variability and spread of delay occurrences. The response variables were the count of running time delay increase (1 min) for the first model and of running time delay decrease (1 min) for the second model. The predictor variables in the model were trackwork, track type, train subtype, train enter status, and time of day.

Data overview

This research utilises a combination of qualitative and quantitative data, summarised in Table 2. The qualitative data, essential for understanding the factors affecting the trackwork scheduling process, was gathered through interviews with maintenance contractors and managers. Complementarily, quantitative trackwork data, encompassing both schedules and operations, was obtained to assess the efficiency of trackwork scheduling and its execution. Additionally, train punctuality data was utilised to evaluate the impact of scheduling inefficiencies on train operations, which is crucially linked to the ultimate objective of trackwork management – enhancing train customer satisfaction.

Table 2 Summary of data used in this thesis.

Dataset Type	Source	Time and Location	Paper
Qualitative Data (Information from Interviews)	The Swedish Transport Administration, Swedish Railway Maintenance Companies	2018, All Sweden	Paper 1
	Swedish Railway Maintenance Companies	2020–2021, All Sweden	Paper 2
Qualitative Data (Information from Documents Study)	The Swedish Transport Administration	2015–2022, All Sweden	Paper 1,2
Planned Possessions (Trackwork Schedules Weekly Updates)	Track Utilisation Plan, The Swedish Transport Administration	Jan. 2020–Dec. 2020, Eight Railway Lines In Sweden	Paper 3
Maintenance Windows and Trackwork Records	Despatcher Center Records	Apr.–Oct. 2019, Jan.–Dec. 2020, Scania, Sweden	Paper 4
Planned Possessions (Trackwork Schedules)	Trackwork Plan / Track Utilisation Plan	2014–2020, All Swedish Railway Network	Paper 5
Train Operations Data	LUPP, The Swedish Transport Administration	2014-2020, All Swedish Railway Network	Paper 5

Qualitative data

Semi-structured interviews were conducted with railway maintenance managers from the Swedish Transport Administration, and site managers and foreman at various Swedish railway maintenance companies. The interviewees, possessing varying levels of responsibility and years of experience, provided diverse insights. The interview results were transcribed and analysed using NVIVO software, as presented in Paper 2.

Furthermore, to build a complete picture of the trackwork planning and scheduling process, in Paper 1 we augmented our interview data with a review of internal regulations and recommendations related to contractor performance and planning processes. These documents were sourced from the Swedish Transport Administration database. The analysed documents include reports written by personnel working at the Swedish Transport Administration, as well as external reports.

Quantitative data

The track utilisation plan contains information regarding planned possessions. The dataset specifies the trackwork identification number as well as the location, denoting the starting and the destination station where the activity is scheduled. The time of trackwork is specified as week number, time (in seconds) and day pattern. A detailed description of the dataset can be found in Paper 3. Records of planned possessions over 2014–2020 in all of Sweden were utilised in Paper 5. The obtained weekly updates of the planned possessions on eight railway lines in Sweden were analysed in Paper 3.

Maintenance windows and trackwork records were provided by the Swedish Transport Administration and collected manually at the despatcher centres in the Scania County. Each record specified the maintenance window's unique identification number, location, start time, and end time. Trackwork records contained the date, start time, end time (from which we can calculate the trackwork duration), and trackwork location. This data was used to estimate the maintenance window utilisation in Paper 4.

The train punctuality dataset contained information about the scheduled and actual departure and arrival times for each station on the assigned train path, with a time resolution of one minute. In addition, each train route had an identification number, train type, and infrastructure information (single, double, or quadruple). This dataset was crucial to reaching an understanding of the broader implications of trackwork scheduling inefficiencies on train punctuality, as explored in Paper 5.

Geographical scope

The geographical scope of this thesis is confined to the Swedish railway network, as illustrated in Figure 6. Our research methodology, particularly in Papers 1 and 2, involved conducting interviews with professionals engaged in maintenance projects across various regions of Sweden. The selection of interviewees was strategically designed to encompass a broad spectrum of projects and locations. This approach was vital as different regions of Sweden present distinct challenges in trackwork scheduling, arising from variations in train traffic volumes, types of train traffic, and track composition. In Paper 3, we delved into the stability of trackwork schedules, analysing data from eight strategically selected railway lines across Sweden, as detailed in Table 3. These lines were chosen for their representation of the national rail network's diverse characteristics, including geographical coverage of both the northern and southern regions and a mix of single and double-track usage, train types, and train traffic volumes. The maintenance of these lines was managed by four different maintenance companies working under regional maintenance contracts.

Table 3 Description of lines analysed in Papers 3 and 4.

Rail line	Length	Track type	Traffic volume (Thousand train km)	Share of freight trains (2020)
South				
Southern Main Line (*Södra Stambanan*)	483 km	Double	16,597	26%
Arlöv–Nässjö (Paper 4)				
West Coast Line (*Västkustbanan*)	283 km	Double	6,635	9%
Norway/Vanern Line with Northern Link (*Norge/Vänerbanan med Nordlänken*)	300 km	Single *	3,613	26%
Varmland Line (*Värmlandsbanan*)	202 km	Single **	2,134	38%
Fryksdal Line (*Fryksdalsbanan*)	82 km	Single	406	10%
North				
Iron Ore Line (*Malmbanan*)	398 km	Single	2,779	73%
Haparanda Line (*Haparandabanan*)	159 km	Single	53	86%
Main Line Through Upper Norrland (*Stambanan genom Övre Norrland*)	626 km	Single ***	5,314	76%

*Single tracks except between * Göteborg and Öxnered, ** Kil and Karlstad, and *** Mellansel and Vännäs*

Paper 4 took a narrower focus due to the complexity and limited availability of trackwork record data. It examined the railway line between Arlöv and Nässjö, depicted in Figure 6, which is a part of the Southern Main Line, one of Sweden's busiest rail corridors. Maintenance responsibility here is delegated to a single maintenance contractor company. Finally, Paper 5 expanded the analysis to include trackwork plans throughout the entire Swedish railway network (marked as a grey line in Figure 6). This comprehensive study aimed to present a complete picture of how train traffic is influenced by trackwork activities across the national rail system.

Figure 6. Swedish railway network, locations analysed in Papers 3, 4, and 5 (own map produced using ArcGIS® software based on data from the Swedish Transport Administration, canvas map source: HERE).

Matching datasets

In the data processing phase, we utilised SQL to match and analyse trackwork records, maintenance windows, and train operation data. The initial step in processing the trackwork dataset involved filtering out any trackwork that fell outside the scope of this research. Specifically, we excluded trackwork that exceeded a 24-hour duration, as these are categorised by the Swedish Transport Administration's maintenance planning department as investment projects. Our research is centred on basic maintenance; therefore, we focused exclusively on possessions that lasted no more than 24 hours. With respect to train punctuality data, our analysis encompassed all trains that successfully completed their journey to the final destination, excluding any cancelled services.

Trackwork schedule updates

Paper 3 examined 32 weekly updates from eight track utilisation plans, each corresponding to a specific railway line in Sweden, focusing on an active period defined by a 13-week rolling horizon. During this period, we compiled trackwork activities occurring both during the day and at night into a dataset of 6,646 activities. We analysed this dataset over the 13-week cycle, comparing the duration of each activity against its duration from the previous week. This comparison identified three scenarios illustrating how trackwork durations were modified over the planning cycle: (1) an increase in the planned duration for the next week, (2) a decrease in the planned duration, and (3) no change from one week to the next.

To further understand the schedule changes, we collected data on several attributes for each trackwork instance. These included geographic location, time of day, month, day of the week, and duration of the trackwork activity. Additional information, such as track type, train traffic intensity, and the proportion of freight traffic, was obtained by matching the train operation data and trackwork data on the basis of location, time, and date.

Maintenance windows and trackwork records

In the obtained dataset, each instance of trackwork was categorised by the location of its respective maintenance window. In Paper 4, we analysed a total of 13 maintenance windows and 826 hours of trackwork. To measure the utilisation rate of maintenance windows, we merged planned maintenance windows and the executed trackwork records by temporal parameters. Subsequently, we delineated the merged data within a grid framework. Within this framework, each horizontal square signified a single minute and each vertical square denoted a segment of the railway track. We attributed one of four distinct statuses to every minute on the network: (1) free, (2) occupied by trackwork during a maintenance window, (3) occupied by trackwork outside of any planned maintenance window, or (4) occupied by a maintenance window without trackwork.

Trackwork and train punctuality

The track utilisation plan marks the locations of trackwork with unique signal numbers that define segments between pairs of stations. In Paper 5, from the total of 225,507 trackwork activities listed in 2017, we defined 3,218 unique track segments, with some segments containing multiple activities. By merging overlapping activities, we eliminated duplication activities and optimised the dataset. Next, we matched train passages from the train operations data with the relevant track segments, considering the various routes trains took over the segments. From 32.6 million recorded journeys, we isolated approximately 27.2 million unique train passages in 3,218 track segments for analysis.

Connections between papers

The interrelationships among the five papers in this thesis, as depicted in Figure 7, support the holistic understanding of trackwork scheduling efficiency. The initial analysis of the trackwork planning and scheduling process was performed in Paper 1. Expanding on this analysis, Paper 2 explored the factors that might affect trackwork scheduling efficiency from the contractor's perspective, presenting an examination and classification of project uncertainties. Paper 3 took this exploration a step further, aiming to quantify how these various factors affect the stability of the schedule. Proceeding from the insights gained in Paper 2, Paper 4 analysed the utilisation rates of maintenance windows. Paper 5 evaluated the negative effects of trackwork on train operations.

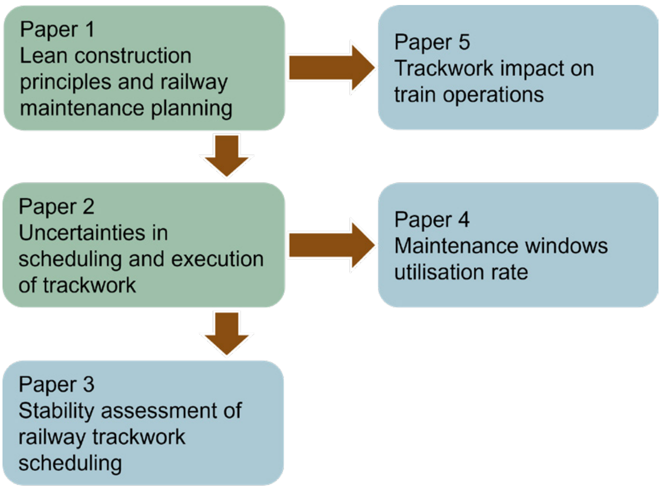

Figure 7.The connection between the five papers included in this thesis.

Connections between maintenance decision levels and papers

The focal point of this thesis is the planning and scheduling decisions made on three management levels: strategic, tactical, and operational. Figure 8 shows the connections between the papers in the thesis, arranged in sequence, followed by the levels of maintenance decision each paper targets.

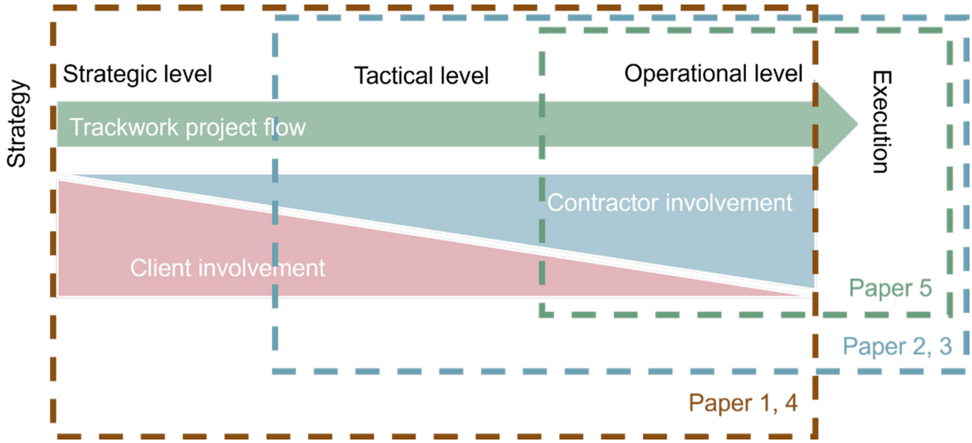

Figure 8. The connections between the five papers included in this thesis and the three maintenance decision levels.

Papers 1 and 4 address all three planning levels of maintenance-related decisions: strategic, tactical, and operational. Paper 1 is focused on all three maintenance decision levels because it investigates the entire process of maintenance planning and scheduling, from the moment maintenance strategy is decided up to the moment when plans are prepared for execution. Paper 4 is related to maintenance decisions at the strategic level, as the maintenance windows analysed in that study are the product of the strategic allocation of maintenance volumes. Furthermore, Paper 4 presents an analysis of how the allocated time on the strategic level is utilised at the operational level, which establishes a logical connection between those two levels. Tactical-level decisions are considered in Paper 4 from the perspective of decisions made at the tactical level to use maintenance windows or perform trackwork at other times.

In this thesis, decisions regarding trackwork scheduling on the tactical and operational levels are analysed in Papers 2 and 3. Paper 2 identifies and classifies uncertainties present in contractors' planning and scheduling of trackwork at the levels of their highest involvement in the decision-making process: tactical and operational. Paper 2 also presents strategies to deal with project uncertainties that are part of contractors' daily routines. Building on the findings in Paper 2, we designed Paper 3, aiming to quantify the effects of uncertainty on planning at the tactical and operational levels and ultimately presenting an analysis of trackwork schedule stability. Finally, the primary focus of Paper 5 is quantifying and understanding the ramifications for train operations of potential mistakes in trackwork planning at the operational level.

Connection between research questions and papers

'What', 'Why', and 'How' are the three fundamental questions that traditionally underpin social science research (Mason, 2017). In the context of this thesis, these questions are intricately woven into the research design. To investigate what inefficiencies occur in the trackwork scheduling process and why they happen, we performed the studies reported in Papers 1, 2, 3, and 4. Our aim was to understand the external factors and workflow patterns that influence decisions in the planning process and identify new information affecting these decisions. Finally, we analysed how train traffic is affected by trackwork and reported our findings in Paper 5. The research questions posed in this thesis and addressed in the five papers are presented in Table 4.

Table 4 Connection between research questions and five papers.

Research questions	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5
RQ1: What factors influence the efficiency of trackwork scheduling, and in what ways?	x	x	x		
RQ2: How and to what extent are trackwork schedules adjusted over time?			x	x	
RQ3: What impact does scheduled trackwork have on train operations?					x
RQ4: In what ways can the trackwork scheduling process be improved?	x	x	x	x	

Answering RQ1, Paper 1 aimed to analyse the trackwork process within the Lean framework. Expanding on this analysis, Paper 2 focused on classifying the uncertainties and their sources in a structured manner based on the theory of uncertainty and organisational design as presented by Galbraith (1974). Paper 3 took this exploration a step further, aiming to quantify how these various factors affect the stability of the schedule. All three studies were designed to improve the understanding of the foundational factors contributing to inefficiency.

RQ2 is addressed in Papers 3 and 4. Expanding upon the classification of uncertainties presented in Paper 2, Paper 3 analysed data from one year of trackwork rolling horizon plans, with a particular focus on weekly changes in these plans. Through regression analysis, the paper shed light on the factors that most significantly contribute to alterations in trackwork schedules. Subsequently, Paper 4 was designed to quantify the extent to which strategic-level decisions regarding maintenance time allocation remain valid at the tactical level. This was achieved by analysing the nuances of maintenance window utilisation and estimating maintenance window utilisation rates.

Paper 5 delved into the impact of scheduled trackwork on train operations, answering RQ3. Extending beyond its primary research question, this study offered a nuanced analysis of how trackwork affects train operations differently under various conditions. It specifically examined the varied effects of trackwork on single versus double tracks and contrasted daytime operations with those conducted during the night.

Papers 1, 2, 3, and 4 answer RQ4 by offering a set of recommendations, each aimed at refining the scheduling process. For instance, Paper 1 explored each step of the maintenance planning process using the Last Planner system framework. By interpreting the advancement practices within the railway process context, it identified specific actions that could enhance scheduling practices. Paper 2, on the other hand, aimed to classify existing uncertainties that affect project flow efficiency. Along with evaluating the feasibility of current strategies, it proposed new strategies that could enhance the trackwork scheduling process. Paper 3 aimed to reveal the most significant predictors of change in trackwork schedules, offering insights to trackwork planners to help them make informed and proactive decisions about trackwork time slot allocation. Paper 4 developed an understanding of why maintenance windows are underutilised, and to what extent. If addressed appropriately, this could resolve the issue of maintenance window underuse.

Results

We present a structured analysis of the trackwork efficiency in Sweden and a list of suggestions for how the planning process can be improved. In this thesis, we analysed the trackwork processes in the Lean production framework. The core of Lean philosophy is creating more value for customers while minimising waste through continuous improvement and respect for people. The aim of Lean philosophy adaptation for any type of process is to achieve efficiency, defined as the rational use of resources, such as time, materials, or labour, and the minimisation of waste. Lean sees the processes in each project existing in a stream, flowing from the initial stage to the final. The trackwork project begins with a strategic plan and finishes with an execution stage (Figure 9). Maintenance management involves maintenance-related decision-making at three levels: strategic, tactical, and operational. On the strategic level, decisions are under the responsibility of the Swedish Transport Administration (the client). As its involvement in the project decreases, decision-making responsibilities shift to the contractors on the tactical and operational levels. Scheduling is present at the tactical and operational levels and is the responsibility of the contractor. The efficiency of the overall project flow is ensured by the efficiency of all the process components in the flow, such as scheduling.

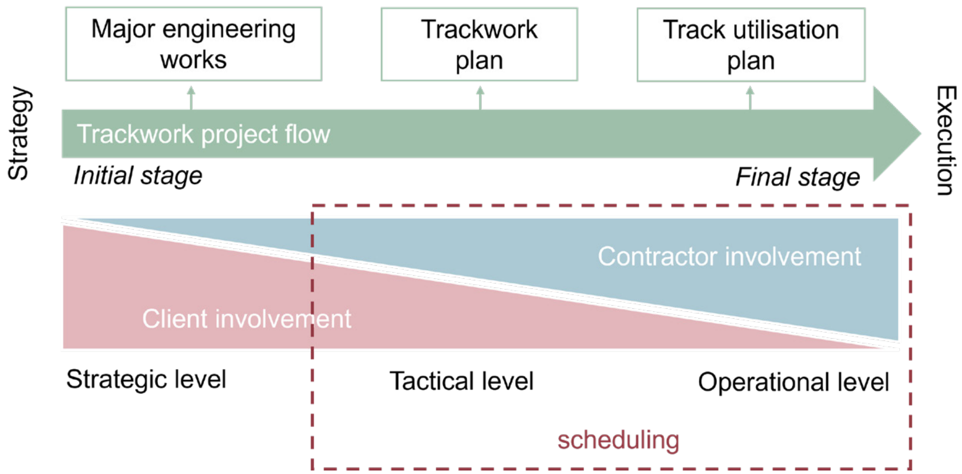

Figure 9.Schematic representation of the trackwork planning and scheduling process following the Lean framework.

Summary of papers

Paper 1: Lean construction principles and railway maintenance planning

Paper 1 investigated the maintenance planning processes in Sweden within the framework of Lean construction principles, particularly focusing on the Last Planner system. The study aimed to identify potential improvements and barriers in the implementation of Lean principles in railway maintenance planning.

Paper 1 describes the trackwork planning and scheduling process (Figure 10) and portrays the timeline of structured decisions regarding maintenance management. It presents three main stages in the maintenance planning. In the trackwork context, the first stage, referred to as 'annual planning', starts with an annually published Network Statement. The Network Statement outlines conditions for traffic during the upcoming train schedule, considering the planned railway capacity restrictions detailed in the trackwork plan. In the next stage of the planning process (at the tactical level), the trackwork plan is updated weekly, with all the latest updates recorded in the track utilisation. Four weeks before trackwork execution, operational planning begins, at which point changes to the track utilisation plan are no longer allowed. This structured approach ensures that all trackwork affecting traffic is coordinated and established well in advance, allowing for systematic and forward-looking planning in railway maintenance.

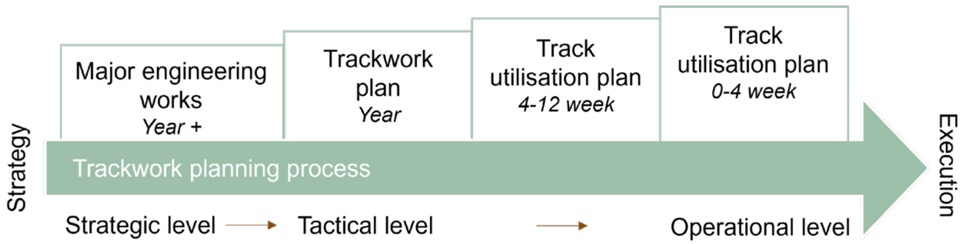

Figure 10. Detailed flowchart illustrating the trackwork planning and scheduling process as delineated in Paper 1.

Paper 1 presents how the stepwise planning characteristic of railway maintenance aligns well with the principles of the Last Planner system. Each step in the planning process can be improved by following the recommendations for stepwise improvement in the Last Planner system. The main applicable principles to enhance efficiency are emphasising detailed planning as execution approaches, collaborative planning with stakeholders, and the removal of constraints on planned tasks. Current planning practices in railway maintenance share several elements with the Last Planner system, especially in the aspects of increasing plan details as execution nears and collaborative involvement in the design process.

Paper 1 utilises the metric of workflow reliability, specifically PPC, as a case study for evaluating maintenance contractor performance. The results show how possession time requested by contractors versus the actual time used could indicate areas for improvement. This metric could be an effective way to evaluate the efficiency of trackwork planning and the ability of contractors to estimate the amount of time on track they actually require.

Lastly, the results identify several challenges in planning; for example, disagreements between the Swedish Transport Administration and contractors. The interviews with project and site managers reveal issues such as poor long-term planning skills among contractors and insufficient possession times for preventive maintenance. Paper 1 revealed instances where contractors finalised plans less than four weeks before execution, highlighting the complexities of the scheduling environment and raising questions about the practicality of existing regulations and their adherence. A significant challenge is knowledge transfer post-contract, with experienced personnel often leaving without sharing knowledge with new workers. Additionally, there is a notable lack of knowledge about Lean principles among contractors, creating barriers to effective implementation. These findings emphasise the need for improved collaboration, knowledge sharing, and education about Lean principles to enhance the efficiency and effectiveness of railway maintenance planning, as inefficient maintenance planning invariably affects service reliability and customer satisfaction. Improving trackwork scheduling efficiency is crucial to reducing infrastructure failures and minimising passenger inconvenience.

Paper 2: Uncertainties in scheduling and execution of trackwork

In Sweden, the planning and scheduling of trackwork on the tactical and operational levels are the responsibility of maintenance contractors. Paper 2, building on the findings of Paper 1, contributes to the understanding of uncertainty management in railway maintenance projects by answering three primary research questions: (1) What are the uncertainties related to trackwork planning and scheduling as experienced by maintenance contractors? (2) How can these uncertainties in trackwork planning and scheduling be classified? (3) What strategies are applied by contractors to effectively manage these uncertainties? Paper 2 aimed to identify and classify uncertainties as well as the strategies employed to manage uncertainties in contractors' day-to-day planning and trackwork scheduling.

Paper 2 reports a structured representation and understanding of external and internal factors affecting trackwork planning and scheduling. We categorised uncertainties and strategies to manage uncertainties and described them at the tactical and operational levels (Figure 11).

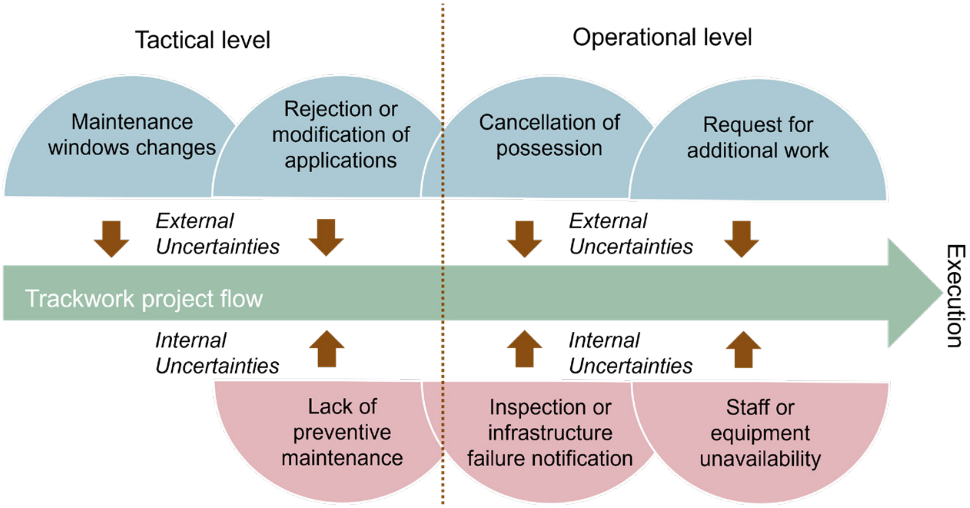

Figure 11. Internal and external uncertainties in railway maintenance planning and scheduling on the tactical and operational levels (Paper 2).

Project uncertainties in trackwork planning

External uncertainties at the tactical level primarily involved changes in allocated maintenance windows and the unpredictability of possession applications (Figure 11). Contractors often faced alterations in maintenance windows that were agreed upon when the contract was signed, leading to scheduling instability. Another significant external challenge was the approval process for possession applications by the infrastructure manager. The unpredictability regarding the duration of approved possessions directly impacted contractors' ability to efficiently plan and execute maintenance activities. Internally, contractors experienced limitations with preventive maintenance, primarily due to constrained time and resources, which led to an emphasis on corrective maintenance.

At the operational level, contractors experienced a high degree of unpredictability in the scheduling process due to unexpected additional trackwork requests from the infrastructure manager as well as adverse weather conditions and infrastructure failures. Internally, contractors dealt with challenges related to crew scheduling, particularly the high costs associated with night shifts and the inconvenient duration of maintenance windows. These events often led to the urgent reallocation of resources and the postponement or rescheduling of planned maintenance activities.

Strategies to deal with uncertainties

Paper 2 presents a categorisation of strategies employed by contracting companies in Sweden to manage uncertainties in trackwork planning and scheduling according to the framework developed by Galbraith (1974). This framework distinguishes strategies based on their aim: either to reduce the need for information processing or to increase the capacity for information processing. The first category of strategies includes scheduling extra track time, effectively creating a safety buffer; negotiating with railway operation companies to determine the most favourable maintenance times; and utilising predefined maintenance windows. The second category encompasses strategies such as enhanced internal communication and dialogue with the infrastructure manager, increasing plan flexibility, proactive trackwork rescheduling, and maintaining an emergency response team for urgent repair needs.

Paper 3: Stability of trackwork scheduling

As revealed in Paper 2, trackwork rescheduling is a response to uncertainty, disruptions, or other unexpected events. Rescheduling involves either adjusting the duration of trackwork or carrying out the scheduled maintenance at a different time than originally planned. Paper 2 aimed to explore the nature of trackwork scheduling by answering two 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 booked time on track in the track utilisation plan?

One of the key findings in Paper 3 was that as the trackwork execution draws near, planning, instead of becoming more stable, becomes more uncertain. In other words, schedule stability decreases as the end of the planning horizon approaches (Figure 12).

Figure 12. Trackwork plan stability estimate for each week in the rolling horizon plan (Paper 3).

The logistic regression model revealed that previous changes, track type, and the timing of trackwork significantly influenced the likelihood of schedule modifications. Specifically, recent changes in trackwork length increased the probability of subsequent changes, whereas accumulated changes reduced this likelihood, suggesting a stabilisation effect over time. Surprisingly, overall train traffic intensity did not significantly impact schedule changes, but the proportion of freight trains did. The analysis also showed that plan stability decreased closer to the operation week, challenging the effectiveness of the current 12-week ‘frozen’ planning period. Additionally, longer planned durations for trackwork tended to have fewer changes, suggesting a strategy similar to holding safety stock in production management. However, this led to a high volume of cancellations and new work additions, indicating a practice of overbooking by contractors.

Paper 4: The use of railway maintenance windows

Maintenance windows are intended to ensure sufficient time on track for basic maintenance. Paper 4 aimed to explore trackwork execution patterns and the utilisation of maintenance windows in the Swedish railway system, with a specific focus on the Southern Main Line. The core objective of this research was to illuminate the disparity between allocated and utilised capacity for railway track maintenance activities, with a focus on the effectiveness of maintenance windows within the Swedish railway network. This research was guided by two principal questions: firstly, determining the extent of trackwork conducted within versus outside planned maintenance windows, and secondly, understanding the utilisation rate of these maintenance windows, including how this rate varied by day of the week, month, location, and capacity utilisation.

The results showed that 10% of total line capacity was reserved for maintenance windows, compared to a total of 11% of total line capacity utilised for maintenance. However, a significant proportion of trackwork, approximately 68%, was conducted outside the designated maintenance windows. Despite the majority of trackwork (76%) being carried out at night, only 32% occurred within the scheduled maintenance windows. The average utilisation rate of these windows was around 34%. Interestingly, this study did not identify a direct correlation between the maintenance window utilisation rate and the capacity utilisation rate on the line. There was a clear discrepancy between the scheduled maintenance windows and the actual execution of trackwork, suggesting inadequacies in the planning process.

Maintenance windows are an operational planning solution designed to uphold railway system reliability. The results presented in Paper 4 highlight a surprising phenomenon: maintenance windows are not widely accepted among contracting companies. Operational efficiency can be enhanced by adopting a more tailored approach to maintenance scheduling, involving contractors early, and potentially extending the durations of maintenance windows. From a policy and practice perspective, this study suggests rethinking the scheduling of maintenance windows to include weekends and introducing incentives for adherence to planned windows. These findings offer valuable insights that could be applied to railway systems in other European countries and potentially other types of transport infrastructure.

Paper 5: Train delays due to trackwork

The primary aim of Paper 5 was to provide a comprehensive analysis of how railway infrastructure maintenance, specifically trackwork, impacts train operations in Sweden. This investigation is crucial, as it delves into the dual nature of track maintenance: while essential for the safety and functionality of railways, it also poses potential disruptions to train schedules and operations. To achieve this aim, Paper 5 focused on two main objectives. Firstly, it sought to quantify the extent to which trackwork contributes to the probability and frequency of train running time delays within the Swedish railway system. A train running time delay is defined as the difference between scheduled and actual train passing time between two stations. Secondly, it aimed to examine the influence of scheduled trackwork on the ability of trains to recover from delays. These objectives are critical for understanding the balance between necessary infrastructure maintenance and the operational efficiency of train services. The study is structured around two central research questions: (1) To what extent does trackwork influence the probability and frequency of train delays in Sweden? and (2) How does scheduled trackwork affect train delay recovery opportunities?

The results demonstrate that trains are 1.43 times more likely to encounter delays of at least one minute when passing through sections with scheduled trackwork. Furthermore, there is a 16% rise in the frequency of such delays. Notably, the impact of trackwork on longer delays exceeding 10 minutes is minimal. On the contrary, the study found that trackwork diminishes the potential for delay recovery, with a 4% decrease in the frequency of delay reductions and an 11% reduced likelihood of any delay decrease.

The implications of these findings are significant, particularly as they suggest that while the effect of trackwork on train delays was relatively small in 2017, the issue could escalate with an increase in both train services and track maintenance activities. This study underscores the need for efficient trackwork scheduling and suggests that improved planning and operational strategies could help mitigate conflicts between trackwork and train operations.

Answers to the research questions

The outcomes of five completed studies provided valuable insights in addressing the research questions posed in this thesis.

RQ1: What factors influence the efficiency of trackwork scheduling, and in what ways?

Project uncertainties

The efficiency of the trackwork scheduling process is influenced by a range of uncertainties both internal and external to the maintenance project. External factors impacting the efficiency of scheduling include changes in maintenance windows, modifications or rejections of possessions in the application process, requests for additional work, and cancellation of possessions. Internal factors encompass issues such as insufficient preventive maintenance, unavailability of staff or equipment, and notifications of infrastructure failures. These uncertainties can significantly affect project performance, often leading to reduced contractor efficiency, more frequent infrastructure failures, and the need for repeated rescheduling of trackwork. Interestingly, reported infrastructure failures are both a cause and a consequence of these uncertainties.

Contractor performance is also affected by factors outside their control. Key elements influencing the efficiency of trackwork include the transfer of knowledge within contractor companies, the level of trust between contracting parties, and the allocation of adequate time on track for maintenance. The trust issue, particularly evident in the allocation of possession time, compels contractors to strategically plan to secure optimal time slots for essential maintenance. Non-compliance with possession application regulations, often perceived as a lack of professional competence by the Swedish Transport Administration, is linked to this trust deficit. These aspects of the contractor–client relationship indirectly impact the efficiency of trackwork scheduling. Furthermore, the limited time allocated for maintenance, coupled with the inability to perform preventive maintenance, is counterproductive for the Swedish railway system and inefficient from a Lean maintenance perspective.

Trackwork rescheduling

When contracting companies experience uncertainties in railway maintenance, their primary response is often to reschedule trackwork. These uncertainties can be viewed as the primary drivers of trackwork schedule changes across all planning levels. Schedule changes may also derive from changes in contract terms, additional maintenance project requests from the Swedish Transport Administration, or shortages of specialists in specific technical areas, infrastructure failures, and urgent repair needs.

From a Lean management perspective, adapting the schedule is seen as an integral part of the process. As projects progress, more detailed information becomes available, making it reasonable to modify plans to accommodate new insights about staff availability or equipment needs. Despite current regulations imposing strict deadlines on the scheduling process, the most frequent plan adjustments happen closer to trackwork execution. This may be due to a lack of incentives from the Swedish Transport Administration to discourage last-minute modifications.

Key factors influencing schedule changes include prior alterations, the type of track (single versus double), the work location (at stations versus between stations), and the timing of the trackwork (daytime versus nighttime and by month). To mitigate these last-minute changes and enhance schedule stability, a strategy involving a 'frozen' period within the rolling planning horizon is suggested. However, in practice, this rule is frequently overlooked, leading to diminished scheduling efficiency and challenging the practical application of Lean principles in this context.

RQ2: How and to what extent are trackwork schedules adjusted over time?

The findings of this thesis indicate that trackwork schedules undergo significant adjustments, primarily in the latter stages of the planning process. The key metrics used to evaluate these adjustments are the utilisation rate of maintenance windows and plan stability. These metrics serve as indicators of plan efficiency across three planning levels: strategic, tactical, and operational.

Our analysis found that only about 34% of the time allocated for maintenance in strategic planning is used for maintenance activities at the operational level. This discrepancy highlights a considerable gap between decisions regarding maintenance needs at the strategic planning stage and the actual maintenance volumes at the execution stage. Annually changed contract terms regarding allocated maintenance windows play a role in this discrepancy as well, as contractors perceive it as an added level of uncertainty regarding the allocated time on track.

The track utilisation plan schedule stability rate gradually decreases as the plan approaches its execution stage. Most schedule adjustments occur between four weeks and one week before the scheduled trackwork. Notably, changes can happen suddenly, including on the day of the trackwork itself. These adjustments are primarily due to the introduction of new work activities, followed by cancellations and changes in the duration of planned trackwork.

RQ3: What impact does scheduled trackwork have on train operations?

The magnitude of the trackwork effect is twofold. It affects train delays, which negatively impacts railway operation services. At the same time, the delay recovery opportunity for train drivers is limited for the areas where the trackwork is taking place. Trackwork is linked to an increased rate of delay occurrences and a higher probability of increased delays. Trains passing through sections with scheduled trackwork are 1.43 times more likely to experience an increase in running time delay. Simultaneously, there is a 16% increase in the expected number of instances where train delays increase by at least one minute, compared to scenarios without trackwork. Conversely, the opportunity for train delay recovery diminishes in the presence of trackwork. The frequency of delay reduction decreases by 4%, and the likelihood of a delay decrease is 11% lower than when there is no trackwork. The sensitivity analysis regarding the size of the delay revealed a more pronounced effect for delays between one and 10 minutes, while the impact of trackwork on delays exceeding 10 minutes was insignificant. This indicates that trackwork primarily contributes to smaller, more frequent delays.

RQ4: In what ways can the trackwork scheduling process be improved?

Adopting Lean principles

Our analysis suggests that revising organisational design strategies for maintenance projects could improve uncertainty management in contracting firms. Implementing Lean maintenance principles, which are not commonly used in Sweden's railway maintenance planning, could significantly enhance efficiency. However, the limited knowledge about Lean principles among the Swedish Transport Administration and its contractors might present initial barriers to implementing these changes.

Leveraging data-driven decision-making

Currently, trackwork planning and scheduling in Sweden are predominantly manual processes. The integration of e-maintenance technologies and advanced planning software could boost efficiency. Transitioning to data-driven decision-making, coupled with the adoption of new technologies in train operation centres, marks a positive trend. Decentralising scheduling to leverage the expertise of individuals in each technical area, supported by e-maintenance systems for improved information flow, can substantially enhance the overall process. This approach fosters continuous improvement and quality tracking.

Implementing consistent performance tracking

The regulations of the Swedish Transport Administration set specific timelines for capacity allocation processes. However, there is a lack of systematic follow-up on contractor compliance and there is no incentive system to encourage efficient scheduling. We propose the introduction of new metrics to assess scheduling efficiency. This approach would offer the Swedish Transport Administration a tool to measure contractors' adherence to regulations and overall performance. These metrics include:

1. Maintenance windows utilisation rate: estimating the percentage of trackwork time used relative to the total booked time in maintenance windows.
2. Measuring the impact of trackwork on train delays: providing a direct indicator of the operational effect of trackwork.
3. Monitoring track utilisation plan stability: identifying unpredictable elements in scheduling.

Discussion

Reflection on the main findings

Maintenance management

In Sweden, the maintenance strategy is decided by the Swedish Transport Administration. Therefore, for contractors, the primary source of information for the planning and scheduling of trackwork derives from the contract itself (Ivina et al., 2021). The regularity of certain types of repairs noted in the contract forms the foundation of the maintenance schedule. Papers 1 and 2 revealed that following the application process, site managers often do not secure sufficient track possession times for preventive maintenance. This shortcoming hinders the efficiency of the Swedish railway system and goes against the principles of Lean maintenance. Unfortunately, failure to perform enough preventive maintenance due to lack of time can lead to frequent emergency repairs, which causes uncertainty in planning and scheduling. These time constraints force contractors to prioritise corrective maintenance. Moreover, according to Paper 2, the main reasons for not completing enough preventive maintenance are a lack of funds allocated for the project and a lack of time on track.

According to planning regulations, works expected to take longer than 15 minutes or that do not have an emergency case must be applied to the track utilisation plan no later than four weeks before execution (Trafikverket, 2015b). However, the interviews conducted for Paper 1 revealed that some contractors lock their plans less than four weeks before execution. These findings raise the question of what circumstances might trigger such a complex environment for efficient trackwork scheduling.

Papers 1 and 2 revealed issues that affect the maintenance planning process and the quality of contractor performance. Project uncertainties arise at the tactical and operation levels and are caused by factors both external and internal to the project. Project uncertainty is typically related to a lack of information or the failure to process all the available information to produce the most concrete decision about the time required for trackwork (Galbraith, 1974). Existing strategies to address uncertainties include communicating with involved stakeholders, scheduling extra time, and maintaining 24/7 response teams. Some existing strategies are benefiting

The Swedish Transport Administration and contractors, and some do not conform to existing regulations.

Possession allocation

Selecting the optimal time for trackwork is a complex task for maintenance contractors. The main operational challenges in maintenance planning lie in scheduling work times and managing resources. Contractors are required to apply for track possession well before proceeding with detailed process planning. This requires contractors to make educated estimates about the duration of their planned activities based on past experience. If their possession application is denied by the planning department of the Swedish Transport Administration, they must reschedule their trackwork and submit a new application. Rescheduling is associated with significant additional costs, as it depends on the complexity of the activity being rescheduled and the time until the rescheduled intervention. This problem has received scant attention in previous research (Lidén, 2015; Sedghi et al., 2021). Additionally, based on the findings of Paper 3, the rescheduling problem demands greater attention, as more changes happen at the last minute.

At present, there is an issue of information overload in the maintenance planning and scheduling process (Kour et al., 2014). The data is processed manually; therefore, decisions depend primarily on the contractor’s experience. This data processing method creates discomfort for maintenance companies and influences the efficiency of the trackwork scheduling process. Moreover, some project managers at the Swedish Transport Administration have accused contractors of having poor long-term planning skills (Paper 1).

Maintenance windows

Maintenance windows, designed to enable the scheduling of trackwork during periods of lower traffic or when tracks are accessible, are essential for efficient railway maintenance. The effects of scheduled trackwork on train operations are analysed in Paper 5 to estimate the scale of the problem. However, as highlighted in Papers 2 and 4, there seems to be a limited focus among contractors on verifying the availability of track time within these windows when scheduling trackwork. Despite the advantages of the new planning regime, contractors do not fully utilise maintenance windows as intended. There are many potential reasons for this, and some were discussed in the interviews with contractors in Paper 2. For example, some maintenance windows are too short for certain types of work, so contractors prefer to search for time on track free from train traffic. These findings confirm the results obtained by Lidén et al. (2018).

Contractors perceive maintenance windows as a source of uncertainty, especially when contract terms change, leading to shorter available windows. This reduction in window time complicates work and increases costs, as the same tasks must be completed in a shorter time, often necessitating extra shifts. This issue is exacerbated when information about available windows is provided late. Interestingly, maintenance windows, initially designed to simplify scheduling, are now a cause of these uncertainties. Paper 4 revealed that 70% of booked trackwork time occurs outside of maintenance windows, impacting the train scheduling process. The release of unused maintenance window capacity just two weeks before train operations hinders efficient capacity management.

Maintenance windows, particularly on double tracks, are designed to allow one track to remain operational with trains moving at reduced speeds. However, for some maintenance companies, ongoing train operations might conflict with safety regulations, necessitating full track closure. Special work safety regulations might be a reason for booking time on track at night and outside of maintenance windows. According to Hedström (2020), a contractor's application for trackwork hours outside of maintenance windows should only be approved if the predefined times are fully booked. Contrary to expectations, our data shows that although planned maintenance windows are only 42% utilised, the majority of trackwork is conducted outside these windows.

To improve the design and utilisation of maintenance windows, a more tailored approach is recommended. This could encompass involving contractors earlier in the contract design stage, lengthening maintenance window durations, and considering weekend windows. Introducing incentives for adhering to maintenance windows could promote more efficient and predictable maintenance processes. It is crucial to ensure maintenance window awareness among train operators to avoid interference with scheduled maintenance. Proper enforcement ensures trains do not disrupt maintenance, maintaining schedule integrity. This alignment between contractors and train operators, facilitated by well-designed maintenance windows and supported by incentives and enforcement, is critical to a more streamlined maintenance process.

Attaining trackwork scheduling efficiency through Lean

Efficiency in trackwork scheduling can be approached from three perspectives: strategic, tactical, and operational. At the strategic level, it involves integrating maintenance windows into the overall capacity allocation process, essential for determining when and where maintenance activities should be conducted. On the tactical level, the focus is on optimising resource allocation. At the operational level, attention shifts to the timing of each task, aiming to maximise cost-effectiveness in the use of available track time while minimising disruptions to train traffic. Across all three levels, applying Lean principles for process optimisation proves to be practical.

Lean production in the trackwork context

Lean operates as a cohesive system. Thus, when implementing Lean practices, it is crucial to view all components in the trackwork flow as integral parts of a single, unified system where all processes are interconnected and interdependent. This includes the capacity allocation process and trackwork scheduling, which must be recognised not as isolated elements but as harmonious components of the overall system (Higgins, 1998).

The five main principles of Lean translated into the context of this thesis are:

1. Value. Understanding what the customer (such as the railway operator or the end user) considers to be valuable, such as safety, reliability, and track availability.
2. Value stream. Defining every step involved in the process, from the planning and design phase to execution. Identifying the weakest components in the process as those that do not contribute value.
3. Flow. Shifting focus from the final product to the process itself. Ensuring a smooth and efficient workflow, minimising delays and interruptions.
4. Pull. Designing processes that respond to the actual needs and demands of the customer. Implementing condition-based maintenance and ensuring work is done when needed.
5. Perfection. Continuously evaluating and improving processes to minimise waste, increase efficiency, and maximise customer value.

Lean implementation

The first step of Lean implementation is establishing a vision, determining the desired destination, and defining the main goal. The purpose of maintenance is to ensure operational reliability. Therefore, the vision in the context of this thesis is a well-functioning railway network where railway track is in good condition, trains are on time, and train operations are uninterrupted. This thesis aims to explore methods of achieving a smooth flow in trackwork plan implementation without interruptions or frequent or unnecessary changes, where customers are defined as passengers and freight train operators.

After defining the vision, it is important to identify and remove barriers to Lean implementation. Detecting waste is the second important goal in the implementation of Lean production. According to Ohno (Bicheno & Holweg, 2009), types of waste include:

- *Overproduction.* In trackwork, overproduction can be linked to excessive lead time, rescheduling, unnecessary equipment moves, and exceeding the required time for trackwork.
- *Waste of waiting.* As with the scheduling process, sometimes contractors must wait for their time-on-track application to go

through. If it is rejected, planning must be repeated, which leads to overproduction waste.

- *Waste of motion.* This refers to poor equipment arrangement or improper lengths of maintenance windows.
- *Waste of knowledge.* This refers to the lack of knowledge transfer within a company.

The Lean formula is designed to balance the amount of work with available resources. The goal is to attain a close to 100% load with some gap, as some underload is desirable. In the context of this thesis, the interpretation of the Lean formula would be:

$$\text{Demand} - \text{Available resources} = \text{Gap},$$

where *demand* is trackwork that must be completed within a certain period and *available resources* is time on track. A *negative gap* means there are not enough resources to do the necessary job and a *positive gap* means there are too many resources to do the job, which can also be considered waste. Possession time booked by maintenance contractor companies is costly, as it blocks trains from operating on the track. If contractors over- or underestimate their production time, it can result in maintenance-related waste. Therefore, it is essential to track time on track used to complete trackwork and compare it with the booked time.

Schedule stability enhancements

Following Lean principles, the efficiency of the trackwork scheduling process is achieved by maximising value and minimising waste. This involves preventing infrastructure failures, optimising the use of time on track, and allocating more time for preventive maintenance. Lean scheduling is about designing processes and procedures that reduce waste in the workplace to maximise value. To illustrate this approach, Table 5 outlines how Lean production principles have been adapted into Lean scheduling practices for railway trackwork. These adaptations aim to optimise planning by striving for zero defects, ensuring realistic scheduling, and minimising disruptions to train traffic.

In Sweden, a common strategy among maintenance contractors to address uncertainties is the rescheduling of trackwork. This scenario illustrates that despite having strategic plans in place, the uncertain nature of operational environments requires frequent and at times significant alterations to trackwork schedules. The need for such adjustments becomes more pronounced as the execution date approaches, highlighting the intricate relationship between strategic planning and the real-world challenges faced in railway maintenance.

To enhance schedule stability, various methods can be employed, although not all are suitable for the context of trackwork scheduling. For instance, the concept of creating a ‘safety stock’ might not be directly applicable, as booking extra-long possessions as a safety measure would be too costly for the railway system. Instead, aligning trackwork scheduling with Lean production principles offers a more viable solution. The adaptation of Lean principles into trackwork scheduling practices aims to establish a more stable and efficient scheduling process.

Table 5. Lean production translated into Lean scheduling.

Lean production	Ways to maximise trackwork scheduling efficiency
Elimination of waste	Realistic planning and scheduling Avoid splitting works into smaller portions Maximise predictive maintenance Minimise infrastructure faults Minimise planning time and eliminate re-planning and rescheduling
Zero defect	Minimal effect on train traffic Maximum use of time on track booked for maintenance
Pull instead of push	Condition-based preventive maintenance Use of maintenance windows Plan creation once all information is available
Decentralisation of responsibilities	Discussions between planning departments Cooperation between planners and technicians Plan for several tasks simultaneously Decisions made by the person who knows more about the task
Vertical information system	E-maintenance Improve the flow of decision information in the contracting company Improve decision-making communication from client to contractor
Continuous improvement	Learning loop Evaluate project flow efficiency

Last Planner system application

Incorporating Lean thinking into project management, especially in the context of maintenance scheduling, entails postponing decisions until the last responsible moment. This approach allows for a thorough exploration and assessment of various alternatives, ultimately leading to more efficient planning processes from a production standpoint. In line with this Lean principle, contractors are encouraged to apply for possession time as close to the execution stage as possible. As a result, the detailed planning conducted by the Swedish Transport Administration could be enhanced by introducing shorter application periods, such as on a weekly basis. While this strategy would enable contractors to perform necessary maintenance at the most suitable times, it is important to consider the challenges it might pose to the overall timetabling process.

This thesis offers a series of suggestions aimed at enhancing the trackwork planning and scheduling process, grounded on the principles of the Last Planner system:

Enhance planning detail: The Swedish Transport Administration should increase the detail of planning while allocating time for maintenance windows. It should also involve contractors in the design process.
Boost collaboration quality: Improve the quality of collaboration between project engineers at the Swedish Transport Administration and contractors. Enhance data exchange and mutual understanding of both parties' needs.
Guidelines for contractors: Create guidelines for contractors on adhering to regulations during the planning process. Implement incentives to encourage compliance with regulations.
Eliminate waste: Remove inefficiencies such as poor time management and possession planning. Gauge the reliability of commitments through metrics like PPC and schedule instability.
Incentives: Design incentives for contractors to encourage the use of maintenance windows and stabilise planning at the tactical stage.
External factors: Do everything possible to avoid late adjustments in contracts and late notifications of new works.
Implement automated tools: These can measure the quantity of work planned and completed by the contractor, providing a new key performance indicator.
Emphasise preventive maintenance: Encourage a proactive approach to maintenance, creating opportunities to monitor the quality of planning and learn from 'less successful' cases.

Contributions of the thesis

Contribution to research

This thesis presents a structured analysis of the railway trackwork scheduling process in Sweden. It offers a fresh perspective on optimising trackwork scheduling by integrating Lean principles and addressing uncertainties at each level of the decision-making process. The aim is to examine the efficiency of the process from a practical application standpoint, focusing on compliance with guidelines, the human factor in following regulations, and real-world scenarios. This method lays the foundation for further development and research, enabling the analysis of each aspect of scheduling independently.

The thesis introduces new metrics to assess schedule efficiency and a classification of factors that affect scheduling efficiency. It presents an analysis of trackwork scheduling stability and the nature of schedule changes. Furthermore, whereas previous research has considered trackwork as one of several variables in train delay analysis, this thesis isolates trackwork to investigate it at scaled levels, thereby uncovering the nuances involved. The research holds broader relevance for the European Union regulated capacity allocation process and underscores the necessity for continual adaptation and optimisation in trackwork scheduling to accommodate the growing demands of railway networks.

Contribution to practitioners

For practitioners, particularly in the Swedish railway industry, this thesis offers practical strategies to enhance the efficiency and reliability of railway maintenance. It advocates the adoption of Lean maintenance principles, a shift towards data-driven decision-making, an improvement of existing organisational strategies to mitigate project uncertainties.

The thesis is highly valuable for railway operations practitioners from two perspectives. Firstly, it suggests improvements in the current railway maintenance planning and scheduling process by applying Lean principles to refine the existing system. This thesis details how these principles can be specifically tailored to the context of trackwork, offering a step-by-step guide for their implementation. Secondly, the thesis encourages the continuous evaluation of process efficiency by applying the recommended measures: maintenance windows utilisation rate, trackwork scheduling efficiency, and the impact of trackwork on train operations.

Each paper included in this thesis serves as a guideline for practitioners aiming to enhance the scheduling process. For example, Paper 1 introduces the PPC metric to monitor the discrepancy between the amount of track time booked and the actual time needed. Paper 2 offers classification of project uncertainties and describes successful mitigation strategies. Paper 3 elucidates the nature of trackwork schedule instability, which can be utilised for future planning advancements. The results in Paper 4 call for an improved design of maintenance windows. Paper 5 introduces a novel method for analysing the impact of trackwork on train delays, a technique not previously used by the Swedish Transport Administration. This analysis could be a vital tool for evaluating trackwork scheduling efficiency.

Future research

Future research should primarily focus on addressing inefficiencies within the current trackwork scheduling process. One of the main directions should be the application and analysis of Lean in the trackwork process, specifically through a design research approach. This would ideally involve conducting smaller-scale case studies within the responsibility of a single contractor company. Such studies would allow for a detailed examination of the implementation of Lean practices and their impact on contractors’ performance metrics, particularly in terms of plan stability measures.

Another direction for future research lies in evaluating the socioeconomic benefits and costs of the existing maintenance window allocation system. This entails a comprehensive assessment of their use, effectiveness, and profitability. Additionally, there is a need to reconsider and potentially redesign the process of planning maintenance windows to enhance their effectiveness. Another angle for future research could be exploring various incentives that could lead to the more efficient use of maintenance windows. Identifying the most effective incentives could significantly improve their utilisation rates. Future research should also focus on improving the design of maintenance windows themselves, which could, in turn, enhance their overall utilisation and effectiveness.

From a practical standpoint, addressing infrastructure failures, which are a major cause of trackwork scheduling process inefficiencies, is crucial. Future studies should investigate the nature of these infrastructure failures and seek to improve the planning process to prevent them. This should be coupled with an analysis of the effectiveness of current maintenance strategies.

Conclusions

This thesis aims to explore the efficiency of the trackwork scheduling process in Sweden. The efficiency of trackwork scheduling is evaluated by three main factors: maintenance windows utilisation, track utilisation plan stability, and the effect of scheduled trackwork on train delays. Based on the results of five research papers, this thesis answers four research questions: (1) What factors influence the efficiency of trackwork scheduling, and in what ways? (2) How and to what extent are trackwork schedules adjusted over time? (3) What impact does scheduled trackwork have on train operations? (4) In what ways can the trackwork scheduling process be improved?

The factors that affect trackwork scheduling efficiency and lead to frequent rescheduling are expressed as disagreement between the Swedish Transport Administration and contractors, poor long-term planning, and insufficient maintenance times. This thesis reports the presence of external and internal project uncertainties at both tactical and operational levels. Externally, contractors struggle with changes in maintenance windows and unpredictability in possession application approvals at the tactical level, while at the operational level, they face unpredictability due to additional work requests, and infrastructure failures. Internally, constraints in time and resources limit opportunities for preventive maintenance, and challenges in crew scheduling, particularly during night shifts, complicate operations.

Trackwork schedule stability diminishes as the execution date nears, with the scheduling process becoming increasingly uncertain. Although, one of the strategies to remedy the project uncertainties is using maintenance windows, most of the trackwork is conducted outside these designated periods. The results also show that scheduled trackwork has a higher effect of smaller but more frequent delays. At the same time, scheduled trackwork reduces the opportunity for the train delay recovery.

To enhance the efficiency of railway maintenance in Sweden, this thesis proposes three key strategies. First, the adoption of Lean principles, which are relatively new to Sweden's railway maintenance planning. Second, the shift towards data-driven decision-making, involving the integration of e-maintenance technologies and advanced planning software, moving away from predominantly manual processes. Finally, the thesis suggests introducing new metrics to evaluate scheduling efficiency, such as the utilisation rate of maintenance windows, the impact of trackwork on train delays, and the stability of the track utilisation plan.

References

Åhlström, P. (2004). Lean Service Operations: Translating Lean Production Principles to Service Operations. *International Journal of Services Technology and Management*, *5*, 545-564. https://doi.org/10.1504/IJSTM.2004.006284

Ait-Ali, A., & Eliasson, J. (2021). European railway deregulation: an overview of market organization and capacity allocation. *Transportmetrica A: Transport Science*. https://doi.org/10.1080/23249935.2021.1885521

Ait-Ali, A., & Lidén, T. (2022). Minimal utilization rate for railway maintenance windows: a cost-benefit approach. *European Journal of Transportand Infrastructure Research*, *22*(2), 108-131. https://doi.org/10.18757/ejtir.2022.22.2.6130

Al-Douri, Y. K., Tretten, P., & Karim, R. (2016). Improvement of railway performance: a study of Swedish railway infrastructure. *Journal of Modern Transportation*, *24*(1), 22-37. https://doi.org/10.1007/s40534-015-0092-0

Armstrong, J., & Preston, J. (2020). Balancing railway network availability and engineering access. *Proceedings of the Institution of Civil Engineers - Transport*, *173*(4), 209-217. https://doi.org/10.1680/jtran.19.00045

Aziz, R. F., & Hafez, S. M. (2013). Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, *52*(4), 679-695. https://doi.org/10.1016/j.aej.2013.04.008

Ballard, G. (1999). Improving Work Flow Reliability. *Proceedings of the 7th Annual Conference of the International Group for Lean Construction*.

Ben-Daya, M., Uday, K., & Prabhakar, M. (2016). *Introduction to Maintenance Engineering* (1st ed.). Wiley.

Bicheno, J., & Holweg, M. (2009). *The Lean Toolbox: The Essential Guide to Lean Transformation*. PICSIE Books.

British Standard Institution. (2010). *BS EN 13306:2010 Maintenance - maintenance terminology*. BSI Standards Publication

Broman, E., Eliasson, J., & Aronsson, M. (2022). Efficient capacity allocation on deregulated railway markets. *Journal of Rail Transport Planning & Management*, *21*. https://doi.org/10.1016/j.jrtpm.2021.100294

Budai-Balke, G. (2009). *Operations Research Models for Scheduling Railway Infrastructure Maintenance* (PhD Thesis, Erasmus University).

Budai, G., Huisman, D., & Dekker, R. (2006). Scheduling preventive railway maintenance activities. *Journal of the Operational Research Society*, *57*(9), 1035-1044. https://doi.org/10.1057/palgrave.jors.2602085

Buurman, B., Gkiotsalitis, K., & van Berkum, E. C. (2023). Railway maintenance reservation scheduling considering detouring delays and maintenance demand.

Journal of Rail Transport Planning & Management, *25*. https://doi.org/10.1016/j.jrtpm.2022.100359
Campbell, G. M. (1992). Master Production Scheduling Under Rolling Planning Horizons with Fixed Order Intervals. *Decision Sciences*, *23*(2), 312-331. https://doi.org/10.1111/j.1540-5915.1992.tb00391.x
Consilvio, A., Febbraro, A. D., & Sacco, N. (2021). A Rolling-Horizon Approach for Predictive Maintenance Planning to Reduce the Risk of Rail Service Disruptions. *IEEE Transactions on Reliability*, *70*(3), 875-886. https://doi.org/10.1109/tr.2020.3007504
Cooper, H. (2004). Lean maintenance maximizes cost savings. *Manufacturing Engineering*, *133*(6).
Council of European Union. (2012). *Directive 2012/34/EU of the European Parliament and of the Council of 21 November 2012 establishing a single European railway area*. Official Journal of the European Union
Creswell, J. W., & Creswell, J. D. (2022). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications.
Deighton, M. G. (2016). Maintenance Management. In *Facility Integrity Management* (pp. 87-139). https://doi.org/10.1016/b978-0-12-801764-7.00005-x
Dirnberger, J., & Barkan, C. (2007). Lean Railroading for Improving Railroad Classification Terminal Performance: Bottleneck Management Methods. *Transportation Research Record*, *1995*, 52-61. https://doi.org/10.3141/1995-07
European Commission. (2011). *White Paper. European transport policy for 2010: time to decide.* Brussels
Eurostat. (2023). *Railway transport - length of electrified lines, by type of current*
Forsgren, M., Aronsson, M., & Gestrelius, S. (2013). Maintaining tracks and traffic flow at the same time. *Journal of Rail Transport Planning and Management*, *3*(3), 111-123. https://doi.org/10.1016/j.jrtpm.2013.11.001
Galbraith, J. R. (1974). Organization Design: An Information Processing View. *Interfaces*.
Gibson, S. (2003). Allocation of capacity in the rail industry. *Utilities Policy*, *11*, 39-42. https://doi.org/10.1016/S0957-1787(02)00055-3
Guenther Schuh, J.-P. P., Melanie Luckert, Philipp Hünnekes, Matthias Schmidhuber. (2019). Effects of the update frequency of production plans on the logistical performance of production planning and control. *Procedia CIRP*, *79*, 421-426. https://doi.org/https://doi.org/10.1016/j.procir.2019.02.115
Hansen, G. K., & Olsson, N. O. E. (2011). Layered Project–Layered Process: Lean Thinking and Flexible Solutions. *Architectural Engineering and Design Management*, *7*(2), 70-84. https://doi.org/10.1080/17452007.2011.582331
Harrell, M., & Bradley, M. (2009). *Data collection methods: semi-structured interviews and focus groups*. RAND Corporation.
Hedström, R. (2020). *Tider i spår för underhållsarbeten (Track Possession Time for Maintenance Work).*
Higgins, A. (1998). Scheduling of railway track maintenance activities and crews. *Journal of the Operational Research Society*, *49*(10), 1026-1033. https://doi.org/10.1057/palgrave.jors.2600612
Inman, R. R., & Gonsalvez, D. J. A. (1997). The causes of schedule instability in an automotive supply chain. *Production and Inventory Management Journal*, *38*(2), 26-31.

Islam, D. M. Z., Ricci, S., & Nelldal, B.-L. (2016). How to make modal shift from road to rail possible in the European transport market, as aspired to in the EU Transport White Paper 2011. *European Transport Research Review*, *8*(3). https://doi.org/10.1007/s12544-016-0204-x

Ivina, D., Olsson, N. O. E., & Winslott Hiselius, L. (2021). Significance of the contractual relationship for the efficient railway maintenance project planning. *Procedia Computer Science*. https://doi.org/10.1016/j.procs.2021.12.093

Kabak, K. E., & Ornek, A. M. (2009). An improved metric for measuring multi-item multi-level schedule instability under rolling schedules. *Computers & Industrial Engineering*, *56*(2), 691-707. https://doi.org/10.1016/j.cie.2006.11.001

Khajehei, H. (2021). *Data-driven models for railway track geometry maintenance* (PhD Thesis, Luleå University of Technology).

Kour, R., Tretten, P., & Karim, R. (2014). eMaintenance solution through online data analysis for railway maintenance decision-making. *Journal of Quality in Maintenance Engineering*, *20*(3), 262-275.

LaForge, R. L., Kadipasaoglu, S. N., & Sridharan, V. (2000). Schedule stability. In *Encyclopedia of Production and Manufacturing Management* (pp. 665-668). Springer US. https://doi.org/10.1007/1-4020-0612-8_846

Lidén, T. (2015). Railway infrastructure maintenance - a survey of planning problems and conducted research. In *18th Euro Working Group on Transportation, EWGT 2015* (pp. 574-583). Elsevier. https://doi.org/10.1016/j.trpro.2015.09.011

Lidén, T. (2016). *Towards concurrent planning of railway maintenance and train services* (PhD Thesis, Linköping University).

Lidén, T., Kalinowski, T., & Waterer, H. (2018). Resource considerations for integrated planning of railway traffic and maintenance windows. *Journal of Rail Transport Planning and Management*, *8*(1), 1-15. https://doi.org/10.1016/j.jrtpm.2018.02.001

Mason, J. (2017). *Qualitative Researching* (3 ed.). SAGE Publications.

Mostafa, S., Dumrak, J., & Soltan, H. (2015). Lean Maintenance Roadmap. *Procedia Manufacturing*, *2*, 434-444. https://doi.org/10.1016/j.promfg.2015.07.076

Narayanan, A., & Robinson, P. (2010). Evaluation of joint replenishment lot-sizing procedures in rolling horizon planning systems. *International Journal of Production Economics*, *127*(1), 85-94. https://doi.org/10.1016/j.ijpe.2010.04.038

Nathanail, E. (2014). Framework for Monitoring and Assessing Performance Quality of Railway Network Infrastructure: Hellenic Railways Case Study. *Journal of Infrastructure Systems*. https://doi.org/10.1061/(ASCE)IS.1943-555X

Nijland, F., Gkiotsalitis, K., & van Berkum, E. C. (2021). Improving railway maintenance schedules by considering hindrance and capacity constraints. *Transportation Research Part C: Emerging Technologies*, *126*. https://doi.org/10.1016/j.trc.2021.103108

Odolinski, K. (2019). Contract design and performance of railway maintenance: Effects of incentive intensity and performance incentive schemes. *Economics of Transportation*, *18*, 50-59. https://doi.org/10.1016/j.ecotra.2019.05.001

Odolinski, K., Smith, A., Wheat, P., Nilsson, J.-E., & Dheilly, C. (2023). Damage or no damage from traffic: Re-examining marginal cost pricing for rail signalling maintenance. *Transport Policy*, *131*, 13-21. https://doi.org/10.1016/j.tranpol.2022.11.013

Olofsson, O. (2019). *Lean Maintenance - Lean Manufacturing Needs Reliable Machines*. World Class Manufacturing.
Olsson, N. O. E. (2006). Management of flexibility in projects. *International Journal of Project Management*, *24*, 66–74. https://doi.org/10.1016/j.ijproman.2005.06.010
Olsson, N. O. E. (2008). Conflicts related to effectiveness and efficiency in Norwegian rail and hospital projects. *Project Perspectives*, *29*(1), 81-85.
Olsson, N. O. E., & Haugland, H. (2004). Influencing factors on train punctuality—results from some Norwegian studies. *Transport Policy*, *11*(4), 387-397. https://doi.org/10.1016/j.tranpol.2004.07.001
Palmer, R. D. (2013). *Maintenance Planning and Scheduling Handbook, Third Edition* (3rd ed.). McGraw-Hill Education.
Palmqvist, C.-W., Johansson, I., & Sipilä, H. (2023). A method to separate primary and secondary train delays in past and future timetables using macroscopic simulation. *Transportation Research Interdisciplinary Perspectives*, *17*. https://doi.org/10.1016/j.trip.2022.100747
Palmqvist, C.-W., Olsson, N. O. E., & Hiselius, L. (2017). Some Influencing Factors For Passenger Train Punctuality In Sweden. *International Journal of Prognostics and Health Management*.
Parry, G., & Turner, C. E. (2006). Application of lean visual process management tools. *Production Planning and Control*, *17*, 77-86. https://doi.org/10.1080/09537280500414991
Peng, F., & Ouyang, Y. (2012). Track maintenance production team scheduling in railroad networks. *Transportation Research Part B: Methodological*, *46*(10), 1474-1488. https://doi.org/10.1016/j.trb.2012.07.004
Peng, F., & Ouyang, Y. (2014). Optimal Clustering of Railroad Track Maintenance Jobs. *Computer-Aided Civil and Infrastructure Engineering*, *29*(4), 235-247. https://doi.org/10.1111/mice.12036
Perminova, O., Gustafsson, M., & Wikström, K. (2008). Defining uncertainty in projects – a new perspective. *International Journal of Project Management*, *26*(1), 73-79. https://doi.org/https://doi.org/10.1016/j.ijproman.2007.08.005
Peterson, A., Wahlborg, M., Häll, C. H., Schmidt, C., Kordnejad, B., Warg, J., Johansson, I., Joborn, M., Gestrelius, S., Törnquist Krasemann, J., Josyula, S. P., Palmqvist, C.-W., & Lidén, T. (2019). *Analysis of the gap between daily timetable and operational traffic*.
Prior, L. (2003). *Using Documents in Social Research* https://doi.org/10.4135/9780857020222
Project Management Institute. (2017). *A Guide to the Project Management Body of Knowledge (PMBOK Guide).* (6th ed.)
Pujawan, I. N. (2004). Schedule nervousness in a manufacturing system: a case study. *Production Planning & Control*, *15*(5), 515-524. https://doi.org/10.1080/09537280410001726320
Pujawan, I. N., Er, M., Kritchanchai, D., & Somboonwiwat, T. (2014). Uncertainty and schedule instability in supply chain: insights from case studies. *International Journal of Services and Operations Management*, *19*(4). https://doi.org/10.1504/ijsom.2014.065670
RailNetEurope. (2022). *Glossary of Terms Related to Network Statements and Corridor Information Documents*.

Rolstadås, A., & Johansen, A. (2008). *From protective to offensive project management* PMI® Global Congress 2008—EMEA, St. Julian's, Malta.

Sasidharan, M., Burrow, M. P. N., & Ghataora, G. S. (2020). A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance. *Research in Transportation Economics*, *80*. https://doi.org/10.1016/j.retrec.2020.100815

Sedghi, M., Kauppila, O., Bergquist, B., Vanhatalo, E., & Kulahci, M. (2021). A taxonomy of railway track maintenance planning and scheduling: A review and research trends. *Reliability Engineering & System Safety*, *215*. https://doi.org/10.1016/j.ress.2021.107827

Siqueira Bueno, P. M., Vilela, P., Christofoletti, L. M., & Vieira, A. P. (2019). Optimizing railway track maintenance scheduling to minimize circulation impacts. In *2019 Joint Rail Conference, JRC 2019*. https://doi.org/10.1115/JRC2019-1298

Smith, R., & Hawkins, B. (2004). *Lean Maintenance*. Elsevier Inc.

Stenström, C., Juntti, U., Parida, A., & Kumar, U. (2016). Track Maintenance Between Trains Simulation. In *Current Trends in Reliability, Availability, Maintainability and Safety* (pp. 373-380). https://doi.org/10.1007/978-3-319-23597-4_26

Su, Z., Jamshidi, A., Núñez, A., Baldi, S., & De Schutter, B. (2019). Integrated condition-based track maintenance planning and crew scheduling of railway networks. *Transportation Research Part C: Emerging Technologies*, *105*, 359-384. https://doi.org/10.1016/j.trc.2019.05.045

Tezuka, M., Munakata, S., & Sawada, M. (2015). Maintenance Schedule Optimization Based on Failure Probability Distribution. In *International Conference on Industrial Engineering and Operations Management*. https://doi.org/10.1109/IEOM.2015.7093732

Thorsén, M., Olsson, N. O. E., & Winslott Hiselius, L. (2018). *Banarbeten – processer och datatillgång (förstudie) (Trackwork - Process and data access (pre-study))*. L. University.

Trafikanalys. (2022). *Rail traffic. Statistics on traffic, transport, vehicles and infrastructure for railways, tramways and subways in Sweden*.

Trafikverket. (2015a). *Ansökan om kapacitet för banarbete i närtid, järnväg (Application for capacity for track work in the near future, railway)*. (TDOK 2015:0426).

Trafikverket. (2015b). *Banarbetstider för underhåll av järnvägsanläggningen (Trackwork time for maintenance of the railway infrastructure)*. (TDOK 2015:0484).

Trafikverket. (2015c). *Koll på anläggningen (Check the facility)*. (SOU 2015-42).

Trafikverket. (2020). *Framtidens järnvägsunderhåll (The railway maintenance of the future)*. (SOU 2020:18).

Trafikverket. (2021). *Summary of "A direction framework for long-term infrastrucuture-planning, for the periods 2022-2033 and 2022-2036"*. (TRV 2020/73376).

Trafikverket. (2022). *Trafikverkets verksamhetsplan 2023–2025 (The Swedish Transport Administration's business plan 2023–2025)*. (TRV 2022/13418).

Trafikverket. (2023a). *Network Statement*.

Trafikverket. (2023b). *Railway - Market and Competition*.

van der Kooij, R. B. K., Landmark, A. D., Seim, A. A., & Olsson, N. O. E. (2017). The effect of temporary speed restrictions, analyzed by using real train traffic data. *Transportation Research Procedia*, *22*, 580-587. https://doi.org/10.1016/j.trpro.2017.03.047

Vieira, G. E., Herrmann, J. W., & Lin, E. (2003). Rescheduling Manufacturing Systems: A Framework of Strategies, Policies, and Methods. *Journal of Scheduling*, *6*(1), 39-62. https://doi.org/10.1023/A:1022235519958

Wang, L., Lu, Z., & Ren, Y. (2019). A rolling horizon approach for production planning and condition-based maintenance under uncertain demand. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *233*(6), 1014-1028. https://doi.org/10.1177/1748006x19853671

Womack, J. P., & Jones, D. T. (1997). Lean Thinking—Banish Waste and Create Wealth in your Corporation. *Journal of the Operational Research Society*, *48*(11), 1148-1148. https://doi.org/10.1057/palgrave.jors.2600967

Yile, L., XueHang, X., & Lei, Z. (2008). *Lean Maintenance framework and its application in clutch maintenance* Proceedings of the International Conference on Information Management, and Industrial Engineering, ICIII,

Zhang, Y., D'Ariano, A., He, B., & Peng, Q. (2019). Microscopic optimization model and algorithm for integrating train timetabling and track maintenance task scheduling. *Transportation Research Part B: Methodological*, *127*, 237-278. https://doi.org/10.1016/j.trb.2019.07.010

Zidane, Y. J. T., & Olsson, N. O. E. (2017). Defining project efficiency, effectiveness and efficacy. *International Journal of Managing Projects in Business*, *10*(3), 621-641. https://doi.org/10.1108/ijmpb-10-2016-0085

Appendix

List of included papers

Paper 1

Ivina, D., Olsson, N.O.E. (2020) Lean Construction Principles and Railway Maintenance Planning. *Proceedings of 28th Annual Conference of the International Group for Lean Construction (IGLC).* Berkeley, California, USA: The International Group for Lean Construction (IGLC), pp. 577-588. https://doi.org/10.24928/2020/0025

Authors' contributions

Ivina D.: Conceptualisation, Methodology, Investigation, Visualisation, Writing—Original Draft Preparation, Writing—Review and Editing.
Olsson N.O.E.: Conceptualisation, Review and Editing, Data Collection, Data Curation, Supervision.

Paper 2

Ivina, D., Olsson, N.O.E., Palmqvist, C.-W., Hiselius, W.L. (2023) Uncertainties in Scheduling and Execution of Trackwork in Sweden. *Public Transport,* https://doi.org/10.1007/s12469-023-00322-x

Authors' contributions

Ivina D.: Conceptualisation, Data Collection, Interviews, Methodology, Data Analysis, Writing—Original Draft Preparation, Visualisation, Review and Editing.
Olsson N.O.E.: Conceptualisation, Review and Editing, Data Curation, Supervision.
Palmqvist C.-W.: Review and Editing, Supervision.
Hiselius W.L.: Review and Editing, Project administration, Funding acquisition, Supervision.

Paper 3

Ivina, D., Ma, Z. (2023) Stability Assessment of Railway Trackwork Scheduling in Sweden. (*Manuscript under review*)

Authors' contributions

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

Paper 4

Ivina, D., Palmqvist, C.-W. (2023) Railway Maintenance Windows: Discrepancies between Planning and Practice in Sweden. *Transportation Research: Interdisciplinary Perspectives.* Vol. 22. https://doi.org/10.1016/j.trip.2023.100927

Authors' contributions

Ivina D.: Conceptualisation, Data Collection, Methodology, Formal Analysis, Writing—Original Draft Preparation, Writing—Review and Editing.
Palmqvist C.-W.: Conceptualisation, Data Curation, Validation, Investigation, Supervision, Review and Editing.

Paper 5

Ivina, D., Palmqvist, C.-W. (2023). The Downside of Upkeep: Analysing Railway Infrastructure Maintenance Impact on Train Operations in Sweden. *Applied Sciences Special Issue: Railway Structure and Track Engineering*., Vol.14 (1), p.125. https://doi.org/10.3390/app14010125

Authors' contributions

Ivina D.: Conceptualisation, Data Collection, Methodology, Formal Analysis, Writing—Original Draft Preparation, Writing—Review and Editing.
Palmqvist C.-W.: Methodology, Data Curation, Validation, Review and Editing, Supervision.

Additional publications:

Ivina, D., Palmqvist, C-W., Olsson, N.O.E., Hiselius, L. (2021) Train Delays due to Trackwork in Sweden. *The 9th International Conference on Railway Operations Modelling and Analysis*: *RailBeijing2021*. Beijing, China.

Ivina, D., Olsson, N.O.E., Hiselius W.L. (2022) Significance of the Contractual Relationship for the Efficient Railway Maintenance Project Planning. *Procedia Computer Science.* Vol. 196, pp. 920-926, https://doi.org/10.1016/j.procs.2021.12.093.