Large Scale Railway Renewal Planning with a Multiobjective Modeling Approach

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Abstract

A multiobjective modeling approach for managing large scale railway infrastructure asset renewal is presented. An optimized intervention project schedule is obtained considering operational constraints in a three objectives model: evenly spreading investment throughout multiple years, minimizing total cost, minimizing work start postponements on higher priority railway sections. The MILP model was based on a real world case study; the objectives and constraints specified by an infrastructure management company. Results show that investment spreading greatly influences the other objectives and that total cost fluctuations depend on the overall condition of the railway infrastructure. The model can produce exact efficient solutions in reasonable time, even for very large-sized instances (a test network of similar size to the USA railway network, the largest in the world). The modeling approach is therefore a very useful, practical methodology, for generating optimized solutions and analyzing trade-offs among objectives, easing the task of ultimately selecting a solution and produce the works schedule for field implementation.

2012 ACM Subject Classification Theory of computation → Integer programming

Keywords and phrases Rail infrastructure, Renewal maintenance, Multiobjective modeling

Digital Object Identifier 10.4230/OASIcs.ATMOS.2018.2

Funding Portuguese Foundation for Science and Technology, project grant UID/MULTI/00308/2013.

Acknowledgements The authors would like to thank Vitor Dias da Silva for his help preparing the manuscript.

18th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS 2018).
Editors: Ralf Borndörfer and Sabine Storandt; Article No. 2; pp. 2:1–2:9
OpenAccess Series in Informatics
Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

1 Introduction

The railway has recognized economic, energy and environmental benefits [2], as well as lower operating externalities when compared to road infrastructure [13]. In recent years, the need to provide for a rising demand of rail services has prompted infrastructure managers to intensify maintenance actions, leading to a range of planning problems [1, 4, 6, 9, 11, 12, 14].

The European Commission, in view of these advantages, has been taking measures to increase the use of this mode of transport, by opening up the market to competition, creating new infrastructure and improving the interoperability and safety of existing networks. Ensuring the safety of people and goods, as well as the normal running of rail services, requires maintenance of the existing railway, much of it degraded after decades of disinvestment. In the context of maintenance, it is important to distinguish between current maintenance and renewal interventions. Current maintenance refers to frequent minor works aiming at maintaining an adequate level of service of the infrastructure, whereas renewal actions are typically more extensive and restore (or modernize) the infrastructure [5].

In this article a multiobjective methodology to plan renewal interventions in the railroad is presented, taking into account three objectives: to spread out investment expenses, as evenly as possible, over project years; to minimize the total renewal costs; to minimize work start postponements on the higher priority railway lines. Equitable distribution is required since large-scale renewal actions require a very considerable financial effort from the infrastructure management company, and it is desirable that this effort is diluted as much as possible over multiple years. Achieving a balanced annual investment plan, without compromising the total financial effort or excessively postponing the execution of the priority works, was the motivation for pursuing the research which is now presented. For recent research concerning other aspects (not just financial) of resource levelling in project management see e.g. [3, 8]. It should be noted that the objectives, as well operational constraints to be respected, were defined by an infrastructure management company operating at national scale, which also provided field data for one of the case studies, as well as model parameter calibrations. Indeed, the proposed model stemmed from interaction between a research institution and a railway infrastructure management company, and therefore authors are strongly convinced of its practical usefulness, given it provides a scientific methodology to deal with a real problem in corporate asset management.

2 Multi-objective model

Following the terminology of [7], “renewal” refers to background interventions subsequent to the natural wear and tear of the infrastructure, “line” refers to major railway lines connecting principal stations, and “section” to parts of a line between two geographic landmarks. These marks are usually stations or junctions but may also be mere kilometer points. Sections are often heterogeneous, in which case they are divided into homogeneous subsections. Sections are what undergoes renewal works.

The model is suitable for treating renewal actions which do not involve prolonged track closure or re-routing of the circulation through multiple alternative routes. Typically these are large-scale, extensive interventions on rails, ballasts, sleepers, etc. and may involve upgrading rail assets. Interventions on other asset types (e.g. catenaries, sub-base) may be included provided they do not lead to prolonged blockades. While a section is under intervention, trains must run at reduced speed, causing delays in services. The model cannot, therefore, allow for an accumulation of works on the same line which may cause excessively large delays. Similarly, the lines do not all have the same socio-economic importance or service intensity, making it is necessary to prioritize the sections to be renewed. The model takes these issues into account and considers two periods of accounting as well, monthly and annual, the first to schedule the field works and the second for budgeting. Both can be changed without affecting the structure of the model.

Indices:
$i = 1, \ldots, M$ railway line sections to be renovated.
$j = 1, \ldots, N$ spanning months.
$k = 1, \ldots, P$ spanning years; $N = 12P$.
$l = 1, \ldots, Q$ railway lines. Each section belongs to a railway line.

Parameters: (units)

$\boldsymbol{C_i^R}$ cost of renewing section i (monetary unit MU).
$\boldsymbol{C_{ij}^{EM}}$ extra maintenance cost of section i if it is not renewed as of month j (MU). These costs are active until the repair works end.
$\boldsymbol{P_i}$ priority for renewing section i (adimensional). Active until repair works on that section are completed. This can also be seen as service inconvenience of not renewing the section.
$\boldsymbol{T_i}$ time span needed for renewing section i (months).
$\boldsymbol{D_i}$ delay caused to railway traffic from having section i under renewal(minutes).
$\boldsymbol{B_{il}}$ 1 if section i belongs to line l, 0 otherwise (binary). Note: in the case studies, no section belongs to two lines, but that is not forbidden.
$\boldsymbol{M_l}$ max delay tolerable for line l (minutes).

Decision variables:

$\boldsymbol{x_{ij}}$ 1 if section i starts to be renewed in month j, 0 otherwise (binary).
$\boldsymbol{F}$ maximum yearly investment (real positive variable).

Auxiliary variables:
$\boldsymbol{A_{ij}}$ 1 if section i is being renewed in month j, 0 otherwise (binary).
$\boldsymbol{U_{ij}}$ 1 if the renewal of section i is not yet finished by month j, 0 otherwise (binary).

Model:

$$\min \ O_1 = F \tag{1}$$

$$\min \ O_2 = \sum_i C_i^R + \sum_{ij} C_{ij}^{EM} U_{ij} \tag{2}$$

$$\min \ O_3 = \sum_{ij} P_i U_{ij} \tag{3}$$

Subject to:

$$\sum_j x_{ij} = 1, \quad \forall i \tag{4}$$

$$x_{ij} = 0, \quad \forall i : j > N - T_i \tag{5}$$

$$A_{ij} = \sum_{j'=j-T_i+1, j' \geq 1}^{j} x_{ij'}, \quad \forall ij \tag{6}$$

$$U_{ij} = \sum_{j'=j-T_i+1, j' \geq 1}^{N} x_{ij'}, \quad \forall ij \tag{7}$$

$$\sum_{j=12(k-1)+1}^{12(k-1)+12} \left[\sum_i \left(\frac{C_i^R}{T_i} A_{ij} + C_{ij}^{EM} U_{ij} \right) \right] \leq F, \quad \forall ij \tag{8}$$

$$\sum_i D_i A_{ij} B_{il} \leq M_l, \quad \forall jl \tag{9}$$

Objective O_1 is implemented by equations formulas (1) and (8), where the 1st member of (8) is the annual investment. The extra costs C_{ij}^{EM} are active until the end of the work, but these costs can be considered in other ways, such as e.g. being active up until halfway the work completion. Objective O_2 has a fixed and a variable part and was thus defined to give the decision maker a better notion of the final values. As for O_3, sections accumulate priority values, month after month, until their respective renewal is complete. The more a high-priority work is postponed, the more it builds up in O_3. Equations (4) and (5) enforce that the works are started at some stage, and in time to finish before the last year ends. Equations (6) and (7) define auxiliary variables and equation (9) are operational constraints which avoid excessive delays in train circulation when a line undergoes multiple works at the same time.

It should be noted that the structure of the operational restrictions (9) allows to model some cases of track closure, namely those in which the movement of people and goods along the closed track section is made by alternative transportation. The only modification is the D_i value, which is usually higher than that caused by reduced speed circulation. In highly congested lines, or lines with feeder branches, the D_i delays may eventually cause knock-on effects (bottlenecks) in circulation. This does not happen in case study 1, but if such effects are plausible in other instances, modifications to (9) might need to be considered.

3 Case studies and results

3.1 Case study 1 – real data

Case study 1 consists of $M = 20$ sections to be renewed, over $P = 5$ years ($N = 60$ months) and belonging to $Q = 17$ lines. The parameters that characterize the sections were obtained by averaging values of their constituent homogeneous subsections, weighted by the length of the latter. The infrastructure management company provided all the data and validated the parameterization mentioned below.

The extra maintenance cost structure considers a negative exponential degradation of the infrastructure, which leads to extra maintenance costs of +3.5% per year on the current maintenance cost, for each year in which the renewal exceeds the recommended term, i.e. for every month j belonging to year k one has $C_{ij}^{EM} = C_{base} \times \left[(1+0.35)^{(\alpha_i-1+k)\times\theta(\alpha_i-1+k)} - 1\right]$, with α_i the number of years for which renewal is overdue and $\theta(x)$ the unit step function. In the case study α_i was 10 years, on average.

Priorities were defined considering the type of service provided by the line (TS) to which each section belongs, the sections present conservation status (CS) and freight traffic volume (FT). Values of 100/90/75/50 for TS and CS, and 100/90/75/50/40 for FT were considered and the final value for priorities was defined by $P_i = 0.5TS + 0.3CS + 0.2FT$. All these parameter values were suggested by the infrastructure management company.

Finally, delays in circulation were calculated considering the length of the sections and maximum train speed under works. Maximum values M_l and works duration T_i were obtained directly from the infrastructure management company.

The Pareto front of the case study was obtained by the epsilon-constraint method (Cohon, 1978) using the IBM CPLEX 12.7 solver, running on a quad-core @ 2.6 GHz CPU. Starting from solutions with O_1 restricted to its smallest possible value and gradually relaxing this value until reaching unrestricted O_1, two solutions were generated for each O_1 value, respectively minimizing O_2 and O_3. Solutions near O_1 optima took a few hours to derive, and were used as starting point for sequent runs, which gradually finished faster, down to just a few seconds per solution. The total CPU time was less than 1 day, for 312 runs. It was found that in all the solutions obtained, the value of O2 never exceeded its optimum by more than 1%, so this objective was discarded, giving rise to the front of Fig. 1 below (values in percentage, for confidentiality reasons, with optimum = 100%):

As can be seen, the front shows a relatively regular behavior, allowing the decision maker to analyse the trade-offs between equitably distributing the investment and accelerating the renewals. The non-dominated solutions that form the front may, for field works planning purposes, be displayed as Gantt schedules. Fig. 2 below shows the schedule for the solution with O_1 <120%, min O_3. Several non-dominated solutions, including this one, were presented to the infrastructure management company and are currently under evaluation for field implementation.

3.2 Case study 2 – large-sized theoretical problem

A large instance was generated, reflecting a problem of size similar to the USA railway network. This is the largest network in the world [10] so it is not expected that considerably larger problems appear in real life. In practice the US market is highly fragmented, i.e. split into several, independent infrastructure management companies, so this instance is purely hypothetical. It was carried out not only to stress-test the model in terms of CPU times, and thus unravel eventual limits to the computational performance of the model, but also to find out under what circumstances objective O_2 becomes important. Field data associated to railway network was randomly generated and the same parameterization of case study 1 was used. However, for case study 2 the α_i were distributed so as to have an average of 25 years backlog and a $P = 10$ years of project horizon was considered. Despite the very large increase in the number of decision variables (now about 600000), the CPU time increase was not very significant, with most runs taking in the range of seconds and runs close to O_1 optimum taking more CPU time (in fact only 4 solutions required more than 20 seconds: 20.7, 22.3, 415.6 and 1412.6 seconds), which was already the case for case study 1. This is a reasonable increase for a problem that is almost 200 times as large. It is thus expectable that just about any real-life problem can be treated in a modern computer, regardless of size.

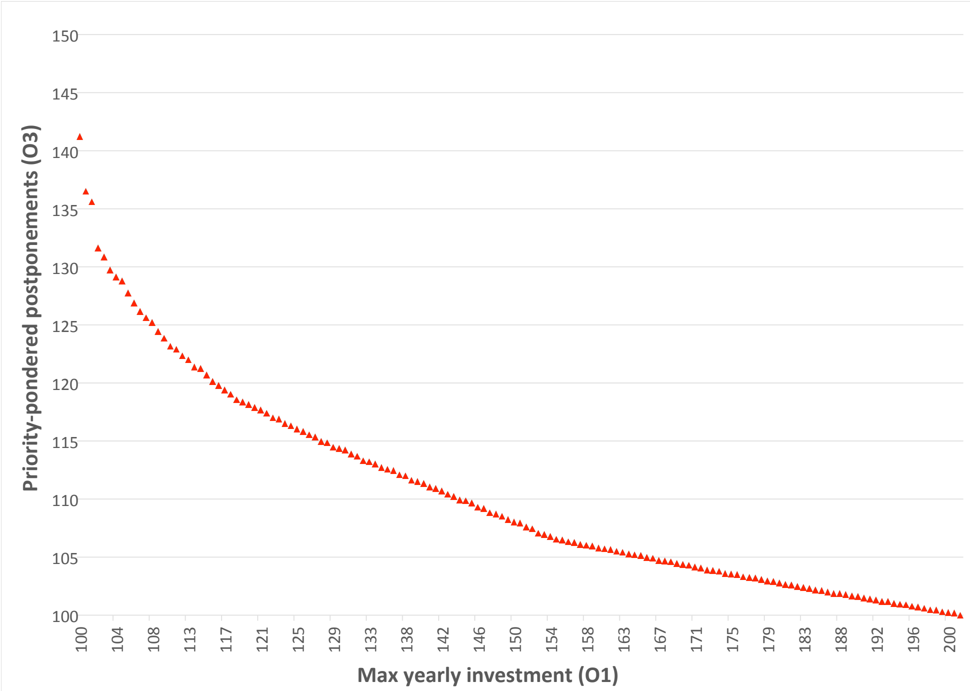

Figure 1 Pareto front for the case study (O_2 not displayed).

As compared to case study 1, in case study 2 optimizing O_1 now leads to greater (percent-wise) degradation of O_2 and O_3, whereas optimizing O_2 and O_3 lead to similar pay-off values. Objective O_2 is now relevant, fluctuating between 100% and 210% (rather than just the 1% of case study 1), showing all objectives are important when the infrastructure is ageing, and the backlog is large. Indeed, if the railway infrastructure is very degraded, objective O_2 should be included in the analysis, especially if the renewal plans span for many years.

Figure 3 shows that if the decision maker allows some increase in max yearly investment (i.e. degradation of O_1), solutions improve considerably in the remaining two objectives. It also shows that, for each value of the O_1 restriction, O_2 and O_3 can only fluctuate in a narrow range of values, making O_1 a very important objective, whose value has a big influence on the two other.

4 Conclusions and summary

In this paper, a multiobjective methodology was proposed for renewal of railway networks planning. The model is linear, soluble in reasonably time and provides a range of solutions for the analysis of trade-offs by the decision maker, each one being translatable in Gantt schedules for later implementation on the field. The methodology is strongly inspired by a real case study and reflects the practice of an infrastructure management company, so it may be especially useful as an asset management tool. It is also easily generalizable to other types of infrastructure, such as highways.

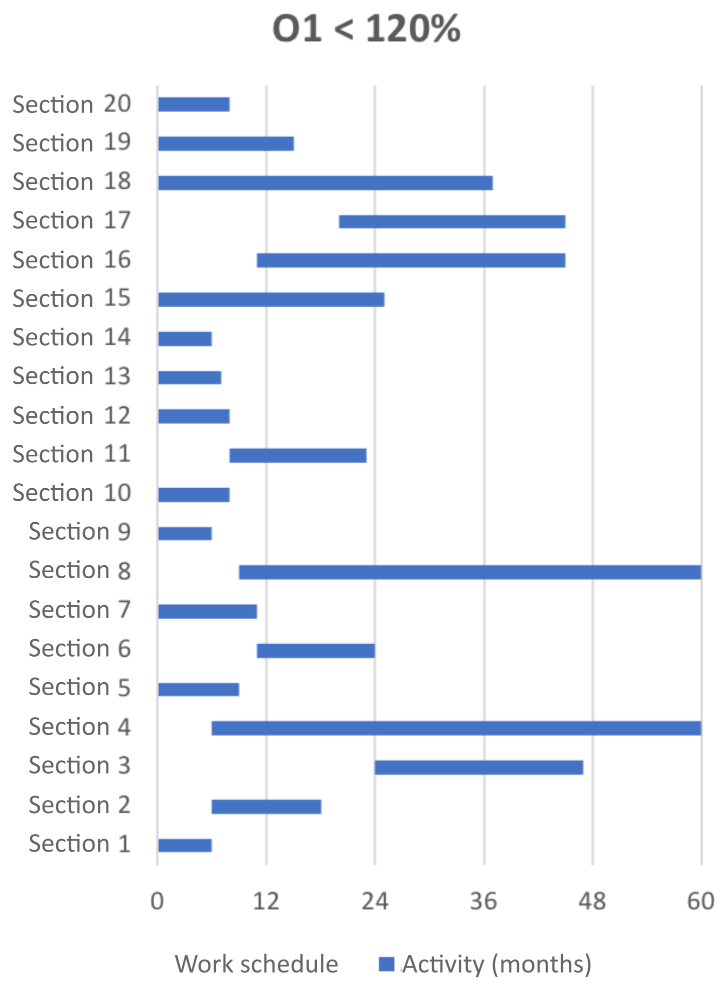

Figure 2 Gantt chart for solution $\min O_3$ with $O_1 < 120\%$.

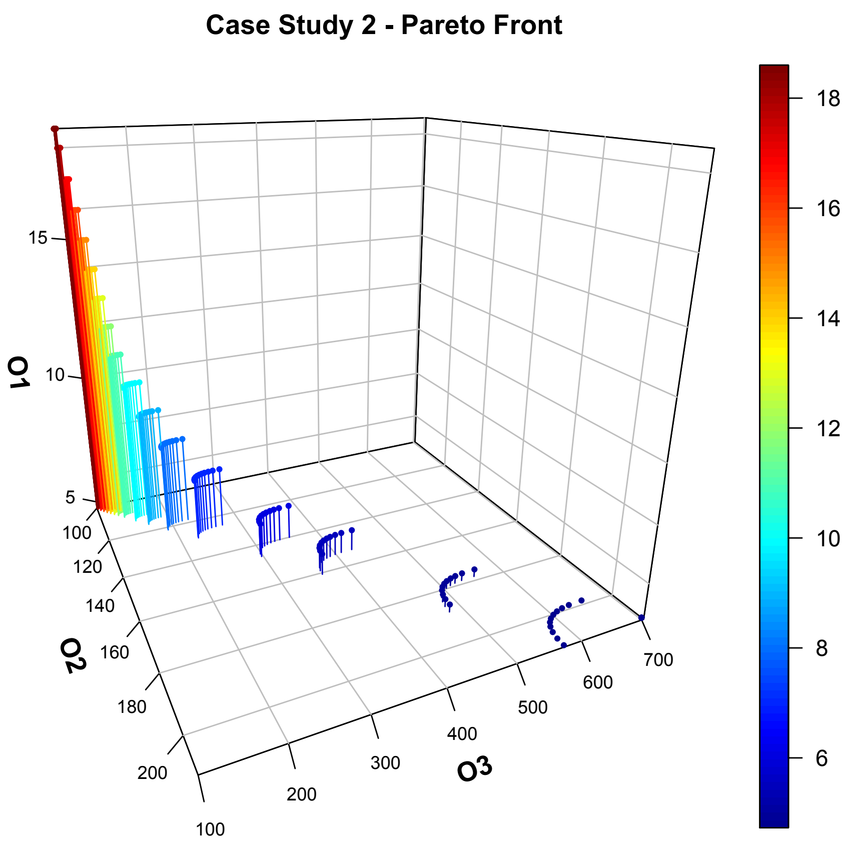

Figure 3 Results for the large-sized instance.

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