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Optimizing train loading operations in innovative and automated container terminals

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Abstract: In this paper the problem of optimizing the train loading operations in innovative automated freight terminals is addressed. In particular, the considered terminal is supposed to be provided with an innovative transfer system allowing to load/unload containers in a fast and horizontal way under the electric line. In these terminals, the timing of the train loading process is crucial, together with the necessity of maximizing the number of containers to be loaded on the train. An optimization problem is stated for determining, while taking into account some specific constraints, the optimal loading plan in order to maximize the number of containers loaded and minimize the set up operations necessary for adapting wagons configurations to the various containers to be loaded. Besides the use of optimal algorithms, a heuristic procedure is also defined for solving the proposed optimization problem. The comparison among the two approaches shows very close performances both in terms of computational time and solutions quality.

1. INTRODUCTION

As universally recognized, rail freight transportation provides a competitive alternative to road transport due to its capacity of moving big quantity of cargo in a more sustainable way. However, rail transport is characterized by a much higher degree of complexity than road one in terms of organization and technologies, with the consequent limitation of its growth. For such reason, adequate emphasis must be put on the methodologies devoted to modelling and optimizing such transportation mode. As provided by [1], numerous research works attempted to plan intermodal freight transportation systems at different decision levels (i.e. strategic, tactical, operational). In [5] the authors distinguish among three levels of planning and control in making decisions to obtain an efficient terminal: the strategic, tactical and operational level. The authors present an overview on decision problems arising at the three different levels. Other recent surveys are [6] and [3] focused on operations research methods applied to container terminals; the authors divide the developed optimization approaches according to the different processes in a seaport terminal: ship planning (i.e. berth allocation, stowage planning and crane split), storage and stacking planning, and transport optimization (divided in quayside, landside, and crane movements). With respect to this classification, this work is devoted to landside transport optimization and presents an optimization approach for the definition of loading plans for trains.

As highlighted in [6], a loading plan indicates on which wagon a container has to be placed; this decision generally depends on the destination, type and weight of the container, the maximum load of the wagon and the train composition. Also the container location in the storage area can influence the loading plan. Moreover, the loading plan concerns operational decisions that obviously are affected by strategic and tactical ones regarding both how the interterminal transport of containers has been organized (that is the handling equipment for the storage area and for the trains) and how the stowage area is managed (i.e. the stowage strategy used).

In the literature, few research studies have been devoted to the load planning problem and these studies are referred to landside intermodal terminals rather than to seaports. In [7] the load train is considered as a subproblem when decomposing the scheduling problems arising during operations of a transshipment yard.

In [8] the authors consider a terminal where containers are transferred to and from trucks on a platform adjacent to the rail tracks provided with a short-term storage area; they propose several techniques for defining the assignment of containers to slots of a train while minimizing container handling time and optimizing the weight distribution of the train. They solve the load plan problem considering only one type of container and without including in the model weight restrictions for the wagons. In a following work [9] they include more types of containers and the objective regards the minimization of the train length. Moreover, in [10] the authors present a comparison among different train loading policies (namely sequential loading, non sequential loading and intermediate combinations) by also varying the stacking strategies in the terminal yard.

The objective of this paper is to state and solve the train loading problem, for a railway terminal provided with an innovative intermodal system, such as the Metrocargo one. This system is patented by an Italian transportation company and permits to quickly move containers on/from trains. This can be achieved by loading cargo units on wagons in a horizontal way and directly under the electric line, so significantly reducing the total handling time and - consequently - the related costs.

The paper is organized as follows. In Section 2 the considered problem is presented. The optimization problem and the heuristic approach are reported in Section 3 and Section 4, respectively. Section 5 highlights the results obtained by the two different approaches and, finally, some conclusions are drawn in Section 6.

2. DESCRIPTION OF THE SYSTEM

The objective of the present paper is the operational planning of an automated railway terminal, such as the Metrocargo system, whose features and benefits are extensively presented in [11]. The main objectives of this innovative system is to increase the freight traffic quota transported by rail, by simplifying and accelerating rail transport operations, so allowing to reduce environmental pollution and social congestion as well.

In traditional intermodal solutions, terminals are off line and highly time consuming shunting operations are needed in order to pull trains towards terminal yards. On the contrary, the system under consideration allows to load/unload trains with automated "shuttles" and automated storage areas directly under the electrical track in a sort of "buttonhole" parallel to the main rail track, which permits to extraordinarily decrease the total train handling time.

The efficiency of a railway terminal is measured by different parameters, the main of which are represented by the speed of loading and unloading operations in addition to the filling capacity of the train. So, the objective of the present work is to maximize the train loading while minimizing the number of changes of the configurations of wagons, that is, the number of movements of the so-called "pins" of train wagons, and respecting some other constraints. In fact, depending on the types of containers that must be loaded on the train, the pins configurations changes, that is, a certain number of pins have to be changed.

The resulting problem is a multi-objective problem with cost objectives that are not homogeneous with the consequent difficulty of attribution of the correct weights in the objective function. So, in order to make the problem mono-objective (maximization of the train loading), the second objective (minimization of the number of pin changes) has been transformed in a configurable constraint of maximum number of pin changes. This also has the advantage of reducing the space of feasible solutions and therefore makes more efficient the achievement of the optimal solution.

Such pins represent projections of the wagon that must be raised for security matters in case of the loading of a container and, vice versa, must be lowered in order to allow the positioning of containers whose length extends above the position of the pins.

Constraints are related to the load configurations related to the specific wagons, referring to the maximum axial weight on wagons and the maximum weight of the train. The types of container considered in the study are the following: 20', 30', 40' and 45'. It should be noted that 30' and 45' containers are loaded into the 20' and 40' slots, respectively, thus using the same pin configuration. However, the additional length related to 30' and 45' containers in respect to 20' and 40' load units, imposes to leave empty slots adjacent to them. For a better understanding about this aspect, refer to Fig. 1 where the red "x" indicate the slots that, when loading a 30' or 45' container, must necessarily remain empty. This means that, for example, if a 30'container is loaded on the central 20' slot of a 3 TEU wagon, it is not possible to load any other container on that wagon (wagon number 1 of Fig. 1). If a 30' container is instead loaded into a lateral slot, the central one will have to remain empty, while the remaining side slot may be loaded with a 20' or a 30' container (wagons 2 and 4 of Fig. 1). Similarly, a 45' containers loaded in a 40' slot does not allow to load a 20' containers on the same wagon (Wagon 3 of Fig. 1).

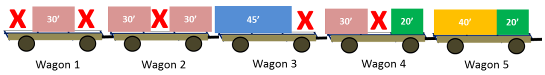

Fig. 1. A possible assignment wagons-containers

Fig. 2) shows the load and weight configurations of a particular type of wagon used on the Italian railway network. More specifically, it shows six different load configurations permitted by the particular wagon concerned. To be able to switch from one configuration to another during the loading of the train, it is necessary to lowering/raising a certain number of pins. The following table shows the number of pin changes required to move from one configuration to another for wagon SGNS (which is a particular type of wagon used by Italian Railways). For example, to switch from the first to the fourth load configuration, it is necessary to handle 8 pins: 6 of these must go down (blue circles in Fig. 2) and 2 must be raised (red circles).

In order to take into account all the possible load and weight configurations, it has been chosen to calculate weight constraints based on lever principles instead of rail wagon tables (like the one in Fig. 2), which also derive from the application of these principles. To better clarify lever principles, it is possible to refer to Fig.2 of [2], where the levers of container c1 and c2 (e1 and e2, respectively) are calculated as the distance between their center of gravity (which is supposed to be in the center of the container) and the attack of one of the two bogies (it is noted that the levers containers are calculated in reference to the same bogie). Furthermore, the distance d between the bogies is known and it is assumed that the tare of the wagon is equally distributed on its two bogies.

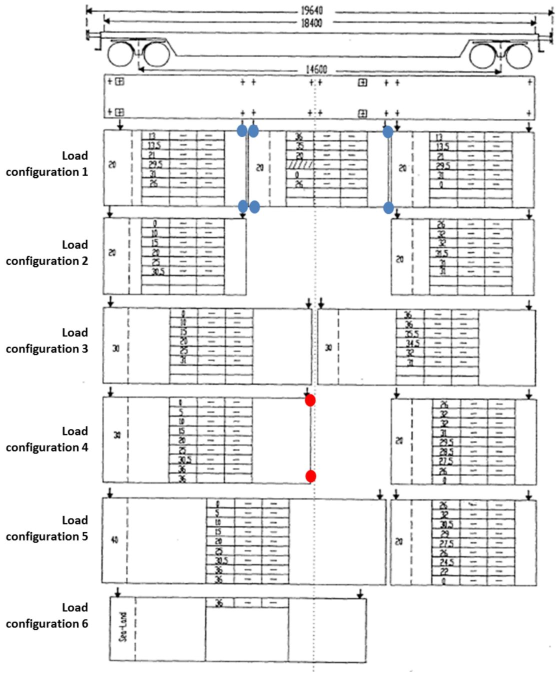

Fig. 2. Wagons-Containers assignments according to the different container types.[13]

These formulas allow to evaluate load configurations settings for each wagon and each configuration positioning of containers and always meet the configurations shown in rail tables as the one shown in Fig. 2.

In order to define the optimal loading plan of the train, two types of methods have been addressed: optimal and heuristic approach. The first involves the formulation and resolution of a mathematical model that allows to reach an optimal solution of the problem; the latter regards the definition of an heuristic algorithm whose efficiency will be compared with the one provided by the optimal formulation.

3. THE MATHEMATICAL MODEL

In this section we want to state the optimization problem whose objective is the optimal train loading plan in automatic terminals. In particular, the decisions to be taken represent the assignment of containers to wagon slots with the final goal of maximizing the train loading and taking into account some specific constraints, firstly the minimization of pin changes.

Let us introduce the following notation:

- C is the number of containers in the stocking area;
- W is the number of wagons;
- S is the number of train slots;
- $\mathcal{S}_w$ is the set of possible slots for wagon $w = 1, \ldots, W$;
- ω_i is the weight of container $i = 1, \ldots, C$ (expressed in tons);
- l_i is the length of container $i = 1, \ldots, C$ (either 20', 30', 40' or 45');
- π_i is the priority of container $i = 1, \ldots, C$, (due for instance to commercial reasons);
- μ_s is the length of slot $s = 1, \ldots, S$ (either 20' or 40');
- $\overline{\omega}_w$ is the weight capacity of wagon $w = 1, \ldots, W$;
- $\overline{\Omega}$ is the weight capacity of the train;
- d_w is the distance between the bogies attachments of wagon w;
- γ_w is the maximum payload for each bogie;
- t_w is the weight of wagon w (tare);
- e_s is the lever of slot s;
- B_W^0 is the initial load configuration;
- B_W is the load configuration set for wagon w;
- $P_{w,b}^0$ is the number of pins needed to pass from the initial configuration B_W^0 to configuration b.

Besides, for the implicit formulation, we need the following new auxiliary variables:

- a_w, representing the payload of bogie a for wagon $w = 1, \ldots, W$;
- b_w, representing the payload of bogie b for wagon $w = 1, \ldots, W$.

Finally, let us introduce the following decision variables:

- $x_{i,s} \in \{0, 1\}$, $i = 1, \ldots, C$, $s = 1, \ldots, S$, with $l_i = \mu_s$, equal to 1 if container i is assigned to slot s and 0 otherwise (note that only $x_{i,s}$ variables for slot-container pairs with the same length are generated);
- $f_{w,b} \in \{0, 1\}$, $w = 1, \ldots, W$, $b \in \mathcal{B}_w$, equal to 1 if weight configuration b is chosen for wagon w and 0 otherwise.

The problem can be stated as follows.

Model

$$\max \sum_{i=1}^{C} \pi_i \cdot \omega_i \cdot l_i \cdot x_{i,s} \tag{1}$$

$$\sum_{s=1}^{S} x_{i,s} \leq 1 \qquad i = 1, \ldots, C \tag{2}$$

$$\sum_{i=1}^{C} x_{i,s} \leq \sum_{b \in \mathcal{B}_w} f_{w,b} \qquad w = 1, \ldots, W \quad s \in \mathcal{S}_w \tag{3}$$

$$\sum_{b \in \mathcal{B}_w} f_{w,b} = 1 \qquad w = 1, \ldots, W \tag{4}$$

$$a_w - \sum_{i=1}^{C} \sum_{s \in \mathcal{S}_w} \omega_i \frac{d_w - e_s}{d_w} x_{i,s} = \frac{t_w}{2} \qquad w = 1, \ldots, W \tag{5}$$

$$b_w - \sum_{i=1}^{C} \sum_{s \in \mathcal{S}_w} \omega_i \frac{e_s}{d_w} x_{i,s} = \frac{t_w}{2} \qquad w = 1, \ldots, W \tag{6}$$

$$a_w \leq \gamma_w \qquad w = 1, \ldots, W \tag{7}$$

$$b_w \leq \gamma_w \qquad w = 1, \ldots, W \tag{8}$$

$$a_w - 3b_w \leq 0 \qquad w = 1, \ldots, W \tag{9}$$

$$b_w - 3a_w \leq 0 \qquad w = 1, \ldots, W \tag{10}$$

$$\sum_{i=1}^{C} \sum_{s \in \mathcal{S}_w} \omega_i \cdot x_{i,s} \leq \overline{\Omega}_w \qquad w = 1, \ldots, W \tag{11}$$

$$\sum_{i=1}^{C} \sum_{s=1}^{S} \omega_i \cdot x_{i,s} \leq \overline{\Omega} \tag{12}$$

$$\sum_{w=1}^{W} \sum_{b \neq B_W^0} f_{w,b} P_{w,b}^0 \leq n \tag{13}$$

$$x_{i,s} \in \{0,1\} \qquad i = 1,\dots,C \quad s = 1,\dots,S \tag{14}$$

$$f_{w,b} \in \{0,1\} \qquad w = 1,\dots,W \quad b \in \mathcal{B}_w \tag{15}$$

The objective function (1) takes into account the maximization of the number of containers loaded giving priority to those with higher length (l), weight (ω_i) and priority (π_i). Constraints (2) ensure that each container is assigned to at most one slot, while constraints (3) make sure that in a slot no more than one container is loaded, taking into account the load configuration chosen. A load configuration is chosen for each wagon thanks to the constraint (4). The control of weights on wagons is assured by constraints (5) - (10). More specifically, constraints (5) and (6) define the value of variables a_w and b_w, i.e. the weight supported by the two wagon bogies; constraints (7) and (8) avoid the exceeding of the maximum weight allowed on each wagon bogie in order to take into account the specific characteristics of wagons and of the railway infrastructure. Finally, constraints (9) and (10) define the ratio between the loads on the two bogies (the weight on a bogie must not exceed three times the weight on the other bogie). The fulfilment of the maximum weight allowed for each bogie and for the entire train is guaranteed by constraints (11) and (12), respectively. The compliance with the maximum allowed number of pin changes is given by constraint (13). Finally, constraints (14) and (15) define the decision variables of the problem.

It is emphasized that the maximum number of pin changes represents a parameter and may therefore be modified from time to time in order to take into account of particular operating conditions. For example, in cases of extreme urgency and when loading operations must be performed in the shortest possible time, this parameter can be brought to zero, thus imposing to leave unchanged the previous configuration of pins on the train. Conversely, in the situation where the time factor is not decisive, but instead it is important to maximize the loading of the train, this parameter can be set great as required, seeking in this way the pin configuration that allows to maximize the number of containers loaded.

4. THE HEURISTIC APPROACH

The heuristic here proposed belongs to the category of GRASP (Greedy Randomized Adaptive Search)[12] or meta-heuristic algorithms commonly used for combinatorial problems. The GRASP typically consists of iterations made starting from successive constructions of a solution using a randomized sorting and subsequent improvements of the solution obtained through a local search. The randomized solutions of "greedy" type are generated by adding to the solution built items from a list ordered according to a priority index. In order to obtain a certain variability in the collection of candidate greedy solutions, chosen items are often placed in a more restricted list of candidates (also known as RCL - Restricted Candidate List) and randomly selected during the construction of the solution. More specifically, the heuristic used for this problem can be divided into two parts that are cyclically iterated:

(1) Algorithm 1: generation of a load configuration for the whole train (X);
(2) Algorithm 2: evaluation of the solution previously obtained by allocating - always heuristically - containers to slots following a particular sorting.

At the beginning, the first solution (X_0) is generated using, as load configuration, the one initially provided (which is determined by the initial pin configuration) and then, through a local search algorithm applied to the load configuration, new solutions are generated and tested.

Algorithm 1 generates the first solution that will be then evaluated through algorithm 2 (that will be later explained in detail); wagons are later sorted in an ascending way in respect to their value - obtained in output by the solution evaluation algorithm - and one of the three wagons is randomly chosen. Then, the load configuration of the chosen wagon is randomly changed (for instance, if a wagon was prepared to accommodate three 20' containers, changing the load configuration it may host a 45' container). So, the new solution obtained is estimated: if it is acceptable from the point of view of the maximum allowable number of pin changes, then the latter solution is maintained and it is verified if the value of its objective function is greater than the best objective function so far obtained. Otherwise, namely the solution is not acceptable, the previous feasible solution is restored and the algorithm begins again. After a certain number of iterations that do not improve the solution ("not improving" iterations), the algorithm stops.

Algorithm 1 is defined in the following.

Algorithm 1 Generation of a load configuration

```
Initialize X = X_0
(Feasible, Value, WagonsValue) = Eval(X)
Initialize BestVal = Value, BestSol = X
Sort(WagonsValue)
WagonChosen = WagonsValue[Random(1, 3)]
CC[WagonChosen] = Rand(1, numCfg)
(Feasible, Value, WagonsValue) = Eval(X)
if (Feasible) then
    if (Value > BestVal) then
        BestVal = Value; BestSol = X;
    end if
else
    Restore Previous X
end if
```

Algorithm 2 describes the procedural steps made in order to evaluate the generated solution. It starts by comparing a load configuration with the initial one, calculating the number of pin changes required. If this number is greater than the one permitted, then the solution chosen assumes value equal to zero being not feasible; otherwise, the allocation of containers to slots is made. The containers loaded are evaluated on the basis of their contribution to the objective function ($length * weight * priority$) and sorted in a decreasing way. For their assignment, the first container of this list is considered and a sequential loading of the train is carried out starting from the first slot of the first train wagon. It is then searched for the slot to which assign the container, which must have the following requirements:

- free (not yet assigned to any container);
- used by the load configuration chosen;

- with a compatible length.

So, weight constraints are verified through the conditions imposed by the lever; if so, the assignment of the container to the slot is carried out and the next container to be loaded is considered. If not, the next slot is tried. It is tried to load the container as long as there are slots available on the train, otherwise the container will not be loaded. At the end of the algorithm, containers that have not been loaded are revived out and it is tried to load them again for one time: in fact, it is possible that a container (such as a very heavy one) has not been assigned to any slot due to lever constraints but subsequently, with other containers allocated, such assignment is permitted. The output provided by this procedure is represented by the assignment of containers to train slots and by the value of wagons.

Algorithm 2 is defined in the following.

Algorithm 2 Evaluation of a solution

$PinChanges = CalculatePinChanges \quad (X, X_0)$
if $PinChanges > MaxPinChanges$ **then**
  $return(notfeasible, 0, 0)$
end if
$Sort(CntrList)$
$TotTrainWeight = 0$
while $CntrList.Count > 0$ **do**
  $Cntr = CntrList.First$
  for $(Slot \quad s)$ **do**
    if $s\ is\ freeAND\ s \in Cfg\,(s.wagon)\ AND\ s.length = Cntr.length$ **then**
      if $(CheckLeverConstr(Cntr, s) = OK\ \ AND\ \ TotTrainWeight + Cntr.Weight <= MaxTrainWeight)$ **then**
        $Assign(Cntr, s)$
        $TotTrainWeight = TotTrainWeight + Cntr.weight$
        $CntrList.remove(Cntr)$
        $Value = Value + Cntr.weight * Cntr.length * Cntr.priority$
        $WagonsValue[s.wagon] = WagonsValue + Cntr.weight * Cntr.length * Cntr.priority$
      end if
    end if
  end for
end while
$return(feasible, Value, WagonsValue)$

5. COMPARISON AMONG THE OPTIMAL SOLUTION AND THE HEURISTIC ONE

In order to clarify the solution methods described above as well as to validate the proposed two approaches, a certain number of instances have been tested. More specifically, the objectives of this section are to assess the sensitivity of the solution by varying the number of pin changes and to compare the optimal solution of the mathematical model with the heuristic. Each instance is identified by:

- "Train composition": trains are composed of certain number of wagons, with a total maximum weight load.
- "State of containers in the yard": ideally, they are all to be loaded on the train. For all the generated instances, it has been assumed to have 100 containers available in the yard: in the boundary case, and in case of a train composed of 17 wagons, if all the containers are 20' empty containers (i.e. non-binding weights), a maximum of 51 containers (3 TEUs per wagon) may be loaded.

The instance generator developed uses the following data (expressed in tonnes):

- weight of a 20' container: (Min,Max,Empty) = (12,24,2.6)
- weight of a 30' container: (Min,Max,Empty) = (15,30.5,3.0)
- weight of a 40' container: (Min,Max,Empty) = (16,32,3.7)
- weight of a 45' containers: (Min,Max,Empty) = (17,34,4.2)

Moreover it uses the following parameters (configurable):

- number of containers;
- % of 20', 30', 40' and 45' containers;
- % of empty containers;
- % of wagons with pins in configuration ♯1 (namely the probability for a wagon to have pins in configuration number 1 in the initial state), ♯2, ♯3, ♯4, ♯5, and ♯6;
- number of wagons;
- maximum weight of the train.

Three classes of instances have been generated, considering 17, 22 and 30 wagons per train respectively.

For each class, ten instances have been considered and for each instance both the mathematical model and the heuristic have been evaluated by varying the maximum number of pins allowed; four cases have been therefore hypothesized: 0, 10, 20 and 30 pin change allowed, respectively.

By analyzing the average values (over the 10 instances considered) obtained for class 1 it can be stated that, as expected, the value of the objective function of the mathematical model is always higher or equal to the corresponding value of the heuristic. However, the percentage differences are minimal, namely 0.97%, 2.31%, 2.20%, 0.82% in case of maximum allowed number of pin changes equal to 0, 10, 20 and 30 respectively.

It is also noted that by increasing the maximum number of allowable pin changes, the value of the objective function increases as well, because it enlarges the solution space. In other words, the possibility of varying the wagons load configurations allows to find more favorable combinations depending on the available containers and their characteristics. Regarding the average number of containers loaded on the train, the heuristic loads a higher number of containers in case of maximum number of pin changes equal to 20 and 30, although with a total lower value (calculated as the product of length, weight and priority) compared with the mathematical model, as underlined by the value of the objective function. Even in this case, however, the percentage differences between the model and the heuristic are negligible: 5.15%, 1.62% , −1.63% , −2.02% in the case of a maximum allowed number of pin changes equal to 0, 10, 20 and 30 respectively.

Moreover, by increasing the maximum number of allowable pin changes, the containers loaded on the train (mainly those of 45' type) increase and, consequently, the relative value of the objective function.

Finally, a computational analysis has been carried out with the goal of testing the efficacy of both the approaches proposed. For each instance class, four different cases have been studied regarding the maximum number of pin changes (namely 0, 10, 20 and 30). Then, for each combination "instance class"-"number of maximum allowable pin changes", 10 instances have been generated.

By comparing the model and the heuristic on the average value of the objective function for the three classes considered, it is obtained that, by increasing the number of wagons constituting the train, it also increases the value of the objective function because more containers can be loaded. However, the gap between the model and the heuristic performance is minimum in the first class ($-0,14\%$) and this is due to the fact that the degrees of freedom are fewer than in the other two classes.

The comparison between the model and the heuristic regarding the objective function value by varying the maximum allowable number of pin changes shows that by increasing the maximum number of pins that can be varied, the objective function value increases because there are more degrees of freedom for maximizing the train loading. Also in this case the gap between the model and the heuristic assumes the minimum value ($-0,03\%$) in the first class.

Table 1 represents in more detail the differences obtained between the model and the heuristic; generally it can be said that the two approaches provide very close results.

# of wagons	Maximum # of pin changes	Model	Heuristic	gap %
17	0	39151,53	39146,33	-0,01%
	10	53447,95	52591,63	-1,60%
	20	60499,79	59408,53	-1,77%
	30	63605,30	62842,19	-1,19%
22	0	50465,97	50424,37	-0,08%
	10	64237,61	63209,85	-1,67%
	20	70436,02	68012,31	-3,54%
	30	73771,85	71933,84	-2,59%
30	0	56901,60	56901,60	0,00%
	10	71344,47	68742,70	-3,61%
	20	80601,14	75264,25	-6,60%
	30	86021,78	80734,56	-6,08%

Table 1. Comparison among the mathematical model and the heuristic.

Finally, it is worth noting that computational times are not here reported being very low (around one second) both for the mathematical model resolution and for the heuristic one, as well as for all the instances considered.

6. CONCLUSIONS

The train loading plan of an automatic rail terminal has been the objective of the present paper, where the terminal under study is an innovative freight rail terminal in which containers can be quickly loaded and unloaded on/from trains under the electric line and in an horizontal way. More specifically the goal concerns the maximization of the train loading while satisfying a certain number of constraints, first of all the wagons loading configurations, which can be varied by moving the so-called wagon "pins".

Both a mathematical model and an heuristic have been defined and implemented in order to solve the problem and an experimental campaign has been carried out with the goal of comparing the two approaches. The results obtained have shown that, if the mathematical model is able to provide the optimal solution, the use of the heuristic, which provides very close solutions to the optimal ones in very quick times, is definitely to be preferred when a commercial solver is not available.

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