Order-based Freight Transportation Operation Planning in Railway Networks

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Abstract. In this paper we propose a planning procedure for serving freight transportation requests (i.e. orders) in a railway network in which the terminals are provided with innovative transfer systems. We consider a consolidated transportation system where different customers make their own requests for moving boxes (either containers or swap bodies) between different origins and destinations, with specific requirements on delivery times. The decisions to be taken concern the path (and the corresponding sequence of trains) that each box follows over the network and the assignment of boxes to train wagons, taking into account that boxes can change more than one train during their path and that train timetables are fixed. This planning problem is divided in two sequential phases: a preprocessing analysis for which a specific algorithm is provided and an optimization phase for which a mathematical programming formulation is proposed. The effectiveness of the proposed procedure is tested on a set of randomly generated instances.

1 Introduction

This work deals with the definition of a planning procedure for a centralized decision maker that must provide a transportation service to different customers by using an available railway infrastructure. The transportation demand from customers is given by a set of orders characterized by a certain number of boxes (in general of different types), an origin, a destination and time delivery specifications. The transportation offer is a railway network in which the number of trains, their schedules and paths are fixed. This railway network is innovative since the terminals are supposed to be equipped with rapid (horizontal) transfer systems for containers and swap bodies. This implies that a container can move from an origin to a destination terminal by changing different trains on its path, as it happens to passengers. Moreover, a peculiar characteristic of the proposed approach is that boxes of the same order can follow different paths on the network.

In the literature it is possible to find many planning approaches for intermodal transportation systems involving modelling and optimization techniques, that can be classified according to the considered planning level, i.e. strategic, tactical and operational, as it is deeply described in [1] and [2]. The problem faced in this paper can be considered as an operational problem combining two important decision aspects. The former

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decision concerns which path a box must follow on the network and in which terminals it must change the train. This aspect is also treated in tactical problems, i.e. service network design problems, as described in [3], in which the optimal paths are searched for aggregated cargo flows instead of single load units as in the present paper. The latter decision aspect deals with the assignment of boxes to wagons of the trains selected to transport them. This aspect has been treated in [4], where rapid transshipment yards are considered as in the present paper; moreover, in [5] a load planning problem, i.e. the assignment of containers to train slots, is treated. In addition, differently from [6] and [7], we assume the train scheduling and routing as given and fixed. Therefore, the problem described in this paper provides a new approach for a planning procedure in a railway network with rapid rail-rail transfers, in which, for each box, the decisions to be taken concern the route to cover, the trains and the wagons to be placed in. Even though all these aspects have been already treated in various works that can be found in the literature, the main novelty of this paper (a preliminary version of this work can be found in [8]) stands in the consideration of all these decision aspects together.

The planning procedure is divided in two sequential phases, so that the output data of the former phase are input data of the latter. In the former phase, called *preprocessing*, each order is considered separately: by taking into account the network structure, the timetables and routes of trains, the origin, destination and time requirements of orders, all the sequences of trains that can be used for serving the boxes of the considered order are computed. In the latter phase, called *optimal assignment*, the assignment of each box to a train sequence and to a wagon of the trains composing the sequence is obtained by considering all the sequences of trains for each order and by taking into account some specific data about boxes and wagons. This is the result of a specific mathematical programming problem.

These two phases of the proposed planning procedure are described, respectively, in Section 2 and in Section 3. The effectiveness of this procedure is then verified with some experimental tests reported in Section 4. The conclusions and future developments of the work are then described in Section 5.

2 Preprocessing

The railway network is described by means of a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ where nodes represent railway terminals and links are railway connections between terminals. The input data of the preprocessing are referred to nodes of the network, a set $\mathcal{R}$ of trains and a set $\mathcal{O}$ of orders:

δ_n fixed cost for handling one box at terminal $n \in \mathcal{N}$
ρ_n hourly cost for the storage of one box at terminal $n \in \mathcal{N}$
Nl_r number of links covered by train $r \in \mathcal{R}$
$\mathbf{L}_r$ vector $1 \times Nl_r$ indicating the path (as a sequence of links) covered by train $r \in \mathcal{R}$
$t^{dep}_{r,l}$ expected departure time on link l *in* $\mathbf{L}_r$ for train $r \in \mathcal{R}$
$t^{arr}_{r,l}$ expected arrival time on link l *in* $\mathbf{L}_r$ for train $r \in \mathcal{R}$
$n^{\mathbf{O}}_o$ origin railway terminal for order $o \in \mathcal{O}$
$n^{\mathbf{D}}_o$ destination railway terminal for order $o \in \mathcal{O}$
t^{in}_o time instant in which goods of order $o \in \mathcal{O}$ are ready at the origin node

$t^*_{min,o}$ minimum delivery time instant for order $o \in \mathcal{O}$
$t^*_{max,o}$ maximum delivery time instant for order $o \in \mathcal{O}$
Np_o number of alternative paths connecting the origin and destination nodes of order $o \in \mathcal{O}$
$Nl_{o,p}$ number of links of path $p = 1, \ldots, Np_o$ of order $o \in \mathcal{O}$
$\mathbf{L}_{o,p}$ vector $1 \times Nl_{o,p}$ indicating the sequence of links of path $p = 1, \ldots, Np_o$ of order $o \in \mathcal{O}$
$\zeta_{o,p}$ cost of path $p = 1, \ldots, Np_o$ of order $o \in \mathcal{O}$ (this cost is related to the priority of path p in comparison with the other paths of the same order; we set $\zeta_{o,p} = 1$ for the primary path, $\zeta_{o,p} = 1.1$ for the secondary path, and so on)

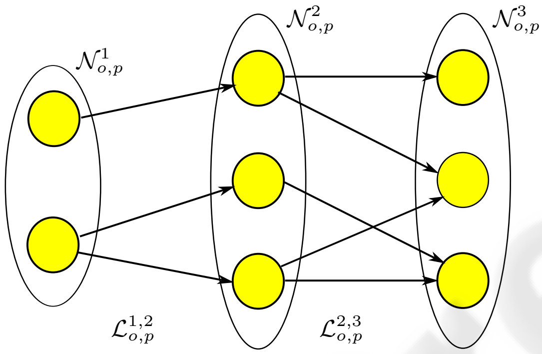

Fig. 1. Graph $\mathcal{G}_{o,p}$ in case $Nl_{o,p} = 3$.

The preprocessing phase identifies all the feasible train sequences for each order by analysing one order at a time and, for each order, each path singularly. Then, proceeding backward from the last link of a path, i.e. the last element of vector $\mathbf{L}_{o,p}$, to the first link, it is necessary to verify whether a train can be used on the considered link. For the last link of a path this is obtained finding all trains arriving in time with respect to the maximum delivery time $t^*_{max,o}$ and leaving not before the time t^{in}_o in which goods are ready at the origin. Going backward, considering the trains selected for a link, we search for those trains in the previous link such that the time connections are respected and, again, the departure time is not before t^{in}_o.

For each order and for each of the Np_o paths of the order, this procedure leads to the creation of a graph composed of $Nl_{o,p}$ partitions. Let us define this graph as $\mathcal{G}_{o,p} = (\mathcal{N}_{o,p}, \mathcal{L}_{o,p})$. As shown for example in Fig. 1 for $Nl_{o,p} = 3$, we denote the set of nodes in the different partitions as $\mathcal{N}^i_{o,p}, i = 1, \ldots Nl_{o,p}$, and the set of links as $\mathcal{L}^{i,i+1}_{o,p}$, $i = 1, \ldots, Nl_{o,p} - 1$. Each node in $\mathcal{N}^i_{o,p}$ is a feasible train in the i-th railway link of path p of order o and each link of $\mathcal{L}^{i,i+1}_{o,p}$ represents the fact that the connected nodes (i.e. trains) are adjacent in a train sequence. For this reason, after creating this graph, all the train sequences are obtained as all the possible paths in this graph. In the following, the backward procedure for the construction of graph $\mathcal{G}_{o,p}$ for order o and for a given path $p \in \{1, \ldots, Np_o\}$ is described. In this procedure the constant Δt

represents the time necessary for a box unloaded from a train in a terminal to be ready for being loaded on another train, and $\mathcal{R}_l$ represents the set of trains covering link l.

initialize $m = Nl_{o,p}$;
set l as the last link of the path;
foreach r *in* $\mathcal{R}_l$ **do**
  if $t^{arr}_{r,l} \leq t^*_{max,o}$ **and** $t^{dep}_{r,l} \geq t^{in}_o$ **then**
    add r in $\mathcal{N}^m_{o,p}$;
  end
end
foreach ρ *in* $\mathcal{N}^m_{o,p}$ **do**
  set $t^*_{\rho,m} = t^{dep}_{\rho,l} - \Delta t$
end
for *i=m-1* **to** *1* **do**
  set l as the i-th link of the path;
  foreach ρ *in* $\mathcal{N}^{i+1}_{o,p}$ **do**
    foreach r *in* $\mathcal{R}_l$ **do**
      if $t^{arr}_{r,l} \leq t^*_{\rho,m}$ **and** $t^{dep}_{r,l} \geq t^{in}_o$ **then**
        add r in $\mathcal{N}^i_{o,p}$;
        add link (r, ρ) in $\mathcal{L}^{i,i+1}_{o,p}$;
      end
    end
    foreach ρ *in* $\mathcal{N}^i_{o,p}$ **do**
      set $t^*_{\rho,i} = t^{dep}_{\rho,l} - \Delta t$
    end
  end
end

After the completion of the backward procedure constructing the graph $\mathcal{G}_{o,p}$, a forward procedure is applied which, for each order o and for each path p, $p = 1, \ldots, Np_o$, identifies $Ns_{o,p}$ train sequences. Each train sequence $\mathbf{S}_{o,p,s}, s = 1, \ldots, Ns_{o,p}$, is a vector $1 \times Nl_{o,p}$ listing the trains for each link of path p for order o. While proceeding forward in the graph, the cost associated with each train sequence is computed. For each train sequence, let $\varphi^n_{o,p,s} \in \{0, 1\}$ denote whether the box changes train in terminal $n \in \mathcal{N}$ (without considering the origin and destination terminal) and $H^n_{o,p,s}$ denote the time (in hours) in which a box is stored at terminal $n \in \mathcal{N}$. Then the cost $C_{o,p,s}$ for the sequence s of path p for order o is computed as follows:

$$C_{o,p,s} = \zeta_{o,p} \sum_{i=1}^{n} \left(\varphi^n_{o,p,s} \cdot \delta_n + H^n_{o,p,s} \cdot \rho_n \right) \tag{1}$$

Finally, we need to define the following sets to state the planning problem described in Section 3:

– $\mathcal{R}_{o,p,s}$, $p = 1, \ldots, Np_o$, $s = 1, \ldots, Ns_{o,p}$, is the set of trains included in sequence s of path p for order o;

– $\mathcal{S}^U_{o,p,n,r}$, $p = 1, \ldots, Np_o$, $n \in \mathcal{N}$, $r \in \mathcal{R}_n$ is the set gathering the indices of sequences of path p for order o so that boxes are unloaded from train r at node n (by definition, it is $\mathcal{S}^U_{o,p,n,r} \subseteq \{1, \ldots, Ns_{o,p}\}$);
– $\mathcal{S}^L_{o,p,n,r}$, $p = 1, \ldots, Np_o$, $n \in \mathcal{N}$, $r \in \mathcal{R}_n$ is analogous to the previous set but refers to loading operations;
– $\mathcal{S}^T_{o,p,n,r}$, $p = 1, \ldots, Np_o$, $n \in \mathcal{N}$, $r \in \mathcal{R}_n$ refers to transfer operations (i.e. trains that pass a given node and do not involve any loading or unloading operations).

3 Optimal Assignment

The definition of the optimization problem is based on the output data of the preprocessing phase as well as the following input data:

Nb_o number of boxes associated with order $o \in \mathcal{O}$
$\pi_{o,b}$ length of box $b = 1, \ldots, Nb_o$ of order $o \in \mathcal{O}$
$\omega_{o,b}$ weight of box $b = 1, \ldots, Nb_o$ of order $o \in \mathcal{O}$
Ω_r maximum bearable weight for train $r \in \mathcal{R}$
K_r cost related to the use of train $r \in \mathcal{R}$
Nw_r number of wagons of train $r \in \mathcal{R}$
$\Omega_{r,w}$ maximum bearable weight of wagon $w = 1, \ldots, Nw_r$ of train $r \in \mathcal{R}$
$\Pi_{r,w}$ length of wagon $w = 1, \ldots, Nw_r$ of train $r \in \mathcal{R}$
σ_n maximum number of handling operations (loading and unloading) for each train at terminal $n \in \mathcal{N}$ (this term depends on the handling capacity provided by each terminal)

The problem decision variables are listed in the following:

– $y_{o,b,p,s} \in \{0,1\}$, $o \in \mathcal{O}$, $b = 1, \ldots, Nb_o$, $p = 1, \ldots, Np_o$, $s = 1, \ldots, Ns_{o,p}$, assuming value 1 if box b of order o is assigned to sequence s of path p, otherwise equal to 0;
– $x_{o,b,p,s,r,w} \in \{0,1\}$, $o \in \mathcal{O}$, $b = 1, \ldots, Nb_o$, $p = 1, \ldots, Np_o$, $s = 1, \ldots, Ns_{o,p}$, $r \in \mathcal{R}_{o,p,s}$, $w = 1, \ldots, Nw_r$, assuming value 1 if box b of order o is assigned to wagon w of train r in sequence s of path p, otherwise equal to 0;
– $z_r \in \{0,1\}$, $r \in \mathcal{R}$, assuming value 1 if train r is used, otherwise equal to 0.

The planning problem is formulated as a 0/1 linear programming (LP) problem whose objective function considers the cost terms associated with train sequences (computed in the preprocessing phase) and train costs.

Problem 1.

$$\min_{\substack{y_{o,b,p,s} \\ x_{o,b,p,s,r,w} \\ z_r}} \sum_{o \in \mathcal{O}} \sum_{b=1}^{Nb_o} \sum_{p=1}^{Np_o} \sum_{s=1}^{Ns_{o,p}} C_{o,p,s} \cdot y_{o,b,p,s} + \sum_{r \in \mathcal{R}} K_r \cdot z_r \tag{2}$$

subject to

$$\sum_{p=1}^{Np_o} \sum_{s=1}^{Ns_{o,p}} y_{o,b,p,s} = 1 \qquad o \in \mathcal{O}\ b = 1, \ldots, Nb_o \tag{3}$$

$$\sum_{w=1}^{Nw_r} x_{o,b,p,s,r,w} = y_{o,b,p,s} \qquad o \in \mathcal{O}\ b = 1,\ldots,Nb_o\ p = 1,\ldots,Np_o$$
$$s = 1,\ldots,Ns_{o,p}\ r \in \mathcal{R}_{o,p,s} \qquad (4)$$

$$\sum_{o\in\mathcal{O}} \sum_{b=1}^{Nb_o} \sum_{p=1}^{Np_o} \sum_{s\in(\mathcal{S}^L_{o,p,n,r}\cup\mathcal{S}^T_{o,p,n,r})} \sum_{w=1}^{Nw_r} \omega_{o,b} x_{o,b,p,s,r,w} \leq \Omega_r z_r \qquad n \in \mathcal{N}\ r \in \mathcal{R}_n \qquad (5)$$

$$\sum_{o\in\mathcal{O}} \sum_{b=1}^{Nb_o} \sum_{p=1}^{Np_o} \sum_{s\in(\mathcal{S}^L_{o,p,n,r}\cup\mathcal{S}^T_{o,p,n,r})} \pi_{o,b} x_{o,b,p,s,r,w} \leq \Pi_{r,w}$$
$$n \in \mathcal{N}\ r \in \mathcal{R}_n\ w = 1,\ldots,Nw_r \qquad (6)$$

$$\sum_{o\in\mathcal{O}} \sum_{b=1}^{Nb_o} \sum_{p=1}^{Np_o} \sum_{s\in(\mathcal{S}^L_{o,p,n,r}\cup\mathcal{S}^T_{o,p,n,r})} \omega_{o,b} x_{o,b,p,s,r,w} \leq \Omega_{r,w}$$
$$n \in \mathcal{N}\ r \in \mathcal{R}_n\ w = 1,\ldots,Nw_r \qquad (7)$$

$$\sum_{o\in\mathcal{O}} \sum_{b=1}^{Nb_o} \sum_{p=1}^{Np_o} \sum_{s\in(\mathcal{S}^L_{o,p,n,r}\cup\mathcal{S}^U_{o,p,n,r})} \sum_{w=1}^{Nw_r} x_{o,b,p,s,r,w} \leq \sigma_n \qquad n \in \mathcal{N}\ r \in \mathcal{R}_n \qquad (8)$$

$$y_{o,b,p,s} \in \{0,1\}$$
$$o \in \mathcal{O}\ b = 1,\ldots,Nb_o\ p = 1,\ldots,Np_o\ s = 1,\ldots,Ns_{o,p} \qquad (9)$$

$$x_{o,b,p,s,r,w} \in \{0,1\} \qquad o \in \mathcal{O}\ b = 1,\ldots,Nb_o\ p = 1,\ldots,Np_o$$
$$s = 1,\ldots,Ns_{o,p}\ r \in \mathcal{R}_{o,p,s}\ w = 1,\ldots,Nw_r \qquad (10)$$

$$z_r \in \{0,1\} \qquad r \in \mathcal{R} \qquad (11)$$

Constraints (3) impose that each box of each order is assigned to one and only one train sequence, while (4) impose the relation between $y_{o,b,p,s}$ and $x_{o,b,p,s,r,w}$ variables. Constraints (5) concern the maximum weight that each train can bear and define the relation between $x_{o,b,p,s,r,w}$ and z_r variables. Constraints (6) and (7) impose that boxes assigned to wagons must be compatible with the wagon length and the weight limitations for each wagon. Constraints (8) regard the maximum handling operations that can be performed for each train at a given terminal.

4 Experimental Results

We coded the preprocessing analysis and the optimization procedure in C♯ using Cplex 11.0 as 0/1 LP solver. Then we ran some experiments to evaluate the performance of the proposed planning approach, after having introduced in the statement of Problem 1 the possibility of not assigning all the boxes. To do this, we transformed equality constraints (3) into not greater or equal to inequalities and we added in the cost function the penalty term

$$M \cdot \sum_{o \in \mathcal{O}} \sum_{b=1}^{Nb_o} \left(1 - \sum_{p=1}^{Np_o} \sum_{s=1}^{Ns_{o,p}} y_{o,b,p,s} \right)$$

in order to minimize the number of possibly not assigned boxes (here M is a constant much larger than any other constant in the objective function).

We analysed two different scenarios for the network and trains, one called *Small* scenario (7 nodes, 20 links and 56 trains) and the other called *Large* scenario (10 nodes, 34 links and 98 trains). The considered planning horizon is one week, 2 types of wagons and 13 typologies of boxes are taken into account, each train covers either 2 or 3 links and has a number of wagons between 6 and 10. Data about orders were randomly generated: in particular, we generated 6 groups of 5 instances, called *SmallA* (20 orders and 3÷5 boxes per order), *SmallB* (30 orders and 4÷5 boxes per order), *SmallC* (40 orders and 5÷7 boxes per order) for the small scenario, whereas *LargeA* (40 orders and 2÷4 boxes per order), *LargeB* (50 orders and 4÷6 boxes per order), *LargeC* (60 orders and 6÷8 boxes per order) for the large scenario. We applied the preprocessing computation and, then, we solved these instances imposing the time limit of 2h for the Cplex solver. The tests were executed on a 2.8 GHz Pentium 4 computer with 2 GB of RAM.

In Table 1 we report the number of variables of the 0/1 LP formulation, the CPU time needed to solve the instance (in seconds), the percentage optimality gap, the number of not assigned boxes in the solution and the number of boxes that the solver proved that cannot be assigned in the optimal solution. We only show the computation time of Cplex solver because the computation time for preprocessing and model building can be considered irrelevant as it was always lower than 30 seconds. Note that, having penalized in the objective function the choice of not serving boxes, the last two columns in Table 1 are obtained as

$$NotAssSol = \left\lfloor \frac{Objective}{M} \right\rfloor \qquad NotAssProv = \left\lfloor \frac{LowerBound}{M} \right\rfloor$$

where $LowerBound$ denotes the value of the best lower bound found by the solver. We computed the optimality gap as

$$OptimGap = \frac{(Objective \mod M) - (LowerBound \mod M)}{Objective \mod M} \cdot 100$$

where the operator $\mod$ finds the remainder of the integer division between two numbers. In this way $Objective \mod M = Objective$ and $LowerBound \mod M = LowerBound$, when $NotAssSol = 0$ and $NotAssProv = 0$, but when not all the boxes are assigned, i.e., $NotAssSol \neq 0$ and $NotAssProv \neq 0$, the gap is computed by considering the objective function and the lower bound without the penalization terms.

Analysing the results in Table 1, we can note that the instances corresponding to the small scenario are solved in a satisfactory way, showing increasing difficulty form

Table 1. Cplex performances.

Instance ID	No. of variables	CPU time	$OptimGap$	$NotAssSol$	$NotAssProv$
SmallA1	16376	2216	*opt.*	0	0
SmallA2	25865	7200	7.83	0	0
SmallA3	25657	7200	0.17	0	0
SmallA4	32048	7200	2.85	0	0
SmallA5	19932	7200	0.02	0	0
SmallB1	36444	7200	5.77	0	0
SmallB2	41232	7200	3.28	0	0
SmallB3	47097	7200	5.40	0	0
SmallB4	44067	7200	2.57	0	0
SmallB5	36086	7200	5.76	0	0
SmallC1	55573	7200	3.06	11	10
SmallC2	72174	7200	4.76	12	11
SmallC3	81883	7200	3.55	5	0
SmallC4	74098	7200	8.77	0	0
SmallC5	63387	7200	3.69	7	7
LargeA1	35127	7200	5.66	0	0
LargeA2	44353	7200	11.98	0	0
LargeA3	29663	7200	2.54	0	0
LargeA4	43084	7200	5.27	0	0
LargeA5	43224	7200	5.00	0	0
LargeB1	83596	7200	11.48	0	0
LargeB2	95004	7200	10.22	0	0
LargeB3	84891	7200	-0.02	2	0
LargeB4	72837	7200	10.13	0	0
LargeB5	94950	7200	9.00	0	0
LargeC1	133251	7200	9.78	3	1
LargeC2	136996	7200	54.54	9	3
LargeC3	163414	7200	$+\infty$	424	0
LargeC4	136600	7200	11.21	19	0
LargeC5	140435	7200	8.04	12	2

Table 2. Cplex performances for group *LargeC* with time limit of 5 hours.

Instance ID	CPU time	$OptimGap$	$NotAssSol$	$NotAssProv$
LargeC1	18000	9.78	3	1
LargeC2	18000	54.54	9	3
LargeC3	18000	6.00	6	0
LargeC4	18000	6.87	2	0
LargeC5	18000	8.04	12	2

group *SmallA* to group *SmallC* (where in 4 over 5 instances some boxes are not assigned in the solution). The instances of the large scenario appear more difficult; in the groups *LargeA* and *LargeB* all boxes are assigned, except for instance *LargeB3* (in this instance the negative gap, that should be impossible by definition of the lower bound, must be considered as a proof of one more box impossible to serve, then it loses its usual meaning). Finally, the results for the instances of group *LargeC* are not very satisfactory. We also solved the instances of group *LargeC* by imposing a time limit for Cplex of 5 hours (as shown in Table 2). For some instances we obtained a significant improvement, whereas for some other instances we found the same results produced after 2 hours of computation.

The groups of instances which can be considered more representative of a real case are groups *LargeB* and *LargeC*. They correspond to a network with 10 terminals and 34 links and to an average request of moving 250 and 420 boxes, respectively. These data can be considered quite realistic, at least for the first implementations in Italy of this innovative railway network that now is not yet applied. Moreover, we consider a time horizon of a week and, again, we think the choice of a weekly planning can make sense in a real application. These computational results make us think that the proposed planning procedure could be applied to a real system if the planning is realized off-line one or two days before the considered horizon. In this case, a much higher time limit (than 5 hours) could be set for the solver, thus probably yielding better solutions. Instead, if the solutions are needed in a short time and larger instances must be considered, it is necessary to develop different approaches (i.e. heuristic techniques) for addressing this planning problem.

5 Conclusions

In this paper we propose a planning procedure in order to meet transportation requests by using the railway network. The considered railway system is innovative because the terminals are supposed to be equipped with fast and automatic handling systems, allowing to make containers change different trains on their path from origin to destination. The solution to this planning problem has been divided in two phases: first the preprocessing analysis and, second, the optimization (solution of a 0/1 LP problem). To evaluate the effectiveness of the proposed planning approach we performed some experimental tests using a set of 30 random generated instances characterized by different dimensions.

The results obtained from these preliminary tests make us think that the proposed approach could be applied to a real system, but further extensions and investigations are needed as well. In fact, since the experimental tests were not completely satisfactory for the largest instances, some further heuristic techniques (e.g., based on relaxation or decomposition) are needed to speed-up and simplify the problem solution. These aspects will be considered in the future development of our research.

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