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Simulation-based multi-objective system optimization of train traction systems

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ABSTRACT

A holistic framework for multi-objective optimization of the traction system configuration of trains with mixed-integer decision variables is presented. Rail vehicles have to be energy-efficient and must be operated on a tight schedule. Furthermore, the number of decision variables to fulfill these objectives is large, and some components (like motors and gears) can only be chosen from a small set of discrete elements. In this work, the overall optimization is achieved by a two level approach: The Pareto front of optimal system configurations is obtained by a multi-objective mixed-integer elitist genetic algorithm (GA) on the upper-level. To capture the influence of a specific system configuration on travel time and energy consumption, a suitable train trajectory optimizer is developed and employed in the lower-level. The train trajectory optimization is solved by sequential quadratic programming (SQP) and considers the power losses of the different components. A case study is presented which highlights the benefits of the holistic multi-objective optimization.

1. Introduction

Rail vehicles have to fulfill multiple conflicting objectives. They have to be cost-effective, but at the same time energy-efficient and must be operated on a tight schedule. Furthermore, the number of decision variables in the design phase to fulfill these objectives is large and some components like motors and gears can only be chosen from a small set of discrete elements, whereas others like the input chokes can be produced with arbitrary parameters.

Up to now much effort has been put into time table and speed profile optimization for given rail vehicles, and there exists a variety of long and well tried software products. Particularly the speed profile optimization problem has a long history with many different solution approaches. Li and Gao [1] introduced a model that can well describe the dynamic behavior of the train movement under the moving block condition. But, finding the best system configuration with respect to the multiple conflicting objectives by simulating each system configuration's performance with individually optimized speed profile has not been applied yet. However, simulation-based system optimization has already been successfully applied to many different engineering problems. Figueira and Almada-Lobo [2] provide a taxonomy that aims at giving an overview of the full spectrum of current simulation–optimization approaches. The purpose of the study is to guide researchers who want to use one of the existing methods and create a standard for a better communication in the scientific community.

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For multiple conflicting objectives multi-objective evolutionary algorithms (MOEAs) are well suited because due to their population-based approach they can find a number of trade-off solutions in one iteration. Deb et al. [3] introduced the famous non-dominated sorting-based MOEA, called NSGA-II which has found many applications. A variant of NSGA-II is implemented in MATLAB^{TM}.

In [4] a numerical model is developed by evolving an efficiency prediction code for the pre-design of radial turbines. The efficiency prediction code includes the mean-line calculations associated with an optimizer based on the NSGA-II version of MATLAB^{TM}. In [5], an optimization analysis of the thermally regenerative electrochemical cycle system is conducted for different heat source inlet temperatures with maximum power output and exergy efficiency as the objective functions. The problem is solved by the NSGA-II version of MATLAB^{TM}. Also Kamjoo et al. [6] use the NSGA-II algorithm in the design of a standalone hybrid renewable energy system comprising wind turbine, photovoltaic panel and battery bank. The aforementioned works have in common that integer constraints are not treated. In this work the algorithm has been adapted to handle mixed-integer variables as well.

Chen et al. [7] introduce a wind farm layout optimization method. A multi-objective genetic algorithm with mixed discrete real integer string is used to represent the wind turbines' positions, types and the hub heights simultaneously. The presented work utilizes mixed-integer decision variables to represent the traction system's component respectively parameter configuration. In [8] a constrained, multi-objective problem (solved by NSGA-II), with mixed-integer variables, from the building design domain is presented. However, unlike in the presented work, a two level optimization with an optimized input trajectory applied to a dynamic simulation model in the lower-level is not performed.

In [9] a framework coupling EnergyPLAN (an analytical simulation model for energy systems) with a MOEA is presented. The framework of this work couples an analytical energy simulation model for the rail vehicle's electrical drive energy to a multi-objective optimization for the component configuration. Thereby optimized input trajectories are applied to the energy simulation model.

In [10] the so-called configuration problem is addressed using simulation associated with a distributed evolutionary algorithm, and it is illustrated through an example from the area of manufacturing system design. The authors conclude that the limitations of this approach are in the development of simulation models, which have to provide the capability of switching from one option to another. In this work, the developed dynamic rail vehicle model utilized by the train trajectory optimizer (lower-level optimizer) fulfills this necessary specification.

For tandem cold rolling in [11] a multi-objective optimization problem is formulated to optimize energy efficiency and damage simultaneously. The authors claim that the obtained Pareto front enables the mill operators to select the most appropriate optimized schedule. Analogous to these objectives, with the presented multi-objective framework Pareto fronts can be obtained and utilized to select the most appropriate traction system configuration according to energy efficiency and traction power (i.e. travel time). This is enabled by the train trajectory optimizer (applied in the lower-level), which is capable of providing the values of these two objectives for each system configuration.

Multi-objective optimization is also applied to optimize the design and operating strategy of electric vehicles. In [12] a multi-objective optimization methodology is applied on hybrid electric vehicles in order to define the optimal powertrain configurations of the vehicle, estimate the cost of the powertrain equipment and show the environmental impact of the technical choices on the lifecycle perspective of the vehicle. Also in the performed case studies of this work (Section 5.3) investment costs (of the traction system) and energy consumption are chosen as objectives. Therefore, here too the obtained optimal trade-off solutions can be utilized as a sound foundation for computing realistic life cycle costs. For a subway vehicle in [13] NSGA-II is utilized to perform a multi-objective optimization of its gradual energy-absorbing structure. Only continuous decision variables are defined. In [14] an applied methodology for multi-objective optimum sizing of hybrid electric vehicle (car) components is developed. However, unlike in the presented work, a true multi-objective optimization is not performed. Instead a weighted sum method is applied. In [15] an optimal driving strategy for electric vehicles powered by batteries is proposed. Energy consumption, acceleration duration, and jerk are considered as objectives. Pareto-optimal fronts are obtained using NSGA-II. However, the effects of (Pareto) optimal system configurations on the aforementioned objectives are not investigated.

In this work the optimal train trajectory (speed profile) is obtained in the lower-level. For electric trains recent works started to consider the electrical net energy required for traction and the influence of regenerative braking on the optimal train trajectory. Martinis and Gallo [16] proposed models and methods to optimize speed profiles in suburban areas with and one without energy recovery systems. Albrecht et al. [17,18] discuss the problem of finding an energy-efficient driving strategy for an undulating track with steep grades subject to a maximum prescribed journey time. The aforementioned works have in common that they do no consider the operating point dependent power losses of the traction system components in the optimization. Furthermore, a multi-objective optimization was not performed.

Domínguez et al. [19] develop a detailed simulator of the train motion and use it for design of optimal Automatic Train Operation (ATO) speed commands for the ATO equipment implemented on line 3 of the Madrid Underground. A variable efficiency model of the traction system as a function of the train speed and the ratio between the required and the maximum force is included. Domínguez et al. [20] use the aforementioned model to design optimal ATO speed profiles taking into account the regenerative energy and the total net energy consumption in substations. A network model for calculating the total energy recovered as well as a model of a train with an on-board energy storage device is presented to calculate a realistic network receptivity. The authors analyze several realistic case studies for the Madrid Underground to assess the achievable energy savings due to possible investments and optimal design of ATO speed profiles. Because the updated