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Railway infrastructure maintenance - a survey of planning problems and conducted research

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Abstract

Railway infrastructure maintenance consumes very large budgets, is complicated to organize and has numerous challenging planning problems. Specifically, the coordination with train traffic operation is of crucial importance. Despite this, little work has been conducted in the operations research area regarding infrastructure maintenance as compared to train traffic operations.

The aim of this paper is to give a comprehensive overview of the railway infrastructure maintenance field, the planning problems it contains and the research that has been conducted so far. We present (i) a catalogue of planning problems, based on a series of interviews with experts and planners representing all major stake holders in Sweden and (ii) an extensive literature overview covering more than 60 research references published until 2014 regarding the use of mathematical methods and optimization for solving such planning problems. From this we extract some statistics and a mapping which identify the major lines of work as well as future research possibilities.

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Keywords: Maintenance planning; Operations research; Railway infrastructure

1. Introduction

Railway infrastructure maintenance is of crucial importance in order to obtain a well functioning transportation system. The actual maintenance work consists of a large amount of different activities, requiring considerable resources and large budgets. The European countries are reported to allocate 15 - 25 billion EUR annually on maintenance and renewals for a railway system consisting of about 300 000 km of track, half of which is electrified, giving an average of 70 000 EUR per km track and year (see EIM-EFRTC-CER Working Group (2012)).

There is however an inherent conflict in deciding how to assign maintenance work slots and train operation paths since these activities are mutually exclusive. This planning conflict becomes crucial on lines with high traffic density and especially when network traffic demand and maintenance needs are increasing.

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In addition, a far reaching deregulation has been going on since the 1980s in Europe, with the overall purpose of opening up for commercial competition. For infrastructure maintenance, this trend has extended the use of maintenance contractors, which raises more concerns regarding contractual forms, public procurement as well as planning.

All these factors - the large volumes, the interrelation between maintenance and traffic, the organizational aspects - motivate efficient and coordinated planning as well as further research. Historically, operations research has however focused more on train operation problems than on infrastructure maintenance activities.

To gain a better understanding of how railway maintenance is organized, planned and performed we have conducted a series of unstructured interviews with 15 experts and planners in Sweden, representing different organizations (infrastructure manager, contractors, operators), planning steps (from procurement to day-of-operations) and major technical activities (measurement, inspection, grinding, power system maintenance, etc). From this study we have identified and described the major planning and scheduling problems that must be solved. The result is presented as a catalogue of planning problems in Section 2. Further, we have conducted an extensive literature review to investigate which problem areas that have been studied scientifically. An overview of the publications found is presented in Section 3. Finally, we present some statistics and a mapping which shows which problem areas that so far have been addressed in the literature.

Scope. We focus on the planning and coordination of infrastructure maintenance and train traffic activities on a commonly used infrastructure. Hence, we are less concerned with the maintenance technique itself and the details of how to perform the actual work. Also we do not treat software tools for asset management and maintenance planning, which have been developed for railway infrastructure purposes over the years (e.g. REPOMAN, TRACS, MARPAS, ECOTRACK, SOG), instead referring interested readers to Guler (2013). Another type of work which we will not cover are simulation models for studying how network capacity, delays, etc, depend on the state of each track section, degradation, maintenance and train traffic (see for example Simson et al. (2000); Podofillini et al. (2005)). Finally, we will not include pure train traffic capacity and timetable work, planning of rolling stock maintenance and robustness of railway schedules in this study.

Infrastructure access and planning process. All activities that require secure access to the railway infrastructure must obtain a (work) **possession** (RailNetEurope (2013a,b). If the possession will be in conflict with or influence a train path we call it a “major possession”, while those not affecting the train operation are called “minor possessions”. The complete planning process for obtaining possessions and train operation slots in Sweden follow EU guidelines and consists of the following steps: (1) Freight corridor planning, where “prearranged paths” for international freight trains are established and coordinated with large major possessions; (2) Preparation and publishing of the network statement, which shall contain all major possessions that the train operating companies must adhere to; (3) Yearly timetable planning, where the basic timetable for all train paths are planned together with the major possessions; (4) Timetable revision planning, where the dated timetables are produced and final coordination of train paths and major possessions is done; (5) Planning of minor possessions, where work which do not affect any train paths are scheduled; (6) Operational planning and control, where the traffic control centers will make operative adjustments, authorize all possessions (including unplanned ones) and control all activities on the railway infrastructure. This process (where steps (1) - (5) is often labelled “capacity planning”), is representative for most European countries.

For further introductions to practical maintenance planning issues, we refer to Aspebakken et al. (1991), which describes a North American setting, and Ferreira (1997), which covers planning problems and aspects faced by a deregulated and timetable governed railway operation, such as those in Europe and Australia. We also refer to Lidén (2014) for a more complete description of railway infrastructure maintenance from a planning perspective.

2. A catalogue of planning and scheduling problems

In this section we list classes of planning and scheduling problems that have been established during our survey. Some of these problems have been identified in the interviews, while others have been recognized by comparison with other operations research fields.

We classify the problems as strategic, tactical or operational. In the strategic class we list problems concerning dimensioning, localization and organization, 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 year), often handling resources as categorized, anonymous objects. In the operational class we list problems concerning implementation and effectuation, covering short time horizons (hours to month), usually handling the real resources.

2.1. Strategic problems

Maintenance dimensioning. The first and fundamental problem is to establish infrastructure quality levels together with policies for maintenance and renewals, i.e. to decide how good the infrastructure should be and the methods for achieving this. It is a question of dimensioning the maintenance volumes and allocate them over the infrastructure network while considering traffic volumes, safety, reliability, economy, etc. The overall system capacity and service level must be handled as well as forecasts regarding degradation.

We have found three lines of research that belong to this class of problems:

- Service life and maintenance frequency determination (see 3.1.1), with 12 publications,
- Network design considering maintenance (see 3.1.2), with 2 publications,
- Renewal scheduling and project planning (see 3.1.3), with 6 publications.

Contract design. The infrastructure manager will split the maintenance into several different contracts, some being national, other regional, some concerning a specific type of maintenance and others bundling smaller tasks together. How these contracts are designed will greatly impact cost, quality and efficiency over long time horizons. The factors that can be varied are: (i) Scope, e.g. geographical split, contract lengths and maintenance content; (ii) Form, e.g. detailed activity specifications, task-oriented volumes or functional requirements, tendering process; and (iii) Terms, e.g. economy, fixed/variable pricing, incentives, indicators and statistics.

We have found no research that treat this problem as a quantitative design problem.

Maintenance resource dimensioning and localization. In order to guarantee adequate service levels (e.g. response times, mean-time-to-repair, etc), the maintenance resources must be dimensioned and localized in an efficient way. This is primarily the concern of each contractor, but sometimes pooling may be used or central warehousing prescribed by the infrastructure manager, in which case the resource planning becomes a common concern.

We have found no publications that focus specifically on these questions and only one where it is partly treated (Peng et al. (2013)).

2.2. Tactical problems

Possession scheduling. This is the focal point for coordination with the traffic and there are several subproblems or ways to address the issue:

- *Major possession scheduling.* Whenever possessions and train paths are in conflict or influence each other, the scheduling solution is of critical importance for the safety, reliability and efficiency, both for operators and contractors. Hence, the scheduling of major possessions is a key planning problem regarding railway infrastructure maintenance since it (i) has a fundamental impact on the traffic capacity, (ii) frames the work planning and cost conditions, and (iii) is conducted all the way from freight corridor to timetable revision planning.

- *Regular possession pattern construction.* Instead of acquiring minor possessions for every basic maintenance activity as late as possible, it can be beneficial to preschedule patterns of well-sized train-free slots that give access to every part of the infrastructure with sufficient intervals. Different activities can then be coordinated to these slots, the capacity planning becomes less burdened and the traffic situation more predictable. The construction of these patterns should consider the needed maintenance volumes, track sectioning, work hours, coordination with traffic and other possessions, operative restrictions past the work place, etc.

- *Possession and work coordination.* Possessions can be coordinated in several ways, e.g. synchronizing possessions to tracks unusable for traffic or "in the shadow" of other possessions, performing small tasks close to or together with larger ones, create possession patterns that fit well with the traffic patterns, etc. A similar approach is to coordinate the work content so as to minimize the possession time and cost. Examples are so called opportunistic maintenance, project combination, possession sharing by two or more work tasks, etc.

- *Timetable compression.* Instead of scheduling possessions early, the timetable construction could be done so as to guarantee a certain traffic free time - either as requirements/constraints or as a separate goal to maximize. These train free slots would then be available for ad hoc maintenance work later in the planning process. This approach would treat some maintenance aspects as a subproblem/addition to the normal train timetable construction.

We have found 15 publications concerning possession scheduling, which are summarized in 3.2.1. They treat variants or combinations of the three first subproblems described above.

Maintenance vehicle and team routing. Several maintenance activities require specialized teams with large and expensive equipment, such as machines for track and catenary measurement, ultrasonic inspection, tamping, grinding, track and sleeper replacement. It is essential that these machines and teams are used efficiently. Furthermore they will consume track capacity when parked on stations and side tracks.

The maintenance vehicle and team routing problem should consider the work tasks to be performed, transportation from and to depots, interruptions, other train traffic, crew requirements, machine service needs and coordination with other tasks.

We have found two lines of research in this problem class:

- Deterioration-based maintenance scheduling (see 3.2.2), with 8 publications - all of which consider tamping,
- Maintenance vehicle routing and team scheduling (see 3.2.3), with 9 publications - where focus is on efficient resource usage.

Rescheduling. Uncertainty is always prevalent, which means that rescheduling is needed in some situations, e.g. when budget volumes change or urgent repair is needed. Questions regarding which jobs to change or cancel, how to reschedule resources, the best way to get back to the master plan will then need an answer - often within a short response time. The amount of changes - both regarding maintenance and train traffic - is affected by the construction of the original plan, which can be seen as a robustness issue.

We have not found any publications treating the rescheduling problem for infrastructure maintenance.

All the tactical problems above can also appear in the operational phase, especially rescheduling which is the core problem in real-time traffic control. Out of the 31 references listed in Subsection 3.2, 6 belong to the operational class.

2.3. Operational problems

Maintenance project planning. When a specific maintenance project shall be performed there are several detailed plans to produce and coordinate regarding equipment, crew and material. The planner(s) need to find appropriate time slots, arrange transportation, get necessary permits, document the operational restrictions around the work area, etc. Crew schedules shall be done according to applicable work regulations and necessary equipment and material shall be ordered and prepared.

We have found no publications that focus on this problem, although AUTOMAIN (2013) treat one of the aspects (transportation between sites).

Work timing and resource scheduling. Safety and maintenance inspections shall repeatedly visit all parts of the infrastructure - with varying frequencies. To some extent these visits should be coordinated with other maintenance activities. Efficient inspection work tours must therefore be constructed which fulfill the prescribed requirements.

Inspections and diagnostic measurements also generate a large number of repair and corrective maintenance actions, each having varying work load and time limits for restoration. The contractors are then faced with the problem of efficiently selecting the exact timing of each action, bundling the tasks together in work packages, assigning them to repair crews and finding suitable possessions.

We have found 6 publications (see 3.3.1) concerning this class of problems.

Track usage planning. At large stations and railway yards, a detailed track usage plan is needed, both for operators and contractors, who must know when tracks are free from rolling stock and available for maintenance. If work tracks are not cleared, additional shunting movements are needed which might reduce the available work time or cause delays if revealed late. Hence, the track usage planning will be revised from time to time. Snow removal on junctions and railway yards is a specific action where this replanning is of crucial importance, especially if adjacent tracks are needed for snow collecting vehicles.

We have found no publications that treat this problem from a maintenance perspective.

2.4. Other aspects

Robustness. In all planning the issue of uncertainty is crucial, especially when plans are produced long in advance, which is customary for railway infrastructure maintenance. For example, a prognosis of the possession times must be made long before the detailed work planning has started, the actual infrastructure status may change substantially before the actual work is done, the resource situation and/or budget restrictions may change, new funding might emerge, etc. How to cope with these uncertainties is a challenging problem, and therefore robustness can be of interest in all of the above described problem classes.

We have found three publications where uncertainty and robustness is considered, namely Higgins (1998); Lake and Ferreira (2002); Zhang et al. (2013a).

Scenario planning. One option for handling uncertainty is to prepare recovery or reduction scenarios. Apart from reoccurring situations like harsh weather conditions, such scenarios could also be prepared for important and crucial accident or repair situations, e.g. a derailing or catenary wire breakage on specific line stretches. Instead of solving these situations in real-time (stressful and with scarce information), better recovery plans can be prepared beforehand, considering factors like fair handling of operators, contractors and customers, knock-on effects, vehicle circulations, emergency handling, work access and passing traffic.

We have found no publications discussing scenario planning.

Real-time maintenance/operational control. The traffic control center handles all train traffic and all work possessions. Additionally, they will manage error reports, accidents and urgent incidents, deciding when to call in maintenance contractors and how to handle all operative situations. The contractors are also faced with a real-time control problem concerning how to select and assign resources to incidents and schedule unforeseen work tasks - preferably maintaining a high level of preparedness and response times.

We have found one publication (Albrecht et al. (2013)) that treat this problem for traffic control centers, but none regarding the contractor side.

3. Literature overview - optimization models for railway infrastructure maintenance planning and scheduling

In the following we will list close to 60 research references. We group them into lines of research and make a very brief thematic comparison of the references. More elaborate descriptions, comparison of features and approaches can be found in Lidén (2014). We use the term “long-term” for planning that is conducted several months or years in advance, usually giving multi- or single year plans, and “short-term” for scheduling that take place less than a month before effectuation, usually giving schedules of one week or less.

3.1. Strategic problems

3.1.1. Service life and maintenance frequency determination

In order to assess the long term economy, the service life of different components as well as policies for inspection, preventive maintenance and renewal intervals are needed. For this purpose, life-cycle cost models have been developed which often consider a standard unit of track with some given traffic load. The studies either aim at (a) condition-based maintenance, where focus is on inspection planning, or (b) prescribed / preventive maintenance, where focus is on maintenance and renewal intervals.

Rail crack inspection and grinding is studied in Podofillini et al. (2006); Lyngby et al. (2008); Liu et al. (2014) while geometry inspection and tamping is studied in Meier-Hirmer et al. (2005); Lyngby et al. (2008).

For prescribed / preventive maintenance, Lamson et al. (1983) study grinding, repair and renewals on a heavy haul freight line. Zhao et al. (2006a) study ballast tamping and renewals and compare different maintenance policies, while Meier-Hirmer and Pouligny (2008) and Gustavsson et al. (2014) consider preventive grinding including grinding depth and Chen et al. (2013, 2014) treat maintenance of electrical power feeding systems.

Finally, Antoni and Meier-Hirmer (2008); Antoni (2009) develop a statistical model that can be used for different types of failing components with replacement maintenance, and apply it to track, signaling and contact wire systems.

3.1.2. Network design considering maintenance

A strategic approach for dimensioning the maintenance volumes is to account for this in the network design decisions. Lai and Barkan (2011) describe a decision support framework for network capacity planning, where maintenance cost is included in the flow cost of running trains. Lai et al. (2013) consider the problem of assigning the appropriate track class to each link in the network, which determine the service level (train speed and riding comfort) as well as the maintenance cost.

3.1.3. Renewal scheduling and project planning

This line of work consider infrastructure networks with varying track quality, traffic load, etc. Thus the maintenance and renewal jobs should be jointly planned over a long time period. Often it is beneficial to combine projects to minimize the track closures and reduce work costs.

Lévi (2001) describe work done at SNCF to obtain a 5 year maintenance and renewal plan, using either historical data or probability models to assess the amount of repairs needed. Zhao et al. (2009) and Caetano and Teixeira (2013, 2014) consider ballast, sleepers and rail, while Andrade and Teixeira (2011) study tamping and renewals, with different approaches regarding traffic considerations, objectives, technique and data sets. Zhang et al. (2013a) study project scheduling of large jobs, focussing on the uncertainties concerning actual deterioration and work start times.

3.2. Tactical problems

3.2.1. Possession scheduling

Among the long-term approaches, we find three different themes: (i) Construction and scheduling of regular possession patterns that give repeated track access (van Zante–de Fokkert et al. (2007) and den Hertog et al. (2005)); (ii) Coordination of maintenance tasks, in order to minimize possesion time and maintenance cost (Budai et al. (2006); Budai-Balke (2009); Pouryousef et al. (2010); Jenema (2011)); and (iii) Adjustment of a given maintenance plan (where the jobs reduce link capacities), so as to maximize the transportation throughput (Boland et al. (2013, 2014)).

Weekly assignment of work crews and scheduling of maintenance jobs on a single track line (with a given train traffic timetable), is addressed in Higgins (1998); Lake et al. (2000, 2002); Lake and Ferreira (2002).

Approaches for scheduling *both* trains and track possessions in the same model are presented in Ruffing (1993), Albrecht et al. (2013) (based on Albrecht (2009)) and Forsgren et al. (2013). In all cases, a small number of maintenance possessions shall be introduced into an existing train timetable, allowing different types of adjustments to the trains. Ruffing (1993) is one of few papers that handle operational restrictions (reduced speed) for trains passing a work site. Albrecht (2009) address the real-time operational control case for a single track line, allow train times to be adjusted but not cancelled while Forsgren et al. (2013) treat the tactical timetable revision planning case, handle a network with both single and multi-track lines, allow trains to be rerouted or cancelled and consider different running times depending on train stops.

3.2.2. Deterioration-based maintenance scheduling

An overview of this field is given in Ferreira and Murray (1997) who also discuss deregulation aspects. Deterioration is usually handled in the strategic or tactical phase, but there are some references (which will be listed in 3.3.1) that consider it in short-term operational scheduling as well.

All the following references concern tamping, although Murakami and Turnquist (1985) describe a general multi-period resource allocation model. Miwa (2002) consider the scheduling of one machine and presents a model that handles several resource and business constraints. The method is further developed in Oyama and Miwa (2006), also adding an initial model that bundle segments into maintenance units. In the papers Vale et al. (2010), (2011) and (2012) interventions must start/end on straight rails and different objectives are studied. Famurewa (2013) schedule two types of tamping machines, making as much use as possible of each work shift. A similar problem is studied in Quiroga et al. (2011), where a set of yearly tamping campaigns are scheduled with special focus on the prediction uncertainty in the degradation model. This uncertainty is also studied in Andrade and Teixeira (2012) where a Bayesian approach is used.

3.2.3. Maintenance vehicle routing and team scheduling

The long-term maintenance team (or gang) scheduling problem (also labelled curfew planning) has been studied by several authors (see Gorman and Kanet (2010); Nemani et al. (2010); Boğ et al. (2011); Peng (2011); Peng et al. (2011); Peng and Ouyang (2012); Borraz-Sánchez and Klabjan (2012)), using different formulations and solution techniques. The aim is to assign and schedule a given set of maintenance jobs on different maintenance teams with varying capabilities, equipment and home locations. All the suggested models handle traffic considerations by imposing constraints on which jobs that can be scheduled simultaneously. As a preprocessing step, Peng and Ouyang (2014) describe a model for clustering small maintenance jobs into week long projects.

In AUTOMAIN (2013) a multilevel, modularized planning system is developed consisting of: (i) Job combination & scheduling for a 1-3 year plan; (ii) Path finding for each machine transportation between sites; and (iii) Detailed movement scheduling with possible adjustments of regular operation trains.

3.3. Operational problems

3.3.1. Work timing and resource scheduling

The construction of periodic rail inspection tours is studied in Peng et al. (2013) (based on Peng (2011)) while all other references in this group treat variants of short-term rectification scheduling.

Zhao et al. (2006b) and He et al. (2014) study the selection of which defects to repair immediately and which to postpone, using statistical prediction models for degradation and failures of sleepers (Zhao et al.) and track geometry (He et al.) respectively. The routing and scheduling of corrective tamping machines / teams is studied in Zhang et al. (2013b) and Heinicke et al. (2014) using statistical prediction models for degradation (Zhang et al.) or time-dependent costs for incurred operative (speed) restrictions (Heinicke et al.). Finally, Cheung et al. (1999) study the weekly scheduling of maintenance jobs on train-free night shifts for the subway of Hong Kong Mass Transit considering a large set of rules and constraints.

4. Summary and outlook

In table 1 we summarize our catalogue of problems. The last two columns give cross references and number of publications found. In total we have 58 references, of which 34% concern strategic, 46% tactical and 20% operational problems. Out of the 9 problem types, 4 have several research publications, 2 are partially treated (shown with parenthesized counts) and for 3 we have found no references at all.

From this we can identify several problem areas in railway infrastructure maintenance planning where operations research methodology might be applicable, such as contract design, resource dimensioning and localization, rescheduling, project planning and track usage. Other aspects and approaches that have attracted little amount of work are robustness, scenario planning and real-time operational control.

If we study the publication dates we find 10 references published before 2004, 15 in the period 2005 - 2009 and 33 during 2010 - 2014. Hence, there is a steady increase that hopefully will continue, since we believe there are plenty of opportunities for studying more problems and methods that address this application area. The work presented here can perhaps facilitate and inspire further such research and development in this interesting, challenging and much needed field.

Table 1. Problem types, classification and references

Problem type	Class	References	# publications
Maintenance dimensioning	S	SF: see 3.1.1	12
		ND: see 3.1.2	2
		RS: see 3.1.3	6
Contract design	S	–	–
Resource dimensioning & localization	ST	(Peng et al. (2013))	(1)
Possession scheduling	T(O)	See 3.2.1	15
Vehicle & team routing	T(O)	DS: see 3.2.2	8
		VR: see 3.2.3	9
Rescheduling	TO	–	–
Project planning	O	(AUTOMAIN (2013))	(1)
Work timing & resource scheduling	O	See 3.3.1	6
Track usage	O	–	–

Column 2 classify the problem as Strategic, Tactical and/or Operational
Column 3 list cross references. The abbreviations are: SF=Service life & maintenance frequencies, ND=Network design, RS=Renewal scheduling & project planning, DS=Deterioration-based maintenance scheduling and VR=Maintenance vehicle routing & team scheduling.
Column 4 give number of publications found - figures in parenthesis denote papers that treat the subject partially.

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