Concurrent planning of railway maintenance windows and train services

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Abstract

Efficiency in public and freight transportation systems is of great importance for a society. Railways can offer high capacity and relatively low environmental impact, but require that several technical systems are tuned and operate well. Specifically there is a tight interdependency between infrastructure and trains. The consequences are that all subsystems must be maintained and that the coordination of infrastructure activities and train operations is essential.

Railway infrastructure maintenance and train services should ideally be planned together, but practice and research about railway scheduling has historically focused mainly on train operations and timetabling while maintenance planning has received less attention — and little research have considered the joint scheduling of both types of activities. Instead the traditional approach has been a sequential and iterative planning procedure, where train timetabling often has precedence over infrastructure maintenance.

This thesis studies how maintenance windows, which are regular time windows reserved for maintenance work, can be dimensioned and jointly scheduled with train services in a balanced and efficient way for both maintenance contractors and train operators. Mathematical methods are used, with the aim of advancing the knowledge about quantitative methods for solving such coordination problems.

The thesis contributes with new optimization models that jointly schedule maintenance windows and train services, investigates the solving efficiency of these models, and studies crucial extensions of the planning problem — primarily for the consideration of maintenance resources. Furthermore, the models are applied to, verified and validated on a demanding real-life problem instance. The main results are that integrated and optimal scheduling of maintenance windows and train services is viable for problems of practical size and importance, and that substantial maintenance cost savings can be achieved with such an integrated approach as compared to a traditional sequential planning process.

The thesis consists of an introduction and overview of the research, followed by six papers which present: (1) A cost benefit model for assessment of competing capacity requests at a single location; (2) An optimization model for integrated scheduling of both maintenance windows and train services; (3) Mathematical reformulations that strengthen the optimization model; (4) Extensions for handling resource considerations and cyclic schedules; (5) A case study for a major single track line in Sweden; and (6) A mathematical study of length-restricted sequences under cyclic conditions.

Sammanfattning

Varje samhälle behöver effektiva transportsystem för människor och gods, speciellt i ett vidsträckt land som Sverige. Järnvägar och annan spårburen trafik är ett viktigt transportslag som ger hög kapacitet och låg miljöpåverkan under driftsfasen, men som kräver att flera tekniska delsystem fungerar väl tillsammans. Speciellt finns en stark ömsesidig påverkan och flera beroenden mellan infrastruktur och tåg. Detta innebär att alla delsystem behöver underhållas och att koordineringen av infrastrukturåtgärder och tågtrafik är viktig.

Idealt sett borde järnvägsunderhåll och den operativa tågtrafiken planeras tillsammans, men historiskt har både praktik och forskning om schemaläggning inom järnväg fokuserat på tågtrafiken och tidtabellerna, medan planering av underhållet har getts mindre uppmärksamhet — och ännu mer sällsynt är forskning som behandlar samplanering av järnvägsunderhåll och trafik. Traditionellt har istället en sekventiell och iterativ planering använts, där tågtrafiken ofta har företräde gentemot infrastrukturunderhållet.

Denna avhandling studerar hur servicefönster, vilka är återkommande tidsfönster reserverade för underhållsarbete, kan dimensioneras och schemaläggas tillsammans med tågtrafik på ett balanserat och effektivt sätt för både underhållsentreprenörer och trafikoperatörer. Matematiska metoder används med syftet att främja kunskapsutveckling om kvantitativa metoder för att lösa sådana koordineringsproblem.

Avhandlingen bidrar med nya optimeringsmodeller som schemalägger både servicefönster och tågtrafik, undersöker lösningseffektiviteten för dessa modeller, samt studerar viktiga utvidgningar av planeringsproblemet — framför allt vad gäller hänsyn till underhållsresurserna. Dessutom appliceras, verifieras och valideras dessa modeller på ett verkligt problemfall. Resultaten visar att integrerad och optimal schemaläggning av servicefönster och tågtrafik är genomförbart för problem av praktiskt intresse och storlek, samt att avsevärda besparingar kan erhållas för underhållskostnaderna med en sådan samplanering jämfört med en sekventiell planeringsprocess där tågtrafiken schemaläggs före underhållet.

Avhandlingen består av en introduktion och en översikt av forskningsarbetet, följt av sex forskningsartiklar som presenterar: (1) En samhällsekonomisk modell för utvärdering av enstaka servicefönster; (2) En optimeringsmodell för samplanering av servicefönster och tågtrafik; (3) Matematiska omformuleringar vilka stärker optimeringsmodellen; (4) Utvidgningar för beaktande av underhållsresurser och cykliska planer; (5) En fallstudie för Stambanan genom övre Norrland; samt (6) En matematisk analys av cykliska sekvenser med begränsad längd.

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During my PhD studies, Transrail Sweden AB have let me have a 20% part time employment with full flexibility regarding work hours. Furthermore, they encouraged the idea to pursue my academic studies — despite the fact that the research idea is not within the company’s core business. This generous attitude and their support has meant a great deal for me, and Per Leanders dedication and perseverance for advancing the railway sector is truly extraordinary.

A special thanks goes to all university colleagues at Linköping University, the Department of Science and Technology, and particularly the division of Communications and Transport Systems in Norrköping. My supervisors Jan Lundgren and Martin Joborn have had a somewhat unusual student in me, but their ability to gently and positively give guidance and support despite having so many other commitments have been very important.

In many aspects, the visit to Australia and University of Newcastle — generously financed by LiU and made possible by the help of both universities — between September 2016 and January 2017 has been the most influential time of my studies. Not only was it a great personal experience, but more importantly my hosts Thomas Kalinowsky and Hamish Waterer, together with their colleagues at the School of Mathematical & Physical Sciences, provided a very stimulating and fruitful blend of inspiration, feedback and collaboration. I have learned tremendously from both of you and treasure the honest and frank cooperation, as well as the productive research outcome and the relaxed social life.

Throughout the different phases of the project I have met with, learned from and gotten help from so many people that I cannot mention you all. A large number of reference persons at Trafikverket, FSJ, BB-Rail, Strukton, InfraNord and Railcare has shared their knowledge, of which Lars Brunsson and Per Hurtig deserves special recognition. Through conferences, seminars and courses I have had the privilege to connect with a wealth of extremely knowledgeable people, which is most valuable for the future.

I also want to express my gratitude towards relatives, friends and family. The bonds that hold us together are invaluable, and throughout periods of hard and sometimes isolated work it has been a comfort and relief to have you all out there – and getting your interested questions and cheers. As for work-life balance the caring of our summer house and the therapy of music, especially rehearsing and playing with the Heisenberg Quartet has been indispensable.

Finally, and most important of all, I thank my wife Sophia for her support, patience and love during all our years together. It's a blessing to live with you. Just like it's a blessing and a gift with our daughter Signe — who managed to take her exam before I did. Well done!

Norrköping, October 2018
Tomas Lidén

This thesis is dedicated to all people that tend to, nurse and take care of our assets, be it things or living beings. You are the everyday heroes towards a more sustainable world, and this is my small attempt to make some of that work more achievable.

Contents

Chapter 1

Research setting

This chapter sets the stage for the conducted research. First the background and aim of the thesis is presented, followed by an introduction to railway infrastructure maintenance and a description of the real-world planning problem under study. Then an overview of the research literature and methodology is given, and finally the research questions are stated.

1.1 Background and aim

Efficiency in the transportation systems is of great importance for a society. Railways can offer high capacity and relatively low environmental impact, but require that several technical systems like track, power distribution, safety, telecommunications and trains are tuned and operate well. Disturbances in any of these systems will degrade the service level. Moreover, failures or degradation in one system may cause damages in the others. This is particularly true for track, trains and power distribution. Thus, maintenance is essential for upholding reliability, transportation throughput and the benefits of the infrastructure system investments.

Railway infrastructure maintenance consumes large budgets, is complicated to organize and offer numerous challenging planning problems. Hence, large benefits can be realised if planning, scheduling and effectuation can be improved. In 2012, the European countries reported that a monetary volume of 15–25 billion EUR were allocated annually for maintenance and renewals of their railway systems consisting of about 300,000 km of track, giving an average spending of 70,000 EUR per km track and year (EIM-EFRTC-CER Working Group, 2012). As a comparison, the gross value added for the rail part of the transportation and storage sector is estimated to 35–55 billion EUR in the European Union (European Commission, 2012). Thus, the maintenance spending amounts to more than 40% of the traffic value.

The figures in Sweden follow the same pattern: During the year 2014 a budget of 8,200 MSEK was used for maintenance and renewals of a 14,700 km track network, i.e 560,000 SEK/km. In the same year the major passenger traffic operator (SJ AB) and freight traffic operator (Green Cargo AB) had a joint turnover of 13,200 MSEK. Thus, the maintenance spending amounts to about 60% of the main traffic operator turnover in Sweden.

Train services and maintenance tasks should ideally be planned together, but are usually treated by different organisations. Historically, practice and research about railway scheduling has focused mainly on train operations and timetabling while maintenance planning has received less attention — despite the large monetary volumes cited above. In particular, there is little research that treat the joint scheduling of train traffic and infrastructure maintenance.

The aim of this thesis is to **advance the knowledge and methods for concurrent planning and coordination of railway infrastructure maintenance and train traffic.** The long-term vision is to find models and methods for integrated planning and scheduling of maintenance and traffic which can be put to practical use and which will improve efficiency for the complete railway system.

All scheduling methods that strive for efficiency in some form needs to define how this property shall be measured, such that different plans can be evaluated and compared. For this reason we use quantitative models and apply them to the problem of coordinating railway maintenance and train services. Specifically we investigate how to measure the costs and effects of the two types of activities, and then develop optimization models that jointly schedule and coordinate infrastructure maintenance and train traffic.

1.2 Railway maintenance

Railway infrastructure maintenance concerns several different systems and components, such as tracks (ballast, sleepers, rails), switches, signalling and power distribution, which cover vast geographic distances. All these components have a tight interdependency, both with each other and with the trains and the rolling stock. Furthermore the safety requirements are rigorous, since the trains have long braking distances with no possibility for evasive manoeuvres. Therefore the access planning and scheduling of both trains and maintenance activities become crucial.

All work activities that require secure access to the railway infrastructure must obtain a **possession** (RailNetEurope, 2013). A possession shall guarantee that no trains will run on the designated area — usually coinciding with a signalling block, one or more tracks on a station or a complete station between the entry signals. Possessions may also impose operative restrictions on neighbouring tracks.

A possession is defined by a unique work id, a possession area, start/end

Table 1.1: Possession time and normal planning horizon for various work activities.

Possession time	Activity	Planning horizon
>8h	Catenary wire replacement	2–3 years
	Track/turnout replacement	2–3 years
4–8 h	Tamping of tracks	1–2 years
	Rail grinding	1–2 years
	Switch replacement	1–2 years
	Catenary inspection & maintenance	2–3 years
1–4 h	Tamping of turnouts	1–2 years
	Ultra-sonic testing	1–2 years
	Fasteners, joints, rail repair	1–2 months
As train paths	Periodic measurement	1 year
	Fast grinding	1 year
0–1 h	Inspection	0–2 months
	Signal repair, vegetation etc	0–2 month
	Slippery rail, snow removal	1 year
1h – x days	Accidents, urgent repair	none

times, work content, contractor, operative restrictions, etc. Possessions correspond directly to **train paths**, which describes a train run with a unique train number, origin/destination, routing, timing, train operator, etc. Possessions as well as train paths may have a repetition pattern, e.g. every week day during a certain calendar period. The specific instance which takes place on a certain operative day, are denoted as a “work (or possession) instance” and a “train service”, respectively.

From a planning perspective it is suitable to categorize the maintenance activities according to how much traffic capacity they consume and how long in advance they are planned. In Table 1.1 different activities are listed according to the needed amount of possession time and how long in advance the planning is usually done.

A more complete introduction to railway system properties, maintenance planning, terminology, categorization, contract types and planning processes can be found in Lidén (2016, Chapter 2).

1.3 Access planning

Scheduling access to the railway infrastructure is the core tactical planning problem for all railway systems. We use the term *capacity access planning* (rather than timetabling) to highlight that all types of activities that utilize the infrastructure capacity are planned.[1]

Capacity access planning can be seen as resource planning for the infrastructure components (stations, lines, yards, tracks, switches, signalling blocks, etc), and includes producing a timetable for the trains as well as possession plans for maintenance and work tasks. Timetables and possession plans will in turn form the basis for other resource plans, such as rolling stock plans and crew schedules for the train operators as well as machine and work force plans for maintenance and renewal contractors.

The amount of train paths and maintenance possessions handled in the capacity access planning indicate the planning effort involved. For the year 2014, there were 7,200 train path and 2,200 possession applications in the Swedish yearly timetable process (Alexandersson, 2015). The total amount of train services was about 900,000. During the operative year an additional 16 - 17,000 possessions were handled, along with a large number of train service changes (32,000 additions and 44,000 cancellations (Transport analysis, 2015)). These figures show the tremendous task that planners and involved parties are facing - a job that still relies mostly on manual work, with limited computational and scheduling support.

Planning of train paths and maintenance possessions are usually performed in different organisations. Partly this can be explained by the fact that each problem is challenging in its own right, but more importantly that there are specific differences between train operations and maintenance work that should be accounted for. In fact, maintenance can almost be considered as "orthogonal" to train traffic, since the former is mainly tied to and organised in bounded geographical areas, while train traffic concerns transportation demand between distant regions. Consequentially, the responsibility for conducting traffic and infrastructure maintenance is usually split into separate organisations or companies (Railway Undertakings (RUs) and Maintenance Contractors (MCs), respectively). Thus, the planning tasks are also divided — each party treating the other type of activities as an unknown or given input — while capacity conflicts must be solved in some coordination or resolution procedure (usually handled by the Infrastructure Manager (IM)). Not surprising, there is often a lack of understanding and sometimes even mistrust between representatives for RUs, MCs and the IM. This situation will almost certainly result in solutions that are less good or even inefficient for one or more of the parties. Thus, it is desirable to find methods that can treat capacity access planning as an integrated problem for both train operations and maintenance.

[1] Occasionally, the shorter form "capacity planning" is used, but should not be confused with the strategic network design problem, which determines the usable traffic capacity.

The planning horizons of train services and maintenance tasks can differ substantially, which — depending on the planning procedure — may favour early applicants and leave costly or even insufficient track access possibilities for other actors. This situation has been observed in Sweden where the increase in rail traffic together with the previous planning regime has forced maintenance to be performed on odd times and/or in shorter time slots which leads to inefficiency and cost increases for the MCs, potentially even reduced track quality and higher governmental spending.

To increase the possibility of suitable work possessions, a new planning regime is being introduced in Sweden, where Trafikverket (The Swedish Transport Administration) proposes regular, 2–6 hour long, train-free **maintenance windows** before the timetable is constructed. The maintenance windows are given as a prerequisite for the procurement of multi-year maintenance contracts as well as the yearly timetable process, which gives stable quotation and planning conditions for the contractors. The regular maintenance work should then be carried out on possessions within the maintenance windows. The overall aim is to increase efficiency, reduce cost and planning burden as well as to improve robustness and punctuality.

1.4 Problem and scope

Maintenance windows will reduce the train scheduling possibilities. As a consequence the window patterns should be designed such that maintenance activities and train operation are coordinated in a well-balanced manner. This is a non-trivial problem for several reasons. First of all, the traffic capacity reduction of a specific maintenance window will spread both upstream and downstream the railway network according to the train service scheduling. Long-distance trains might also encounter several maintenance windows which can increase the travel times and the risk of disturbances. Furthermore, the window patterns within a certain maintenance region must be possible to utilize efficiently for the available maintenance resources (crew and equipment). The utilization rate depends on factors like the window sizes and scheduling, work and rest time regulations, travels to and from the work sites, etc. Ultimately, the usefulness of the maintenance windows should exceed the costs and constraints they impose on the train traffic.

This thesis concerns the planning and scheduling of maintenance windows together with train traffic. The problem is to dimension and schedule maintenance windows and train services concurrently and in the same modelling framework. Primary aspects are the train and window scheduling, network capacity, train operational costs and maintenance work costs. Additional aspects that might be included are resource considerations, disturbances, utilization, etc. The problem can be classified as a long term tactical planning problem, that precludes the detailed train timetabling and scheduling of possessions, but where the coordination and scheduling of both train services and maintenance windows shall be decided.

This research applies primarily to railway systems with timetabled traffic consisting of a mixture of different types of trains — similar to the situation in most European countries. The network wide consequences of the scheduling of both train services and maintenance windows will be considered, with the intention of being able to treat large infrastructure networks.

Infrastructure renewals, closures and upgrades that occur infrequently and require many hours or days to perform will not be considered. Instead the focus is on short and high volume maintenance activities that are done regularly over the seasons. These activities (e.g. inspections, service work, adjustments, component replacement, preventive maintenance, small repair, etc.) typically takes less than a few hours to complete, as shown in Table 1.1, and should be performed on the scheduled maintenance windows.

The volume of maintenance work will be treated as known and given beforehand. Thus, the decision on how much maintenance to perform is not considered. Neither do we consider the specific activities that will take place during a certain maintenance window or how the practical work itself can be efficiently performed. This is also an important field of study, which may include project planning, lean work organization approaches, automation of manual work, spare part planning, modular components, etc. As a consequence, degradation models will not be studied, nor how to find accurate estimates for the future maintenance needs.

1.5 Research context

Planning of train operations has been extensively studied in the research literature and a common terminology for the different planning steps has been established — consisting of for example line planning, timetabling, routing, shunting, rolling stock and crew planning, rescheduling and dispatching (Caprara et al., 2007, 2011). Several surveys have also been published which focus on particular planning steps, like train timetabling (Cacchiani and Toth, 2012), rescheduling (Cacchiani et al., 2014) and dispatching (Corman and Meng, 2014). Handbooks, such as Hansen and Pachl (2008) and Borndörfer et al. (2018), describe important problems in the field and methods that are used, primarily simulation and optimization.

Despite the vast train scheduling literature, there are few publications that consider the coordination with infrastructure maintenance. No such research has been found for the long term tactical phase or the timetabling problem. The short term replanning or timetable adjustment problem have been studied, but then maintenance is treated as fixed track closures — not as activities to be scheduled. Examples of such work are: Vansteenwegen et al. (2015) (robust rescheduling due to planned track closures on large stations and junctions); Louwerse and Huisman (2014) and Veelenturf et al. (2015) (rescheduling of timetables, rolling stock and crew during ma-

Table 1.2: Planning problems and main stakeholders

Class	Problem	Stakeholder
Strategic	Maintenance dimensioning	IM
	Contract design	IM
	Resource dimensioning and localisation	MC
Tactical	Possession scheduling	IM, (MC)
	Vehicle & team routing	(IM), MC
	Rescheduling	IM
Operational	Maintenance project planning	MC
	Work timing & resource scheduling	MC
	Track usage planning	IM, MC

jor disruptions in operational dispatching); and Van Aken et al. (2017a,b) (timetable adjustment for multi-day infrastructure possessions).

Planning of infrastructure access for maintenance and work tasks has received relatively little research attention compared to train operations, and hence a common terminology for the different planning steps and problem types has not yet evolved. One attempt to structure the various problems has been presented in Lidén (2015), where nine problem types are identified and described. The problems are classified as strategic, tactical and operational as shown in Table 1.2 along with their main stakeholders (IM or MC). The strategic class concerns dimensioning, localisation and organisation, with time horizons of one to several years. Tactical problems include scheduling, timetabling and construction of plans covering a medium long time horizon (weeks to a couple of years), often handling resources as categorized, anonymous objects. The operational planning problems concern implementation and effectuation, covering short time horizons (hours to months), where the actual resources must be considered.

The literature overviews in Lidén (2015) and Lidén (2016) reveal an increase in research publications, particularly from year 2005 and onward. The tactical problem types have received most attention (more than half of the publications), and among these more than 1/3 address possession scheduling, which reflects the importance of this problem type.

In the maintenance oriented research literature, there are several publications that treat long term tactical planning, but none that also schedule train services. Either the traffic considerations are handled: (i) implicitly, as in Zante–de Fokkert et al. (2007); (ii) as restrictions for the maintenance scheduling, see for example Peng and Ouyang (2012) and Borraz-Sánchez and Klabjan (2012); or (iii) as flows to be maximized, as in Boland et al. (2013), Savelsbergh et al. (2015) and Pearce and Forbes (2018).

For short term tactical planning there are a few publications that schedule *both* train services and maintenance possessions. The real-time operational control case for a single track line is treated in Albrecht et al. (2013)

while the timetable revision case for a network is studied in Forsgren et al. (2013) and Luan et al. (2017). These examples of combined approaches use an existing timetable as starting point and solution reference. Furthermore, only a small number of work activities, usually one at a time, are considered.

In summary, no research literature have been found that treat a long-term tactical planning case where many maintenance windows and train services shall be coordinated and jointly scheduled. Hence, there exists an identified research gap.

1.6 Research methods

The chosen research methods come from transport economics and operations research, both of which belong to the field of applied mathematics. By "applied mathematics" we here mean the use of mathematical methods to address real-world problems occurring in engineering, industry, business and society. The purpose is to provide quantifiable measures and propose analytical and structured methods that supports managers, planners and engineers to make better and more informed decisions.

Transport economics (see e.g. Button, 2010) deals with various economical questions within the transport sector, for example demand modelling, pricing, mode choice, cost-benefit analysis, etc. The basic assumption is that transport choices will be based on supply and demand where a generalized cost is used for capturing the essential decision factors, such as ticket price, travel and waiting time, comfort, etc. Well established model frameworks and project appraisal guidelines have been developed which are used to evaluate and compare infrastructure changes and different transport network services. Methods, such as congestion charging, taxation, etc, have successfully been used for influencing traffic flows.

Operations research (Hillier, 2014) deals with complex and often large-scale decision-making problems by applying various analytical modelling and solution techniques, such as statistics, queueing theory, simulation, artificial intelligence, logics and optimization. The models can be used for describing and explaining the behaviour of a real-world system, predicting the outcome under different conditions, and/or suggesting high-quality or even proven optimal solutions. The problems are often computationally demanding and have spurred development in computer science, algorithmic design, logics and mathematics.

Optimization is a technique for finding the best possible solution to a mathematically formulated problem. The value of a solution is measured by an objective function and the possible (or feasible) solutions may be restricted by different types of constraint relations. There are several classes of optimization problems, depending on what types of variables, objective and constraint functions that are used. A commonly used and well-studied problem class is when having a mixture of real and integer valued variables with a linear objective and linear constraint functions — which is labelled as mixed integer linear programming problems (MILP). The integer restrictions make the problems mathematically more challenging and various solution techniques like branch-and-bound, branch-and-cut and decompositions have been developed to address such difficulties. An important feature of linear problems is that it is possible to get a bound for the optimal value and hence the so called optimality gap can be calculated — which is a proven certificate of how far a certain solution is from the best possible one. Several commercial and scientific MILP solvers exist, which can handle very large problems with thousands of variables and constraints.

In summary, transport economics provides methods for doing cost-benefit studies and assessment of transportation alternatives, while operations research provides optimization techniques for solving difficult planning and scheduling problems. These methods are suitable for the research problem considered here.

1.7 Research questions

Based on the previously introduced problem description, the research context and the chosen methods we can now summarize the research requirements and formulate the research questions that are treated in this thesis.

Requirements: Quantitative planning that jointly handles maintenance windows and train services needs to have a valuation method that enables the comparison of both activities and a scheduling method that captures the essential aspects of the real-life problem, which can be solved efficiently, and gives reasonable and useful solutions.

Questions:

- Q1: How can costs and effects on both maintenance and traffic be quantified when reserving train-free maintenance windows in the timetable?
- Q2: How can optimization methods be used for solving the integrated planning of maintenance windows and timetabled train traffic?
- Q3: Which additional problem aspects should be considered in such an optimization model and how can they mathematically be formulated?
- Q4: How is the solving performance affected by different problem structures, aspects considered and model formulations?
- Q5: What planning results will be obtained when using such integrated optimization scheduling on real-life problem instances?

In Chapter 2 we will describe how these research questions have been addressed and treated in the various papers.

Chapter 2

Conducted research

This chapter summarizes the conducted research. First some notes are made regarding the research design together with some practical aspects of the work. Then the six papers are described and the results obtained in each of them, followed by a summary of the contributions and how they map to the research questions. Finally, a discussion and some suggestions for possible future work conclude the chapter.

2.1 Research design and practical notes

The research has been conducted in a series of studies, labelled as follows:

Survey An overview of railway infrastructure maintenance, planning problems and published research. Reported in Lidén (2014, 2015).

Assessment Cost-benefit and economical valuation methods for single maintenance windows and their impact on train traffic. Tests and evaluation of a specific practical case. (Paper 1)

Optimization model The original optimization model with computational experiments on a set of synthetic test instances. (Paper 2)

Reformulations Model reformulations and experiments that verify the improvements. (Paper 3)

Resource considerations Model extensions for the inclusion of maintenance resource aspects. (Paper 4)

Case study Application of the optimization methods on a real-life problem, including modifications for handling cyclic schedules. (Paper 5)

Cyclic sequences Mathematical analysis of length restricted sequences with cyclic boundary conditions. (Paper 6)

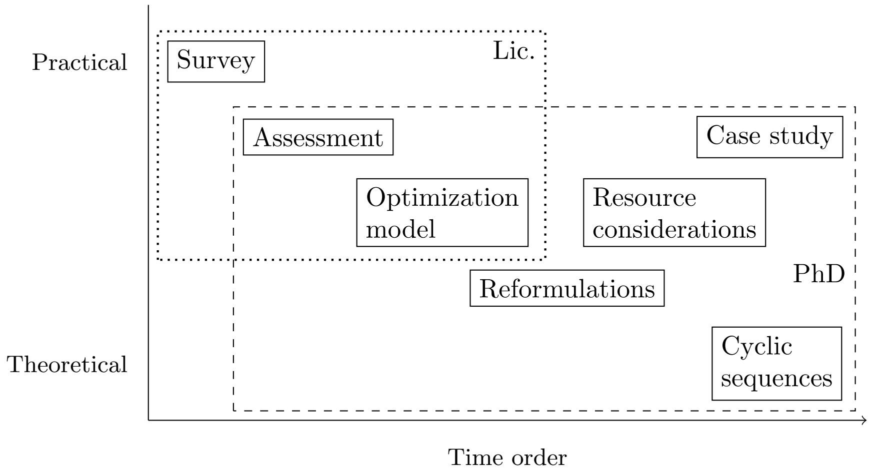

Figure 2.1: Roadmap of conducted studies, mapped out in time order (horizontally) and practical/theoretical content (vertically). Dotted box shows the scope of the licentiate thesis. Dashed box shows the scope of this thesis.

The different studies are shown in Figure 2.1, where the horizontal axis shows time order and the vertical axis roughly indicates the level of practical/theoretical content of the corresponding papers. The scope of the licentiate thesis (Lidén, 2016) and this thesis are shown with dotted and dashed boxes respectively.

In the following, the methods and tools used for the different papers are summarized along with some practical information of the studies.

Transport economy, cost-benefit analysis (Paper 1)

The study was done between October 2014 and April 2015. The work was driven by a practical case concerning a specific line stretch in Sweden where Trafikverket wanted to introduce a two hour long maintenance window during day time. The analysis required a common valuation and comparison method, which was developed during the study. Data was supplied by Trafikverket and the results were discussed in close cooperation with them.

For the assessment of costs and benefits when introducing a maintenance window, three different models were used: maintenance costs were calculated with an analytical model, using standard calculus and implemented in a spreadsheet tool; freight traffic was treated by estimating scheduling adjustments, runtime changes and possible train service rejections in a simple timetabling model, implemented in `MATLAB` (*MATLAB and Statistics Toolbox Release 2013b*); passenger traffic was treated in a model based on existing methods from transport economics, implemented in a spreadsheet tool.

Mathematical modelling, optimization (Papers 2–4)
The original optimization model was developed May 2015 – February 2016, and was reported in Paper 2. Model reformulations were investigated August – October 2016 and resulted in several improvements (Paper 3), which formed the basis for extending the model with maintenance resource considerations during October – December 2016 (Paper 4).

The optimization model was developed in an iterative approach, by documenting the mathematical formulation and coding it in `Python` (*Python Language Reference, release 2.7*), using `Gurobi` (*Gurobi Optimizer*) as optimization solver. Logging and graphical visualisation was used when debugging and the test instances were generated directly in `Python`. Care has been taken to store the instances such that reproducibility shall be possible — using the `JSON` format (*JSON Data Interchange Standard*) and making the instances publicly available. Version control has been done with `Git` (*Git source code management system*).

Case study (Paper 5)
The real-life problem instance was selected together with Trafikverket and the study was performed August 2017 – March 2018.

Network and timetable data was collected from official sources at Trafikverket along with maintenance data and background statistics provided by experts and contact persons. The case study was planned together with a reference group, with selected experts consulted during the study and a review/dissemination of the results at the end of the work. A study and result report in native language was prepared so as to enable all participants in the reference group to comment on the details of the work.

Mathematical analysis (Paper 6)
The mathematical properties of cyclic length restricted sequences has been studied intermittently between January 2017 and August 2018. The first question was whether the strong integral properties of the model for restricted length sequences (which was used in Papers 3 and 4), would remain under cyclic conditions (which was used in Paper 5). If not, the following question was what could be done to tighten the model.

The methods have consisted of practical experiments conducted with `polymake` (Assarf et al., 2017) along with mathematical analysis and proofs.

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Paper 2 Lidén, T., Joborn, M. (2017). An optimization model for integrated planning of railway traffic and network maintenance. *Trans-*

portation Research, part C, 74, 327–347. doi:10.1016/j.trc.2016.11.016

Paper 3 Lidén, T., Waterer, H. (2018). Reformulations for integrated planning of railway traffic and network maintenance. Submitted for journal publication.

Paper 4 Lidén, T., Kalinowski, T., Waterer, H. (2018). Resource considerations for integrated planning of railway traffic and maintenance windows. *Journal of Rail Transport Planning & Management*, 8.1, 1–15. doi:10.1016/j.jrtpm.2018.02.001

Paper 5 Lidén, T. (2018). Coordinating maintenance windows and train services — a case study. Submitted for journal publication.

Paper 6 Kalinowski, T., Lidén, T., Waterer, H. (2018). Tight MIP formulations for bounded length cyclic sequences. Submitted to *Journal of Discrete Optimization.*

Authorship

In Papers 1–5, the author of this thesis is the main contributor, who has done all the research, experimenting and writing, with the co-authors providing support, advice and reviews. In Paper 6, the main work, contributions and writing has been done by Thomas Kalinowski, with Hamish Waterer providing modelling ideas, and Tomas Lidén initiating the study, doing experimental work and discussing/reviewing the material.

Dissemination

The research has been presented at various conferences and seminars, of which the primary occasions for each paper has been:

Paper 1 CASPT, 19–23 July 2015, Rotterdam, The Netherlands

Paper 2 TRISTAN IX Symposium, 13–17 June 2016, Oranjestad, Aruba

Paper 3 ATMOS, 23–24 August 2018, Helsinki, Finland

Paper 4 RailLille, 4–7 April 2017, Lille, France

Paper 5 Transportforum, 10–11 January 2018, Linköping

Paper 6 Zuse Institute Berlin, 9 May 2018 (Hamish Waterer)

2.2 Summary of the papers

Paper 1 (Assessment)

This paper addresses the issue of how to establish quantitative, societal economy measures for comparing conflicting capacity needs from infrastructure maintenance and traffic operations at a single location in the railway network. A model is presented, consisting of three parts, which calculates (1) changes in maintenance cost, (2) adjustment costs for freight traffic, and (3) changes in passenger traffic and travel demand, when introducing maintenance windows of varying size. The model is demonstrated on a real life case study.

The main contribution of the paper is the sub-model for the maintenance part, consisting of analytical equations for calculating the change in cost depending on the available train free time. It is shown that the maintenance time is inversely proportional to the window size and how the placement of overhead (setup) time — inside or outside of the possession window — affects the total time and cost.

The sub-model for freight traffic considers the change in operator costs, when train services need to be adjusted or possibly rejected due to the maintenance windows. A homogeneous single track line with symmetric train traffic is studied, and the model estimates the runtime differences as a function of the number of opposing trains and line capacity usage.

The sub-model for passenger traffic is based on existing methods from transport economics which consider the detailed travel demand, alternate transport modes and how the travel patterns will change when train services are modified due to the introduction of maintenance windows. As a consequence of changes in perceived passenger cost, the travel demand will also change, from which a net effect can be calculated both for the customers (consumer surplus) and operators (producer surplus).

The paper finally shows how to apply the costing models in a real life case study, concerning the Swedish Northern Main Line. In this specific case, societal economy will benefit when introducing a daily 2h maintenance window, given the limited amount of trains that are affected and that bus replacements are offered.

Paper 2 (Optimization model)

This paper presents an optimization model for solving the integrated railway traffic and network maintenance scheduling problem. The aim is to produce long term tactical plans that optimally schedule train free maintenance windows together with a set of train services. The intended use case is when an infrastructure manager wants to find a pattern of maintenance windows to be used during a multi-year period as a method for assuring stable planning conditions for both maintenance contractors and train operators. The model can however be used in any situation where train services and time slots for infrastructure maintenance should be coordinated.

The problem is modelled as a mixed integer linear programming problem (MILP), which uses a spatial and temporal aggregation for controlling the available network capacity. In this way, larger networks and longer planning horizons become manageable. The problem size is shown to grow linearly with the planning horizon if the train scheduling windows are limited in size.

Computational experiments on a set of synthetic test instances with about 40–50 trains per day show that a MILP solver can find near optimal solutions to weekly network instances as well as double track instances (where trains can pass a working site) within 1h on a laptop computer. If train traffic is completely stopped by the maintenance tasks (as for single track lines) the problems are harder to solve. The largest such instances solved to optimality in 1h of computation are 1–2 days long.

The effect of reducing the train scheduling flexibility is studied and it is shown that tight scheduling bounds can be used for the network instances, while larger scheduling flexibility is needed for the single track line instances. Some other problem reductions are also analysed, which can be beneficial in some cases but does not give any profound effect on solution performance.

The paper discusses aspects that make the problem hard to solve, some of which are due to the instance data and some that are due to the mathematical properties of the model. Data instances that (i) are close to the capacity limits, (ii) require cancellations to be considered or (iii) have little cost guidance between structurally different solutions are more complicated to solve. As for the numerical properties, the linear relaxation of the problem is weak which can be seen when studying the development of the linear bounds during the solution process and the difficulty of closing the optimality gap. The underlying reasons are attributed to weak bounds for the train counting over the time periods. Methods for improving the linear bounds and strengthening the model are identified as interesting research continuations.

Paper 3 (Reformulations)

This paper describes improvements in the mathematical formulation of the basic optimization model, with the aim of strengthening the model and improving the solving performance. The improvements concern both the scheduling of trains and the scheduling of maintenance windows, and substantial speed-ups are shown in the computational experiments.

The train scheduling is improved by changing cumulative entry/exit variables to binary detection variables, and by turning implicit link usage variables into explicit ones. These changes increase the number of variables but decrease the number of constraints. The linear relaxation does not become tighter, but the reformulation leads to a model structure that the MILP solver can take advantage of, as shown by the computational results.

The maintenance scheduling is improved in two ways. First, some constraints are aggregated with respect to the choice of window options. Secondly, a stronger model for enforcing the correct window lengths and separation between windows is used, based on Queyranne and Wolsey (2017). These changes, especially the second one, improves the linear relaxation of the model which gives a substantial performance gain.

The net effect of these reformulations is that three more instances (out of 14) can be solved to optimality, the optimal solutions are reached quicker (with a speed-up between 2 and 10 times) and one more instance reaches an optimality gap of less than 1.0% (which can be considered an acceptable solution quality with the cost factors used).

Paper 4 (Resource considerations)

This paper extends the reformulated optimization model by considering maintenance resource costs and constraints for crew availability and work time regulations. Crew resources are divided into bases, where each base covers a subset of the infrastructure network (with possible overlaps). Each maintenance window is assigned a crew resource such that the resulting crew schedules will respect limitations on maximum working hours per day and minimum rest time between the working days.

The objective function is extended with cost components for the number of crew used, the length of their working days (which includes pauses between maintenance assignments) and number of network links visited. The modelling of the crew assignments and handling of work time restrictions is based on the same strong formulation for length restricted sequences (Queyranne and Wolsey, 2017) as utilized for the window lengths and their separation in Paper 3.

The computational experiments are performed on the same set of synthetic test instances as used in Papers 2 and 3, plus some additional network instances. Five different crew base configurations are tested and compared towards a baseline (without resource considerations). The crew base configurations differ regarding the link coverage of the bases — from one large base covering all links, to several small ones, with or without any overlap between the bases.

The results show that crucial crew resource limitations can be correctly handled, with a moderate increase in problem size and solution time. Problems with small crew bases with no or small overlaps are easier to solve, while large bases and large overlaps make the problem harder.

Paper 5 (Case study)

This paper concerns a case study for one of the major railway lines in Sweden — 913 km long and mostly single track — through the northern part of the country. The traffic consists of a mix of long- and short-distance freight traffic, intercity passenger trains and regional commuter trains. A daily traffic load of 82 trains shall be coordinated with maintenance windows that give access to all parts of the track for at least two hours per day.

The purpose of the study is to validate the model on a real and demanding planning problem, and obtain results that apply in similar planning situations. For this study, one day periodic production plans (for regular week days) are wanted and therefore the optimization model is adjusted so as to handle cyclic scheduling.

Extensive experiments are performed, in order to study the effect of different window options and resource considerations, study the cost sensitivity, evaluate and compare the obtained plans to current timetables, and estimate the benefits of doing integrated rather than sequential planning.

The primary result is that optimal cyclic one-day plans can be produced for trains, maintenance windows and maintenance resources. For the studied scenario, two hour long windows can be achieved with small adjustments of the trains (amounting to an increase in train running cost of 0.5%). The results are stable for cost uncertainties, and the train costs must increase by more than 30% in order to change the structure of the window solutions. By considering the maintenance resources it is possible to produce window schedules that use less maintenance crews and are much more efficient for the contractors. However, the cost increase for the trains needs to be constrained in order to get reasonable traffic plans and avoid cramped schedules. Based on a comparison with manually constructed plans from Trafikverket, the solution structures look reasonable and useful as guidance for constructing the real window patterns. Finally, it is estimated that using an integrated planning approach (where maintenance and trains are jointly planned) instead of a sequential approach (where an existing or new train timetable has precedence over the maintenance windows) will give maintenance cost savings of 11–17%, without incurring any large cost increases for the train traffic.

Paper 6 (Cyclic sequences)

This paper is a mathematical analysis of length restricted sequences for cyclic schedules. The purpose is to show whether the strong formulations in Queyranne and Wolsey (2017) still hold for the cyclic case, motivated by the fact that cyclic schedules is an important feature (and used in Paper 5).

First, the necessary conditions for the relation between the number of time periods and the upper and lower bounds on the sequence lengths are defined. Then it is shown that the flow formulation is still valid but that the integral properties are lost in the cyclic case. An extended flow model (which creates a limited number of network copies) is proposed which is shown to give an integral polytope. Then, the formulation in the space of state and start-up variables is studied. It is proven that the formulation is valid, but again the polytope of the basic model is non-integral. Some valid inequalities are derived and sufficient conditions are given for when they are facet-defining. Finally, a disjunctive extended model is presented which gives the convex hull of the problem.

2.3 Contributions

The research questions stated in Section 1.7 fall into three groups, namely: Q1, which concerns the valuation and comparison of maintenance windows and train services; Q2–4, which concerns the development of an integrated optimization method; and Q5, which concerns the usage and validation of such optimization methods on real-life problems.

We now repeat the research questions and present the contributions made for each of them.

Q1: How can costs and effects on both maintenance and traffic be quantified when reserving train-free maintenance windows in the timetable?

- Economical figures (primary and marginal costs) have been proposed and used for quantifying and comparing maintenance and train services (Papers 1–5).
- An analytical model for calculating the maintenance cost depending on available train free time and placement of setup times have been developed (Paper 1).
- A framework, suitable for cost-benefit assessments, for analysing a single maintenance window have been presented and applied on a real-life case study (Paper 1).

Q2: How can optimization methods be used for solving the integrated planning of maintenance windows and timetabled train traffic?

- A mixed integer linear programming model has been developed, consisting of two scheduling parts — one for the train services, and one for the maintenance windows — which are coordinated by an aggregated capacity usage model, based on train counting in discrete time periods (Paper 2).
- Detailed scheduling of train services has been proposed, which considers departure and arrival times for each link and node in the network, durations of train running as well as dwell times. A less detailed scheduling model has been suggested for the maintenance windows, according to a time period division which coincides with the capacity control mechanism (Papers 2–5).
- The capabilities of the optimization model have been demonstrated on both a set of synthetic test instances, made publicly available, and a real-life problem instance (Papers 2–5).

Q3: Which additional problem aspects should be considered in such an optimization model and how can they mathematically be formulated?

- Extensions for handling maintenance resource considerations (Paper 4) and cyclic scheduling (Paper 5) have been thoroughly studied.
- Various model extensions, such as runtime supplements for trains passing a maintenance site, and for train meetings on single track links, have been discussed along with suggested model formulations (Paper 2).

Q4: How is the solving performance affected by different problem structures, aspects considered and model formulations?

- Experimental studies have shown that synthetic multi-day instances can be solved to near optimality within one hour of computation time (Papers 2–4).
- The scheduling flexibility of the train services have been shown to have a fundamental impact on both problem size and solving performance (Paper 2).
- Reformulations for both the train and window scheduling have been studied, which give a mathematically stronger model and substantial performance improvements (Paper 3).
- A theoretical study of cyclic length restricted sequences has shown that the integral properties are lost for the cyclic case. Facet-defining valid inequalities have been derived, along with an extended disjunctive model which gives the convex hull (Paper 6).

Q5: What planning results will be obtained when using such integrated optimization scheduling on real-life problem instances?

- A case study has verified that optimal schedules can be obtained for cyclic one-day real-life instances of practical interest. The solutions have been validated by reviews and by comparison with existing, manually produced plans (Paper 5).
- Marginal cost changes for maintenance and train adjustments have been shown to be more important than their absolute cost differences. Furthermore, it has been shown that the obtained schedules are stable for relatively large cost uncertainties (up to 30%) and that resource considerations give solutions that are much more efficient for the maintenance contractors (Paper 5).
- Integrated planning of maintenance and trains have been estimated to give maintenance cost savings of 11–17% as compared to sequential planning (where an existing or new train timetable has precedence over the maintenance windows), without incurring any large cost increases for the train traffic (Paper 5).

2.4 Discussion and future work

This thesis shows that it is possible and beneficial to integrate the planning of network maintenance and train operations, with the use of quantitative methods. Based on the estimated maintenance savings with integrated planning, it is possible to calculate the potential value of using such methods in the actual planning on a national scale as follows: The total government spending for maintenance and renewals of the national railway in Sweden has been 7,800–8,400 MSEK for the years 2014–2017. About 20% of this is spent on regular maintenance, which amounts to about 1,600 MSEK per year. Thus the estimated maintenance saving for using integrated planning of maintenance windows and train services (11–17%) would amount to about 225 MSEK per year, if it applies to all types of lines and traffic situations. Even though this potential is not fully achieved, it should be clear that substantial benefits are possible, either as monetary savings or the possibility of increasing maintenance activities in order to get more “value for money”.

Every model of a real-life problem will be based on assumptions, choices, limitations and simplifications made by the developer or researcher. Some of the model choices made in the different steps of this research will now be highlighted and discussed:

Valuation and assessment of costs and benefits Economical figures, based on primary costs for conducting maintenance and train operations, together with marginal costs for adjusting the timings due to other activities have been used to quantify and coordinate maintenance windows and train services (Q1). All other aspects have been ignored — or assumed to be measurable with similar secondary or generalized costs. Thus, the effects on issues like planning efficiency, work fulfilment, operational stability, timetable flexibility and future track quality have not been considered in this research. Several of these aspects, and especially those that are conflicting, are interesting subjects for future work — possibly in a multi-objective setting.

Optimization model An aggregated capacity model has been used (Q2), which is sufficient for a long-term tactical plan, but doesn’t handle the detailed conflict resolution (meet/pass planning) of an operational timetable. Furthermore, the capacity control as well as the maintenance window scheduling use discrete time intervals which has some important implications. As discussed in Paper 5, this model has a tendency to group train services “on top of each other” in the solutions, which may underestimate the schedule adjustments needed for a feasible planning of the train services. A closer analysis of these properties is a subject for future studies, with the purpose of suggesting how to appropriately set the capacity limits or finding alternate or adjusted model approaches.

Resource considerations has been thoroughly investigated for the maintenance window scheduling (Q3 and Paper 4), but not for the train operations.

The primary resource consideration for train operations is the handling of rolling stock rotations, which is another interesting subject for future research. Possible modelling approaches are to include explicit vehicle connections or to control the rolling stock balances at the origin and destination nodes.

Solving performance The performance results have shown that modern MILP solvers are capable of producing optimal or near-optimal solutions to synthetic multi-day instances (Q4) or cyclic one-day real-life instances of practical interest (Q5). However, long solution times have been observed for several instances, particularly when including resource considerations. Although several hours or days of computation could be acceptable when working with long-term planning problems, the usability would be improved with heuristic methods that give high quality solutions quicker and enable interactive experiments with end users and planners. Future case studies for other traffic situations, network layouts and maintenance situations will show if more efficient solution techniques are necessary to develop.

Application and usage A long single track line has been extensively studied in Paper 5, but other cases, such as double or multi-track lines, networks, etc, should also be studied under varying traffic patterns. Such work is planned together with Trafikverket, with the intention of paving the way for the possibility of using optimization-based methods as scheduling and decision support in the regular capacity access planning process.

This thesis has shown that coordinated planning of maintenance and operations has major benefits for railways. Other infrastructure systems have not been studied, but it is likely that similar benefits can be achieved in other application areas. Some examples could be road networks, power distribution, water, sewage, central heating, etc. The methods studied in this thesis could possibly be transferred to these types of problems. In any case, the application of operations research methodologies to other maintenance planning problems is a promising area of work, which could make important contributions towards more sustainable solutions in the future.

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Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-152491

Paper 1

Dimensioning windows for railway infrastructure maintenance: cost efficiency versus traffic impact.

Lidén, T., Joborn, M. (2016)
Journal of Rail Transport Planning & Management, 6.1, 32–47
doi:10.1016/j.jrtpm.2016.03.002

Paper 2

An optimization model for integrated planning of railway traffic and network maintenance.

Lidén, T., Joborn, M. (2017)
Transportation Research, part C, 74, 327–347
doi:10.1016/j.trc.2016.11.016

Paper 3

Reformulations for integrated planning of railway traffic and network maintenance.

Lidén, T., Waterer, H. (2018)
Submitted for journal publication

Paper 4

Resource considerations for integrated planning of railway traffic and maintenance windows.

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Journal of Rail Transport Planning & Management, 8.1, 1–15
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Paper 5

Coordinating maintenance windows and train services — a case study.

Lidén, T. (2018)
Submitted for journal publication

Paper 6

Tight MIP formulations for bounded length cyclic sequences.

Kalinowski, T., Lidén, T., Waterer, H. (2018)
Submitted to *Journal of Discrete Optimization*