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Transportation Research Procedia 3 (2014) 651 – 659
Transportation Research Procedia
www.elsevier.com/locate/procedia

17th Meeting of the EURO Working Group on Transportation,

EWGT2014, 2-4 July 2014, Sevilla, Spain

Short-term rail rolling stock rostering and maintenance scheduling

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Abstract

This paper describes an optimization framework for railway rolling stock rostering and maintenance scheduling. A key problem in railway rostering planning requires covering a given set of services and maintenance works with limited rolling stock units. The problem is solved via a two-step approach that combines the scheduling tasks related to train services, short-term maintenance operations and empty runs. A commercial MIP solver is used for the development of a real-time decision support tool. A campaign of experiments on real-world scenarios from Trenitalia (Italian train operating company) illustrates the improvement achievable by the approach when compared to the practical solutions.

Selection and peer-review under responsibility of the Scientific Committee of EWGT2014

Keywords: Railway Planning and Policy · Transit Assignment · Rolling Stock Rostering · Maintenance Scheduling

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1. Introduction

This work addresses identification and analysis of a framework for optimizing short-term maintenance planning and rolling stock rostering. Rolling Stock Management (RSM) is a main cost factor for Rail Undertakings. In order

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Selection and peer-review under responsibility of the Scientific Committee of EWGT2014
doi:10.1016/j.trpro.2014.10.044

to reduce the costs due to railway operations, every company should address the joint problem of rolling stock rostering and maintenance scheduling since they are strongly related parts of the same problem. Maintenance optimization can be a key factor to increase the productivity of railway companies. At the same time, in a competitive globalized and multimodal market, RSM is one of the competitiveness key factor because services quality level depends on it. The strategic relevance of RSM, in particular of maintenance scheduling, is thus due to the reduction of needs (such as platforms and human resources) and to the enhancement of quality standards (such as vehicle reliability and cleaning). The problem to cover a given set of train services and maintenance works is a key problem in railway planning process.

The main objective is typically the minimization of the number of rolling stock units, while secondary objectives are to minimize the number of empty runs and to maximize the distance travelled by each train between two maintenance operations of the same type. First, the rostering and maintenance optimization problems are formulated by a graph theoretical approaches that involve short-term maintenance operations, the scheduling tasks related to train services and empty runs are studied by Giacco et al. (2012). The constraints of the maintenance optimization problem require that the different types of maintenance operations must be carried out for each train periodically. The various maintenance tasks can only be done at a limited number of dedicated sites. Starting from the solutions of the rostering and maintenance optimization problems, another graph theoretical approach is adopted to optimize workshop management and in particular to minimize the number of drivers involved and to verify the feasibility of the maintenance plan at each site have been addressed by Giacco et al. (2012-2013-2014). For a set of timetables and rolling stock categories, flexible versus rigid plans are compared in terms of empty runs and train services defined in each timetable.

For different feasible frameworks and different kinds of timetables, we evaluate mixed-integer linear-programming (MIP) formulations for train rostering and maintenance scheduling problems. The following questions are addressed: “How can the timetable be executed by an efficient use of resources such that the overall railway company costs are reduced? Which is the maximal improvement that can be achieved? At which cost?". We give an answer to these questions by performing an assessment of key performance indicators.

The computational evaluation presents the efficiency of the new solutions compared to the practical solutions. Experimental results on real-world scenarios from Trenitalia show that the optimization approach can reduce significantly the number of trains and empty runs when compared with the current plan. We use a commercial MIP solver for developing a decision support tool that computes efficient schedules in a short time.

2. Literature review

The railway industry is huge source of problems that can be modeled and solved by using Operations Research techniques. Many of these are still handled without automation and optimization. Such problems exist in several forms and arise at different levels in the planning process for a railway company. The complete railway system managing is highly complex and it is often divided into a lot of sub-problems which are interconnected. Given an objective to achieve, a very difficult task is to understand what problems are involved and how they are related. Interesting surveys and research works on railway planning have been presented by Abbink et al. (2004), Alfieri et al. (2006), Ahuja et al. (2005), Cacchiani et al. (2010-2012), Caprara et al. (2011), Cordeau et al. (1998), Hansen and Pachl (2008), Huisman et al. (2005), and Lingaya et al. (2002). From our point of view, the literature is too focused on manufacturing setting in order to reduce the occurrence of a failure, while unfortunately the coordination of maintenance and rolling stock scheduling is still under investigated. We next discuss some relevant publications addressing the rolling stock rostering and railway maintenance planning problems.

2.1. Rolling stock rostering

Given the departure and arrival times as well as the expected numbers of passengers, rolling stock circulation deals with the assignment of locomotives and carriages to the timetable services, while rolling stock rostering focuses on the assignment of a roster to each individual train unit. The latter problem should include rolling stock maintenance operations in the roster. Several objective criteria can be considered that are related to operational costs, service quality and reliability of the railway system. The problem calls for determining for each trip the locomotive types and their number, and the carriage types and their number. These quantities are related with the maintenance problem. In fact in a sparse network it is necessary to take into account the maintenance operations and build a schedule for them; on the contrary, in a dense network, the maintenance operations can be handled easily.

Ramani and Mandal (1992) developed an optimization-based decision support system that aims at minimizing fleet size. Locomotives and cars are treated separately and equipment switching is not considered. Bussieck et al. (1997) surveyed mathematical programming methods for public rail transport planning. The authors state that the problem of assigning rolling stock to a set of scheduled trains can be formulated as a multi-depot vehicle scheduling problem and present a review of several papers on that subject. Cordeau et al. (2000-2001) proposed an optimization system for an equipment cycling problem. This model is solved by a Benders decomposition (2000) and a column generation approach (2001) embedded in a branch-and-bound search. Brucker et al. (2003) propose an optimization approach for routing of railway carriages. Fioole et al. (2006) focused on the problem to determine the rolling stock circulation for a generic week. They deal with an extension of the problem described by Peeters and Kroon (2008). In Cadarso and Marín (2011), a rolling stock and train routing problem is addressed. The rolling stock subtask is to assign material to satisfy the timetable of a railway network, while the train routing subtask is to determine the best sequence for each material. Since the combined problem is not solvable by commercial solvers, they propose a new heuristic based on Benders decomposition. The objective function is to minimize a cost-based function related to commercial train services, empty movements, shunting and passengers in excess. In Cadarso and Marín (2012) a rolling stock and timetable joint model is studied, this context has permitted to study a recovery problem with rapid transit rail network disruption (Cadarso et al., 2013). The latter analytical approaches do not model short-term maintenance operations and do not evaluate their cost impact.

2.2. Railway maintenance planning

The maintenance management is an important function of most industrial and service organizations. In the specific case of high-speed trains, a considerable amount of the lifecycle costs is spent for maintenance operations. To increase the productivity, railway companies are putting a great deal of effort into maintenance optimization. Preventive maintenance is undertaken to keep equipment in a specified condition. The scheduling of maintenance activities is an important topic since smart scheduling would allow to reduce the overall budget for maintenance. Maintenance activities include safety aspects and cleaning operations, and are required to conserve the original conditions of each resource, for example by compensating the wear of the rolling stock asset or of the railroad infrastructure. Rolling stock maintenance is a major area of railway management in which optimization could be helpful to increase productivity and service quality, and to be competitive in a global market place.

Sriskandarajah et al. (1998) have developed a genetic algorithm for the optimization of maintenance overhaul scheduling of rolling stock with some maintenance planning considerations. Five years later, Penicka et al. (2003) introduced a formal model of the train maintenance routing problem. However, they do not address the rostering problem with maintenance constraints. Furthermore, they observe that the joint study of rostering and rolling stock maintenance is appropriate for long-distance trains only. Mároti and Kroon (2005) presented a mixed integer formulation for the maintenance routing problem in which the shunting process is considered the process bottleneck. Budai et al. (2006) discussed the preventive maintenance scheduling problem and the minimization of the time required for performing maintenance operations. The heuristic algorithms compute nearly optimal solutions by combining maintenance activities on each track. Wang et al. (2007) proposed a multiple criteria decision-making problem and evaluated maintenance strategies for different equipments. The problem is formulated as an integer program and a branch and bound algorithm is used for its resolution.

3. Problem description

The rolling stock rostering and railway maintenance planning problems are mainly solved separately. So the links between the two problems are often neglected. This work focuses on the interaction between them. The rolling stock rostering problem focuses on train units and deals with the design of rosters to cover given scheduled services. The general goal is to minimize the cost of the rolling stock assignment. The maintenance planning problem focuses on maintenance workshops and consists of scheduling preventive maintenance operations for each rolling stock unit after a certain number of kilometers or hours, depending on the train schedule and rolling stock type.

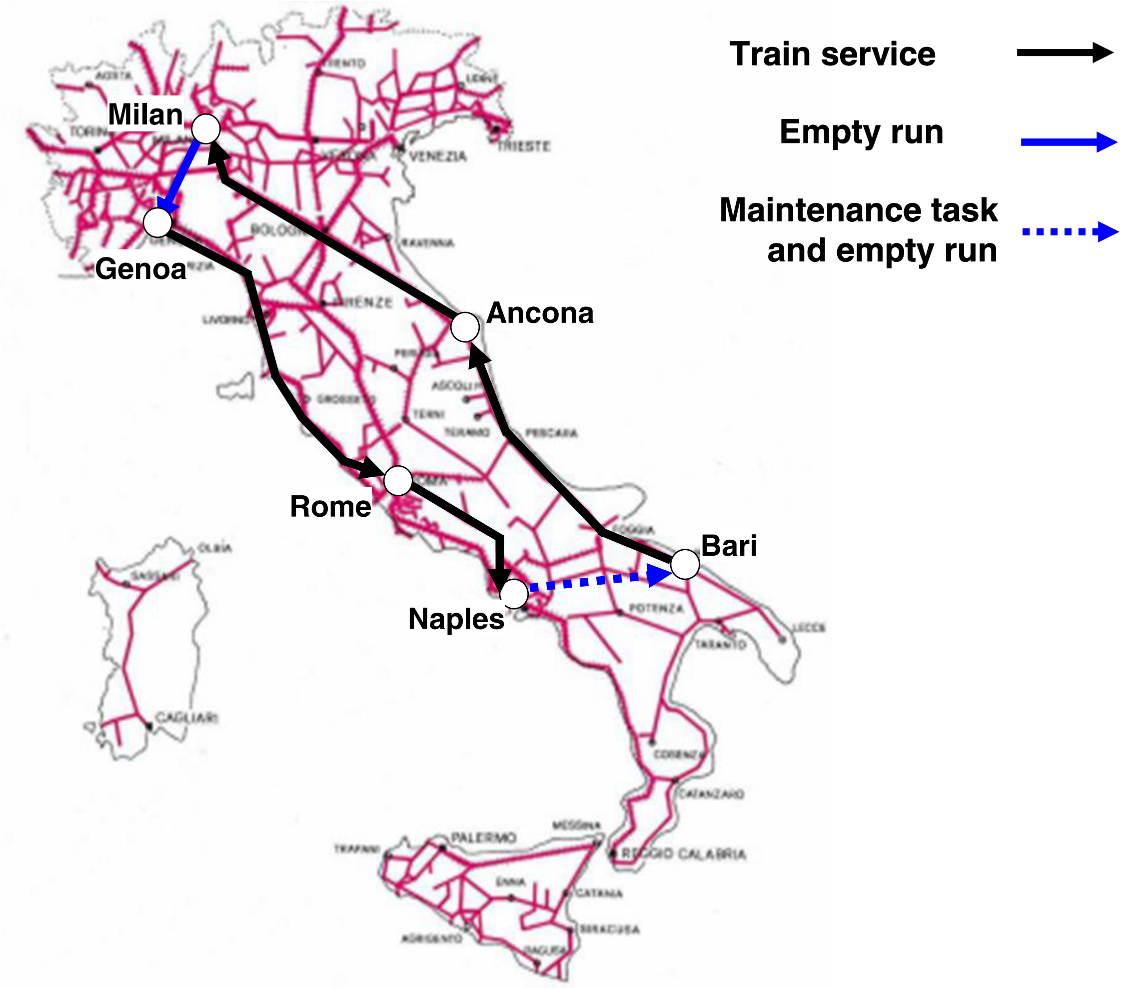

Figure 1 – The Italian railway network and an example of a roster

This paper studies a general problem with special attention to the rolling stock and maintenance constraints of interest for Trenitalia. The Italian railway network is shown in Figure 1. However, in this paper we focus on high-speed lines only. Besides the 1350 km of lines equipped with ERTMS technology (source RFI, December 2013) high speed trains travel on other lines at lower speed, e.g., on the lines between Genoa and Rome or between Bologna and Bari. We consider a macroscopic description of railway traffic flows in a large railway network. The network is composed by a number of tracks and stations. A train route is a path between two given stations, with a specific travel time. A train service i is a route from a departure station d_i at departure time t_{di} to an arrival station a_i at arrival time t_{ai} that must be covered by a specific train. A roster is a cycle spanning over several working days that covers all the services and the required maintenance tasks. Figure 1 shows the Italian railway network and an example of a roster with four services (Bari→Ancona; Ancona→Milan; Genoa→Rome; Rome→Naples) and two empty runs (Milano→Genoa and Naples→Bari), the latter of which includes maintenance operations in the Naples workshop. The roster, however, may include other maintenance operations performed at some stopping station, e.g., in Rome between the two services Genoa→Rome and Rome→Naples.

We assume that the same timetable is repeated every day. In other words, we consider a cyclic timetable and do not study its variability e.g. in case of high/low demand days. With this assumption, finding a roster spanning over k days allows to cover all services in a day with k trains, since all services can be covered with k trains that repeat the same roster, each one scheduled one day after the previous one.

4. Framework

The problem is solved through a two-step approach: the rostering problem for each asset unit type is solved in the first step and provides input data for the maintenance scheduling problem. We next briefly describe each module and the models developed in Giacco et al. (2012-2013-2014) to solve it.

4.1. Rolling stock rostering approach

The rostering problem is to compute a rolling stock roster that covers a set of commercial services and minimizes the costs related to the asset units, including the empty runs. Specifically, this module optimizes the distance run by asset units of various types between consecutive maintenance operations. We suppose the timetable is cyclic and the assignment of asset units to commercial services follows the principles defined by Trenitalia. As described in Giacco et al. (2013), the rolling stock rostering problem corresponds to find a Hamiltonian cycle on a graph made by commercial services (nodes) and by feasible pairs (edges), representing service or maintenance activities to be provided. The main cost components to be taken into account in the rostering problem are associated to the number of asset units needed to cover a set of services plus the amount of empty runs and maintenance operations. The former one is usually considered the most important, and therefore the rostering problem has been formulated as a traveling salesman problem with additional constraints and variables. In order to guarantee the respect of maintenance expiry and to guarantee efficiency with respect to the two latter cost components, additional constraints may force the optimal solution of the rostering problem to be at least as efficient as the solutions currently in operation with respect to all cost components. The output is a cyclic roster including the schedule of maintenance activities. Specifically, for each maintenance activity a time window of [minimum starting time, maximum completion time] to be satisfied by the associated location.

Figure 2 shows the graph representation of the roster shown in Figure 1. In the model in Figure 2, train services are nodes, each labeled (from left to right) with origin and destination stations, departure and arrival times. Arcs are used to sequence train services and to include possible maintenance operations and empty runs between two consecutive services, besides possible waiting times in the station. Each arc (*i*,*j*) is weighted with the number of days needed between the end of service *i* and the end of service *j*, the weight being zero if the two services can be performed in the same day. In the solution in Figure 2, the train starts, for example, with the service Genoa→Rome, after which there are about four hours and half that can be used for some maintenance operation in Rome. Then, the train performs the service Rome→Naples, which can be completed within the same day. Since the next service starts in Bari, an empty run is needed to reach Bari. In this case the time elapsed between the two services allows some further maintenance operation to take place in the Naples workshop. Then, after the service Bari→Ancona, the train waits for three minutes on the platform in Ancona and continues with the service Ancona→Milan. Eventually, it moves from Milan to Genoa with an empty run.

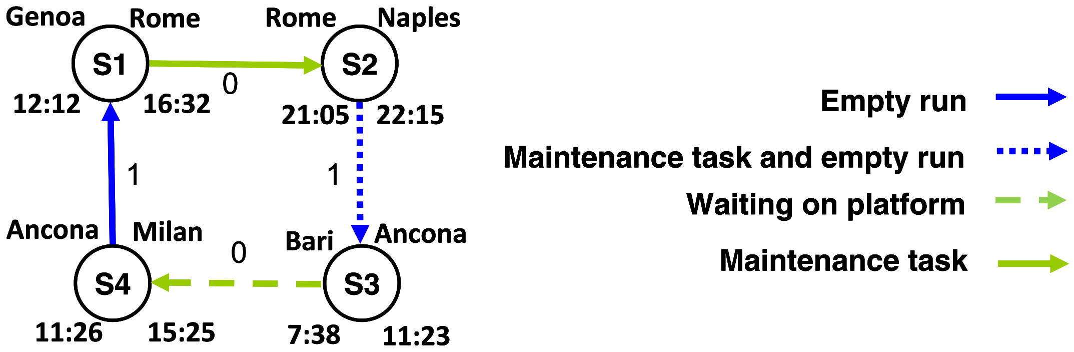

Figure 2 – The graph model for the roster in Figure 1

4.2. Station and workshop scheduling

A maintenance site is where maintenance work is performed and can coincide with a station or not. Each maintenance site is dedicated to specific types of maintenance work, such as: interior or exterior cleaning, refuel (only for diesel units), regular inspection, repair (scheduled or not) and technical check-up. Each type of maintenance task must be performed regularly, i.e. within a maximum time limit or a maximum number of kilometers from the last maintenance of the same type. Since performing some maintenance task too often would cause an unnecessary cost for the company, each type of maintenance task should be performed in the proximity of its maximum limit. The Naples workshop is one of the key points of the Italian railway system for several maintenance services, in particular for high speed trains. Other workshops are, for example, in the areas of Rome and Milan. Figure 3 shows the layout of the Naples workshop, which is the one studied in this work. It consists of various indoor/outdoor tracks for light maintenance, wheel profiling, washing, cleaning, inspection and other services.

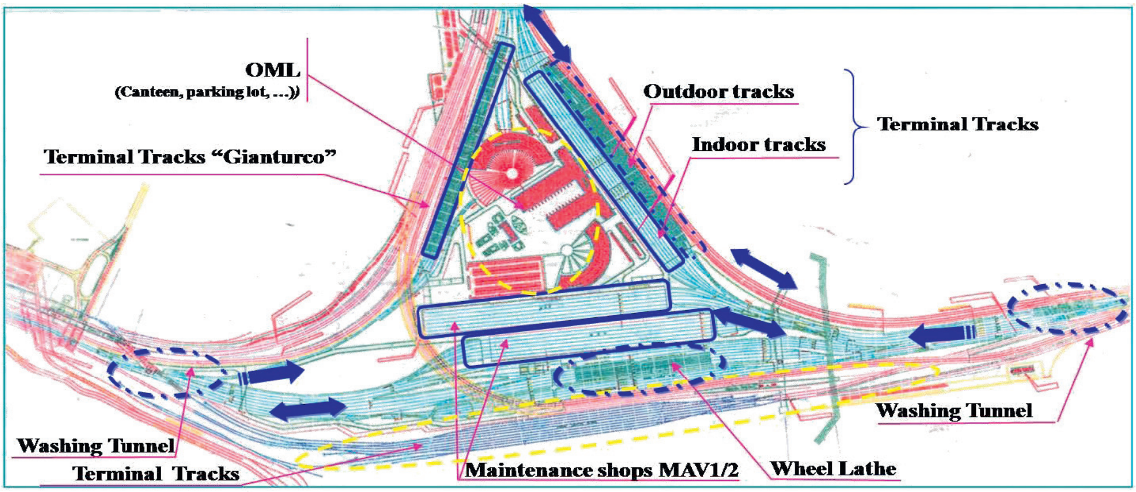

Figure 3 - Naples workshop layout

Maintenance operations have to scheduled in passenger station and workshop. There are constraints on the maintenance activities that have to be performed by each train and on the time windows that are defined in the rolling stock rostering plan. A workshop must manage the assigned asset units within the assigned time windows for the maintenance operations specified by the solution to the rostering problem. However, the solution should be robust enough, to be able to absorb small perturbations of the circulation. To this aim, the time windows are usually larger than the sum of all activities to be performed, so that some recovery time is available. Sometimes, the workshop acts as a space buffer to store trains between consecutive services since passenger stations may have no space available to receive trains too early with respect to the scheduled departure time, so that trains often have to be moved within the workshop until they can be released to the passenger stations. For this reason, the objective function adopted in this work is the minimization of the number of train movements in the workshop area. As for the model structure, the workshop scheduling problem can be viewed as a job shop scheduling problem with routing flexibility and other additional constraints, including release times and deadlines for the operations, limited buffer space and constraints on the transportation network, which limits the feasible routes for a given job (we refer the interested reader to D'Ariano et al. (2007) and Corman et al. (2009-2010-2011-2012-2014) regarding some literature on job shop scheduling applied to railway transportation problems). Giacco et al. (2014) introduced a formulation of this type for the maintenance scheduling problem at a dedicated site. The latter paper shows that a commercial solver is able to solve practical-size instances of this problem in a few minutes, so the proposed formulation can also be adopted to compute good quality solutions in real-time.

5. Computational results

This section presents a set of computational experiments on real-world cases from the Trenitalia timetable of year 2011. Practical rosters are considered and the studied problems are solved via CPLEX MIP solver 12.0.

5.1. Description of the instances

Table 1 gives information on five practical timetables (Column 1). The first four timetables (T1–T4) are based on real cases, and will be compared with the practical solutions, while the fifth timetable (T5) is hypothetical, and has been created to test the computational limits of the tested approach. Specifically, T1 uses locomotives only, while the other four (T2-T5) utilize different types of high speed trains.

For each timetable scenario of Column 1, Table 1 presents the following information. Column 2 shows the rolling stock categories. Specifically, T1 uses locomotives only while the other four (T2-T5) utilize different types of high speed trains. For each category, Columns 3 shows the number of train services scheduled in the timetable. Column 4 gives the number of railway cars, Column 5 the total length of each car (in meters), and Column 6 the deadline of its maintenance works (in kilometers).

Table 1 Description of the train services scheduled in each timetable

Timetable Scenario	Rolling Stock Categories	Num Train Services	Railway Cars	Total Length [m]	Maintenance Deadline [km]
T1	Loco E444	46	1	17	>>1500
T2	ETR 485	20	9	237	1500
T3	ETR 600	26	7	237	1500
T4	ETR 500	78	11	328	1500
T5	ETR 600+500	104	18	237/328	1500

5.2. Results on the rolling stock rostering problem

Table 2 presents the computational results on the five timetables (Column 1). Column 2–3 describe the practical solutions in terms of the number of empty runs and train services defined in each timetable. To compare the optimal solutions with the practical ones, Column 4 shows the results when the maximum number of empty runs is fixed to the same value used in practice (i.e. the value shown in Column 2). Differently, Columns 5–6 report on the solutions obtained when the empty runs are flexible and are treated as additional variables that can be selected in a range of [0, 10] values.

For the set of experiments with fixed empty runs, the average computation time of CPLEX is around 10 seconds. In case of flexible empty runs, the average computation time of CPLEX is around 1 minute for T1, T2, T3 and T4, while T5 requires around 7.5 minutes.

Table 2 Assessment of the practical and optimal solutions

Timetable Scenario	Practical Solution		Optimal solution: Fixed empty runs	Optimal solution: Flexible empty runs	
	Empty Runs	Train units	Train units	Empty runs	Train units
T1	0	26	25	9	20
T2	0	9	8	0	8
T3	0	10	10	0	10
T4	8	40	38	10	35
T5	8	50	48	10	42

Computational results in Table 2 show relevant potential application of the proposed formulation for improving the current practical solutions. For timetables T1, T2 and T4, the optimal solution also compares favorably with the practical roster. A total reduction of up to 4 trains is needed to cover all services. Another observation is that the model with a fixed number of empty runs performs worst than the model with a window of min-max values for the empty runs. This is due to the additional flexibility added in the latter model that is able to reduce the necessary rolling stock. When relaxing the constraint on the empty runs, the maximum gain is obtained for timetable T1 for which the optimal solution with flexible empty runs presents a 23% reduction in the number of trains needed to cover all services.

5.3. Results on the short-term maintenance problem

The optimal solutions provided by CPLEX have been compared with the practical plans developed at a Trenitalia's maintenance site located in Naples. Based on an extensive analysis of 100 working days, the comparison with the practice shows that in around the 96% of all instances CPLEX is able to compute a better solution with respect to the one adopted in practice. In the remaining 4% CPLEX achieves the same solution. As for the improvement achieved by CPLEX, the number of savings with respect to the practice is often between 2 and 3 train movements (around 42% and 38% respectively), while a reduction of 1, 4 or 5 movements is achieved in a smaller number of instances (around 13%, 1% and 1%).

6. Conclusions

This paper evaluates a two-step approach for optimizing rolling stock rostering and short-term maintenance planning. The rolling stock rostering problem is to find a minimal cost Hamiltonian cycle in a graph with service pairings, empty runs and maintenance tasks, while the maintenance scheduling problem is to find a viable schedule at each maintenance site respecting the constraints given by the rolling stock rostering solution. Computational results on a commercial MIP solver show a thorough assessment of timetables and rosters. The proposed approach is considerably effective in reducing the company costs compared to the practical solutions, both with and without considering flexibility of rail operations.

Future research will be dedicated to the study of objective functions directly related to the monetary costs of rostering, maintenance and empty runs, representing the preferences of the railway company. Open issues are related to balance the use of resources when routing trains in wide-networks and to the limit the workload for the maintenance operators. Additional research directions should also be focused on developing methods for acyclic timetables and advanced algorithms for complex and large instances. For instance, relaxing the sub-tour elimination constraints could be used to compute lower bounds to the optimal solution of the rostering problem.

Acknowledgments

This work was partially supported by the Italian Ministry of Research, Grant number RBIP06BZW8, project FIRB "Advanced tracking system in intermodal freight transportation". Preliminary versions of this work have been published in Giacco et al. (2012-2013-2014).

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