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A simulation-based approach for the optimal design of signalling block layout in railway networks

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ABSTRACT

To meet the growing demand in railway transportation, practitioners are more and more required to upgrade or substitute the signalling system in order to increase the capacity of the network. Existing approaches for the design of the signalling layout, usually tend to maximize the technological efficiency of the system by shortening the length of block sections, thus reducing the minimum line headway and the energy consumption but increasing investment costs. This paper presents a design approach addressed to identify the signalling layout which minimizes the investment and management costs, while respecting the required level of capacity. To solve this problem an innovative design framework is introduced which integrates a stochastic multi-train simulation model within a "black-box" optimization loop. Results obtained from an application to a real metro line confirm the effectiveness of such method in finding the solution which minimizes total costs for the line manager. A comparison with the block layout which maximizes the technological efficiency highlights that the obtained solution constitutes a satisfying trade-off between total costs and network performances.

1. Introduction

Nowadays practitioners in the field of railway systems need to identify adequate design solutions to satisfy international recommendations on quality of service, energy consumption and above all to meet the growing demand for passengers and freight transportation. Currently, these topics are considered as the main objectives of a European project called ON-TIME [1] which involves the most prominent railway undertakings, infrastructure managers and universities of several European countries.

In certain cases the adoption of optimized timetables that maximizes the exploitation of system capacity [18,19] is not enough to accomplish the requirements for minimum line headway (that ask for the achievement of a certain threshold for the maximum capacity of the network). In this case interventions on the infrastructure layout and/or the signalling system are necessary. Modifying the network layout can be very expensive especially when dealing with underground lines, that is why upgrades or substitutions of the signalling system are usually preferred. In practice given a certain technology, the signalling layout is commonly designed according to an approach of "maximum technological efficiency" which tends to achieve the maximum level of capacity that can ever be obtained for a certain signalling technology. In scientific literature, different approaches have been proposed for metro lines that are mainly addressed to identify the configuration of the signalling system (i.e. the design solution) that minimizes line headway (i.e. maximize network capacity) and/or train energy consumption. The major shortcoming with all these approaches is related to their tendency to minimize the length of block

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sections, consequently increasing the number of blocks and the investment costs for their installation. High investment costs are indeed an obstacle to the practical realization of the system, especially when only limited funds are available. Another drawback is that candidate signalling layouts are evaluated disregarding the factors that are mainly responsible for degrading the capacity, the punctuality and the energy efficiency of the system, i.e.: the stochastic disturbances to operations and the interactions among trains on the network. The performances relative to each design solution are indeed assessed by considering that only a single train runs on the network (without the presence of other trains) in undisturbed conditions (i.e. no random perturbations).

To this purpose, the present paper introduces an approach for designing railway signalling systems under stochastic conditions, which aims at identifying the layout of block sections that minimizes the overall costs for both installing and managing the system, while respecting technical requirements relative to the maximum network capacity. This design problem is solved by employing an innovative framework which integrates a stochastic multi-train microscopic model for simulating railway traffic with a "black-box" optimization algorithm called OptQuest/Multi-Start. In this way a simulation-based optimization loop is obtained, that consents to assess the effects of design solutions taking into account the interactions amongst trains as well as random disturbances to operations, as it is in the reality.

The main contributions that this paper intends to give are:

- Automatizing the current design process of railway signalling layout, that is mainly manual, by using an advanced tool that automatically generates candidate signalling layouts by means of an optimization algorithm and evaluates their performance via simulation of railway traffic.
- Addressing the design of railway signalling layout to a different objective that is no more to get the maximum capacity possible for a given signalling system, but to minimize the total costs over the whole system lifecycle while satisfying technical requirements on network capacity.
- Overcoming the limits of the approaches proposed so far in literature, by developing a simulation-based optimization framework that evaluates candidate signalling layouts considering both the interactions among all scheduled trains and the effects of stochastic disturbances to train operations (e.g. unplanned extensions of dwell times at stations).
- Showing by means of an application to a real case-study, that important advantages in terms of investment and management costs are obtained when the signalling layout is designed by using the proposed method instead of the typical approach used in current practice.

The paper is organized as follows: Section 2 gives a review on scientific approaches proposed in literature for the optimal design of signalling systems. Section 3 explains the problem of designing the layout of railway signalling describing the current practice and the proposed approach to maximize the economic efficiency while respecting technical constraints on capacity. Section 4 depicts the developed framework. In Section 5, the application to a real mass rapid transit line is illustrated and results are compared with those returned by employing the typical approach used in current practice, for the same case study. Conclusions and final comments are reported in Section 6.

2. Literature review

2.1. Simulation–optimization and its applications in railways

Simulation-based optimization stands for a programming problem (usually stochastic) whose objective function is evaluated by means of an experimental simulation. Due to the complexity and the stochasticity considered within the simulation, the objective function is (i) usually subject to several levels of random noise, (ii) not necessarily differentiable, and (iii) expensive to evaluate from the computational standpoint. It is intuitive that simulation–optimization problems can be intractable if the optimization problem has a large number of variables and/or the simulation involves many parameters and many interactions to be described. The mathematical formalization and the computational complexity of optimizing via simulation is clearly described in some work of Fu [2,3]. The same author provides moreover an extensive state-of-the art relative to the most advanced mathematical techniques used to solve simulation-based optimization problems. Specifically the following main approaches can be enlisted:

- *Sample average approximation* mainly considers a set of samples that is large enough in order to turn back the stochastic problem into a deterministic-like one. Of course this does not mean that the simulation–optimization problem becomes deterministic but that this can be solved by means of tools usually used for non-linear programming or even convex optimization if possible. Due to the random noise in input to the simulation model, it happens that two different solutions of the search space can have a similar value of the objective function. This limitation, typical of stochastic optimization problems, complicates the convergence of the algorithm towards the optimal solution. When applying the sample average approximation approach, the convergence of the optimization algorithm is generally improved by enlarging the number of samples, since in this way it is reduced the effect of the random noise in the input parameters. For more information it is possible to refer to the works of Homem-de-Mello et al. [4] and Kleywegt et al. [5].