Modeling and Optimising Infrastructure Upgrade Deployment in Railway Networks Operating Cyclic Timetables

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1 INTRODUCTION

Railway infrastructure plays a critical role in shaping the quality of timetables. As railway systems age and passenger and freight demand increases, modernizing tracks, signaling systems, and stations becomes crucial to maintaining reliable service and resolve bottlenecks. For instance, the digitalisation of railway infrastructure can significantly impact train timetables through the reduction of travel time and headway requirements, but while the effects of infrastructure upgrades on minimum travel time and minimum headway requirements can be estimated in advance, the ability of timetables to take advantage of those gains is unknown until timetables are generated. Furthermore, the deployment of infrastructure upgrades is a lengthy and costly process subject to many constraints which should be planned strategically.

The majority of the literature that studies the implementation of railway infrastructure upgrades focuses on the minimization of costs to meet capacity requirements. An overview of different works in the literature is presented in Table 1. In the case of the digitalisation of the railway

Table 1 – *Models for Railway Network Design Problems in the Literature*

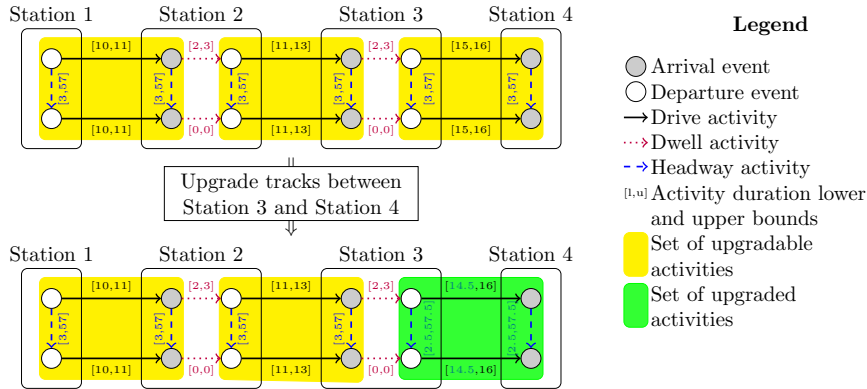| | Objective | Multi-Period | Timetabling | |
			Macroscopic	Cyclic
Kuby *et al.* (2001)	min cost	✔		
Bärmann *et al.* (2017)	max (freight) profit	✔		
Seyedvakili *et al.* (2020)	min cost	✔		
Schöbel *et al.* (2013)	min cost			✔
Friesen *et al.* (2024)	min cost		✔	
Sander *et al.* (2023)	min cost		✔	
Nachtigall & Voget (1997)	min waiting times		✔	✔
This paper	min travel time	✔	✔	✔

Figure 1 – *Example of infrastructure upgrade effects on activity duration bounds in a simple event-activity network.*

infrastructure, the focus should not be solely on which infrastructure upgrades to implement but on determining the optimal deployment order such that benefits can be reaped as infrastructure upgrades are implemented. This research focuses on the deployment of infrastructure upgrades over multiple periods. To that end, we formalize the problem as the Railway Infrastructure Upgrade Deployment Problem (RIUDP) designed to guide decision-makers in planning the phased deployment of new technology across a railway network, taking into account both the costs and societal benefits of the upgrades

Our contributions are fourfold. First, we introduce the RIUDP as a new problem focused on planning the phased deployment of infrastructure upgrades in a railway network. Second, we present an exact Mixed Integer Linear Programming (MILP) formulation for the RIUDP. Third, we propose two solution methods aimed at selecting cost-effective infrastructure upgrades. Fourth, we illustrate the importance of infrastructure upgrade choice over multiple periods on a case study focused on the deployment of European Railway Traffic Management Systems (ERTMS) on the Dutch Railway Network.

2 PROBLEM DESCRIPTION

Input to our problem is a railway infrastructure network, a set of potential railway infrastructure upgrades over sections of that network with associated costs and known effects on minimum travel times and headway requirements of train services, and a planning horizon consisting of multiple periods with associated available budgets. In this problem, we focus on the deployment of railway infrastructure upgrades on a network operating cyclic timetables, i.e. timetables where train schedules repeat at regular intervals. To evaluate the realizable gains that can be derived from the implementation of infrastructure upgrades, cyclic timetables are generated for each period within the planning horizon.

Timetables are modeled by the means of event activity networks $G = (E, A)$ where E is the set of events representing the arrivals and departures of train services at train stations, and A is the set of the drive, dwell, and headway activities representing the movements and interactions of trains in the network. The duration of each activity is associated with a lower and upper bound which can be affected by the implementation of an infrastructure upgrade on the segment of the network containing the activity. This is exemplified in Figure 1 where upgrading the tracks between station 3 and 4 reduces the bounds associated with the drive and headway activities between these stations.

Given the input aforementioned, the RIUDP is to determine the optimal sequence and timing of infrastructure upgrades across the network, subject to budget constraints, to ensure the highest possible return on investment, measured in terms of reduced travel time for passengers.
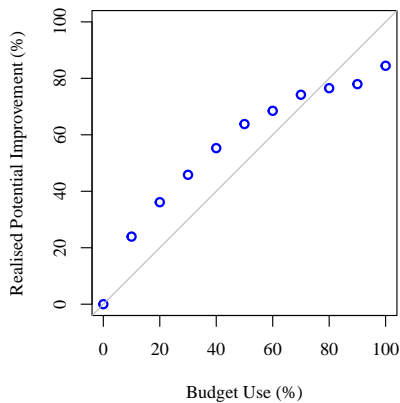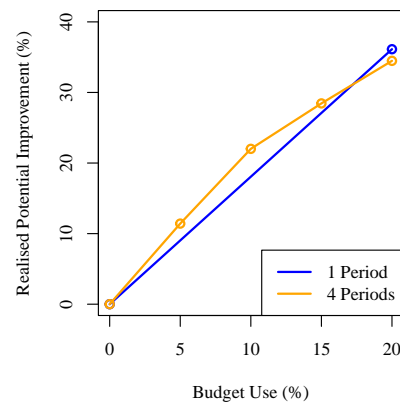
(a) *Single period optimisation*

(b) *Multi-period optimisation for 20% of the budget*

Figure 2 – *Preliminary results; The results are presented in terms of realised potential which is a scale using 0 as the best found solution for the non-upgraded network and 100 as the best bound for the fully upgraded network.*

3 METHODOLOGY

We model the RIUDP by the means of a MILP formulation. In the formulation, infrastructure upgrade decisions subject to budget constraints are defined using binary variables. The generation of cyclic timetables is modeled in our formulation through constraints derived from the Periodic Event Scheduling Problem (PESP) formulation of Serafini & Ukovich (1989) that were adapted to model the effect of infrastructure upgrade deployment on activity duration bounds. Since we are evaluating infrastructure upgrade decisions over multiple periods, the formulation contains cyclic timetabling constraints for each period evaluated.

Integrating infrastructure upgrade deployment decisions and timetabling constraints for multiple timetables entails a lot of complexity, rendering the ability of commercial solvers to tackle the problem limited. We propose two heuristics to solve the RIUDP. The first method is to reduce the MILP formulation to a Binary Integer Programming (BIP) formulation, similar to a multi-period knapsack problem, where we use an estimate of the benefits of selecting an upgrade without constructing a full timetable. Solving this model to optimality can take a long amount of time for multiple periods, hence, we also present a greedy method where infrastructure upgrades are ranked and selected based on their expected cost-effectiveness. Evaluating the quality of these solutions is then done by sequentially optimising the timetables for each period. The solutions derived from these heuristics can also be used as starting solution when trying to solve the full MILP formulation.

4 RESULTS

We present results for a case study of the deployment of ERTMS on the Dutch railway network using the peak-hour weekly timetable of the trains operated by the NS (Dutch Railways). We consider a cyclic timetable of 1 hour and schedule events with a precision of 0.1 minute. The event activity network is composed of 12,459 events, 40,825 activities, and 81 infrastructure upgrades defined between intersections of the infrastructure network. Section 4.1 presents preliminary results for a basic form of the problem. Future experiments based on these results and extensions of the problem are discussed in Section 4.2.

4.1 Preliminary Results

Our preliminary results are presented in Figure 2. All experiments were run for 4 days, 3 of which using the sequential optimisation approach, followed by 1 day solving the full model using a commercial solver.

Figure 2a show that infrastructure upgrade decisions for low budgets have a significant effect on the quality of the timetable. These improvements primarily come from the resolution bottlenecks in most congested parts of the network. After these initial gains, increasing the available budget leads to decreasing marginal improvements. It is noteworthy to mention that the increase in realised potential from 90% of budget use to 100% of budget use is quite significant. This is likely due to the absence of infrastructure upgrade choice needed for 100% of budget use, allowing the solver to fully focus on optimising the timetable. These results highlight that our results for lower budget percentages are likely far from optimal, and that larger running times or better solving methods are necessary, even when considering a single planning period.

Figure 2b shows for a budget of 20% the difference between single period planning and 4-periods planning. When considering multiple periods, we observe that initial cost-effective investments are prioritized, as gains from the first period can carry over to subsequent periods. However, these initial gains come at the cost of worse timetables in later periods when compared to timetables with infrastructure upgrade decisions made over a single period.

4.2 Future research

As the instances studied in this paper are too large to prove optimality of the results, we aim at performing longer experiments to validate our results and ensure a fair comparisons. Furthermore, we will to explore and compare the effectiveness of our suggested heuristics.

In this project, we also want to consider different variations of the problem that take into account operational aspects of infrastructure upgrade deployment. These aspects include regional equity requirements, ensuring that the whole budget is not allocated only to the central area of the network, and connectivity requirements, as alternating signaling systems on tracks are general undesirable from an operational perspective. Models containing these additional constraints have been formalised and implemented, and the effect of these additional constraints on the objective will be presented at the conference.

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