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Supporting the design of railway systems by means of a Sobol variance-based sensitivity analysis

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ABSTRACT

Recently the growing demand in railway transportation has raised the need for practitioners to improve the design of railway systems. This means to identify a configuration of the infrastructure components (e.g. number of rail tracks, type and layout of the signalling system, layout of station tracks) and the operational schedule (e.g. train headways, scheduled dwell times) that improves given measures of performance such as the level of capacity, the punctuality of the service and the energy saving.

Planners and designers involved in this process have the hard task of determining sound design solutions in order to achieve certain levels of network performances in a cost-effective way, especially when investment funds are limited. To this aim, a sensitivity analysis can support early decisional phases in order to better understand dependencies between performances and design variables and drive the decisional process towards effective solutions.

In this paper, the Sobol variance-based method is applied to this purpose. A practical application has been carried out for a mass transit line in the city of Naples. Such study has investigated how train delays and energy consumption are affected by variations in design variables relative to the operational plan, the signalling system and factors related to the layout of station platforms. Results highlight the ability of this analysis in explaining the effects of different design solutions from a statistical point of view and finding the most influential factors for a given performance. This aspect suggests to practitioners the usefulness of this approach in addressing decisions towards cost-effective interventions.

1. Introduction

Recently railway operators and infrastructure managers are more and more involved in decisional activities which strongly aim at attaining higher performance levels of railway networks in terms of increased capacity, reduced energy consumption as well as improved robustness and stability of operational plans and the infrastructure layout. In particular these issues have gained a wide relevance to face the massive increase that railway demand has had in the last years. For this reason these topics are currently considered amongst the main objectives of a European research project on railway systems (called ON-TIME: Optimal Networks for Train Integration Management across Europe, www.ontime-project.eu), supported by the 7th European Framework Programme, in which many of the most prominent railway undertakings, infrastructure managers and universities from different EU member countries are directly involved.

The variables of a design problem are called *decisional variables* or *design parameters* and are represented by characteristics of the service plan and/or the infrastructure that need to be modified to improve a given measure of performance. For

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instance, in the case of railway systems, the level of network capacity can be increased by changing decisional variables such as the train headway, the scheduled dwell time at stations or also the layout of station tracks, the length of block sections and/or the technology of the signalling system (e.g. installing an ETCS level 1 instead of a multi-aspect system where trains brake by respecting consecutive signals that progressively impose more restrictive speed limits). When a value or a configuration is attributed to each one of the decisional variables, this set of values/configurations represents a solution to the design problem and is named *design solution*. Actually, the practical implementation of a design solution always implicates an investment of a certain amount of resources which can be intellectual, economic or both. In turn, such solution should also ensure that the desired improvement of network performances is attained, by employing the least amount of resources (or it should guarantee a satisfying trade-off between performance levels and investments) in order to pursue the classical economic principle of maximizing benefits while minimizing costs. This matter assumes particular importance especially when funds available by involved stakeholders are restricted, as more and more is happening nowadays. Anyway, identifying a cost-effective design solution is not an easy task to perform, since a deep analysis of the problem is required to understand: (i) which are the measures of performance to deal with, (ii) which is the gap between actual and desired performance levels, and above all (iii) which decisional variables actually need to be designed in order to achieve the requested standards in a cost-effective way. The answer to this last question is usually quite hard to find and needs a wide comprehension of how the performance(s) to improve is (are) sensitive with respect to different design variables; that is to understand how these latter affect a certain network performance, and to what extent the variability of this performance can be apportioned to such variables. In this way, it is possible to improve a certain measure of performance by addressing the interventions only on those variables which mostly condition it, without wasting resources for acting also on parameters that instead are non-relevant for that performance. In this sense, a similar approach can lead to cost-effective design solutions.

To this purpose, this paper illustrates the application of a variance-based sensitivity analysis which aims at identifying for a railway network how certain performances are sensitive to variations of different design parameters. In particular the case of a real Mass Rapid Transit line in the urban area of Naples (called "Cumana" line) is examined to understand how train delays and energy consumption are influenced by design parameters relative to: the signalling system (length of block sections and type of system), the operational plan (service headway) and to factors regarding characteristics of station platforms (in terms of average and standard deviation of station dwell time distribution). The scope of this paper is not addressed to determine a cost-effective design solution for improving a performance, but to show how a mathematical application of a consolidated technique like the Sobol one, is able to reveal input–output relationships also for complex systems, explaining statistical dependencies as well as effects on network performances due to the interactions among design parameters. This study consents to have a wider comprehension of the behaviour pattern concerning the system and allows to identify which parameters are of key relevance for a certain network performance. During preliminary design stages, this information can be very useful to practitioners in order to drive intervention decisions also for achieving cost-effective solutions. Since the Sobol method is based on a Monte-Carlo framework, an "own-built" microscopic simulation model of railway networks (called EGTRAIN) is used in this study to accurately evaluate the impacts induced on performances by variations in input parameters.

Section 2 gives a brief description of the techniques for sensitivity analysis available in literature and an overview on the applications in the field of railway systems. A detailed illustration of the Sobol variance-based method is provided in Section 3. Section 4 shows features of the "own-built" microscopic model used to evaluate the effects of systematic changes in input parameters, while Section 5 describes the application to the Cumana line, illustrating the relative results. Final comments, and conclusions are presented in Section 6.

2. Literature review

2.1. Methods for performing sensitivity analysis

Sensitivity analysis is defined as the study of how the variation in the outputs (measures of performance) of a certain system can be attributed to different variations in the inputs (decisional variables) of the system itself (Saltelli et al., 2004, 2008).

Several methods and techniques to perform sensitivity analysis are available in literature and among the most used it is worth mentioning: input/output scatter-plots, sigma-normalized derivatives, standardized regression coefficients, elementary effects, and variance-based techniques. In the following a brief description of the first four methods is given while a more detailed explanation of the variance-based technique is provided in Section 3, since this is used in this paper. For the interested reader a deep examination of each method can be found in Saltelli et al. (2008).

2.1.1. Input/output scatter plots

This is a graphical method where the sensitivity of a given output with respect to different inputs is evaluated by means of a visual examination of its scatter plots against each one of the inputs considered.

Let the system under investigation be mathematically represented as:

$$Y = f(Z_1, Z_2, \ldots Z_r), \tag{1}$$