A decomposition approach for optimizing truck trips for a single carrier

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Abstract—This paper proposes a heuristic decomposition approach for scheduling truck trips with the goal of satisfying the demand of a container single carrier while minimizing its costs. The approach foresees three phases: a pre-processing step, in which the demand is decomposed in two parts and a set of rules for combining trips are defined, and two optimization phases. The first mixed integer linear optimization model allows to combine trips two by two in order to decrease the number of empty or partially empty trips, while the second optimization problem enables assigning trucks to trips with the goal of minimizing travel costs. The efficiency of the proposed methodology is analyzed using a real simple case over a local network and the results are presented.

I. INTRODUCTION

Container transportation plays an increasingly important role in international freight logistic activities as well as local ones. The transportation modes most utilized for moving freight cargo in the territory is definitely the road transport, thanks to its capability of providing a door-to-door service and to its higher flexibility and capillarity in comparison with other transportation modalities. However, the high impact caused by road transport, both in terms of network congestion and environmental pollution, imposes to make this kind of transport as efficient as possible, with the goal of reducing the number of trucks transiting on the road network and minimizing empty or partially empty trips. The use of the full capacity of a truck is crucial not only for the reduction of carrier costs, but also with regards to the external effects caused by road transport on society and environment (i.e. fuel consumption, air and noise pollution, etc.).

Many freight carriers operate regional distribution centers from which they dispatch their truck fleet to the pick up/delivery points of their orders. These trucks usually perform multiple trips during a day, from their distribution center to various customer locations.

The problem of serving the demand for single and multiple carriers has been extensively treated in literature. One of the first studies is the one provided by Gavish [1] which presents a method for serial combination of truck trips to minimize the total cost of deadheading, subject to constraints on the allowed combination. Also [2] proposes a model that can be used in real time to decide, under uncertainty, how to allocate the truck fleet while anticipating the future consequences of the current decisions; in this work it is assumed that the first dispatch is deterministic and the remaining ones are stochastic.

Assuming homogeneous container types and sizes and both owned and chartered fleets with different hauling costs and working time lengths, [3] studies the optimal assignment of these fleets to a set of delivery and pickup point pairs in order to minimize the total distribution cost. A dynamic model based on the rolling horizon on a time horizon of one day is proposed for minimizing routing costs, resource assignment costs and container repositioning costs. The cost of pairing is defined as the sum of pairing cost and the cost of repositioning trucks for future demand.

Chung et al. [5] elaborate several mathematical models of container truck transportation problems, both with single and multiple commodities. They formulate the basic problem where every vehicle can transport exactly one container at a time, and the multi-commodity problem with a combined chassis used in transporting two 20ft containers or one 40ft container. To solve the problem a solution algorithm based on the Insertion Heuristic is introduced. Jula et al. [6] combine the pickup and delivery nodes to formulate the truck transportation problem as a multiple travelling salesman problem with time windows. In [7] the problem of allocating a set of trips to a mixed fleet of trucks operating from a single terminal is analyzed. Such a problem is often faced in regional distribution of large volume products where a truck may be assigned several closed trips from the same origin during a work shift.

In [8], a truck scheduling problem for container transportation in a local area with multiple depots and multiple terminals is addressed. Four types of movements of containers (inbound full, outbound full, inbound empty and outbound empty) as well as time windows at both the origin and the destination are considered in this study.

The present work proposes a heuristic scheme with the aim of maximizing trucks capacity usage by effectively pairing the trips before assigning them to trucks, with the final goal of minimizing internal costs of the carrier. In this study, in addition to considering empty and full trips, partially loaded trucks are also taken into account using a capacity utilization factor. McKinnon [9] indicates that vehicle utilization defined as the ratio of vehicle-km to ton-km is one of the factors that influences externalities. In fact, if vehicle utilization is improved, then it will be possible to reduce the amount of vehicle kilometers and the related detrimental effects. [10] studies vehicle utilization through a literature review, which includes contributions from different approaches.

Most of the transport literature is focused on the most gen-
eral elements of transport demand and few studies are able to really include vehicles utilization and its determinants.

The paper is organized as follows. In Section II the problem under consideration is described; Section III presents the heuristic approach for optimizing a single carrier truck trips. Section IV proposes some experimental results tested on a simplified case study and, finally, some concluding remarks are reported in Section V.

II. DESCRIPTION OF THE PROBLEM

The objective of a truck carrier is to serve its demand by minimizing its costs, which in turn means the maximization of its revenues. If the routing of trucks are not properly optimized and trucks perform empty or partially empty trips, the carrier costs increase.

So, the main goal of the present problem is to assign trucks to trips in order to minimize the truck carrier costs; more specifically this objective is pursued through both the optimization of the routing of the fleet of the carrier and the minimization of the unused capacity of trucks while meeting the carrier transportation demand.

To this aim, a heuristic is proposed with the goal of minimizing the total costs of a single truck carrier, who has to satisfy a certain demand of container transportation over a particular network. This objective is pursued by trying to combine different trips served by the same truck, so allowing to both minimize the total empty trips (i.e. trips from the depot to the container pick up point and, vice versa, from the container delivery place to the depot) and to utilize as much as possible the full capacity of trucks.

In the proposed work, some assumptions have been made. Firstly, it is supposed that the number of trucks located at the depot is adequate for meeting the demand to be served by the carrier; this is a quite realistic assumption, since the number of trucks usually does not represent a strong constraint for a truck company which, in case of necessity, can rent them. Then, only 20 feet and 40 feet container types are considered, being these the most used typology. Moreover, all the trucks used by the carrier have a capacity equal to 2 TEUs, and time windows in relation to trips are neglected (i.e. trips can start and finish at any moment without time constraints). Besides, two types of costs are considered: the transportation costs (which are dependent on the distance covered by vehicles, i.e. trucks) and the costs arising from performing empty or semi-empty trips (i.e. only 1 TEU carried on a truck). It is also possible to consider resource costs (i.e. driver and truck) and container repositioning costs [2], but in the present work they are not taken into account. Finally, it is assumed that only one depot is available by the carrier.

Let us consider a generic network, which is modelled as a graph \( G = (V, A) \), being \( V \) the set of nodes and \( A \) the set of links. Nodes represent the points of picking up and delivery of containers - i.e. the companies that represent the carrier customers - while links represent portions of the road network that connect these points (which are assumed to be the shortest path). The considered transportation demand is defined in terms of containers.

The set of nodes is further composed of nodes representing origins and destinations of trips and nodes related to the presence of depots in the network. The first type of nodes is denoted with \( V^d \), the second one with \( V^s \) \( (V^s \cup V^d = V) \). Each link \( l \in A \) is associated with a transportation cost \( c_l \).

The problem data can be divided in two main groups, related to trucks and trips. For what concerns the first group let us denote with:

- \( m = 1, \ldots, M \), the number of trucks available by the carrier;
- \( T_m, m = 1, \ldots, M \), the time availability (expressed in minutes) for truck \( m \).

As for the trips, the following notation is applied:

- \( N \), with \( \text{card}(N) = N \), is the overall set of trips;
- \( t_n, n = 1, \ldots, N \), is the travel time for serving trip \( n \) (expressed in minutes);
- \( C_n, n = 1, \ldots, N \), is the cost for serving trip \( n \) and it is given by the sum of all the links composing trip \( n \):
\[
C_n = \sum_{l \in \mathcal{L}_n} c_l;
\]
- \( \mathcal{L}_n \subset A, n \in N \), is the set of links that must be covered to serve trip \( n \); such a set of links includes the links connecting the depots to the nodes that are origin or destination of trips.

Moreover, let us consider the concept of capacity utilization factor which defines the usage of the capacity of a truck moving on a link. More specifically, the utilization factor of a link is equal to the number of TEUs moved on that link when serving a particular trip. When executing a single trip \( n \in N \); the capacity utilization factor of link \( l \in A \) is denoted by \( \rho^l \).

Fig. 1 provides a simple network made of 4 nodes, 10 links and 1 depot. The demand for each trip is expressed in number of TEUs and is shown on each arc (no container is carried on a link if no number is shown).

![Fig. 1. Example of a generic container demand over a network of 4 nodes](image)
• a pre-processing phase, in which the demand network is decomposed into two secondary networks and trips paths are defined;
• a first optimization phase (phase a), in which trips are combined two by two with the objective of reducing the unused trucks capacity, i.e. minimizing empty and partially empty trips. The outcome of this phase is a new network with redefined paths;
• a second optimization phase (phase b), in which trucks are assigned to trips so as to minimize travel distance costs.

In the following, the above mentioned phases are explained in details.

A. Pre-processing phase

The pre-processing phase foresees two steps: the decomposition of the network into two parts and the definition of paths to combine trips according to a pre-defined set or rules.

More specifically, the original demand network is split into a “full network”, which can be served by using full truckloads, and a “partially full” network that can be served by exploiting only a part of the capacity of trucks; in this way we can try to combine trips of the partially full network with the goal of minimizing total costs, as it will be explained in detail later in the paper. The splitting process is made as follows: for each link, the relative demand is divided by two. If the number obtained is even, the whole demand on that link is assigned to the full network; if it is odd, the lower integer number is assigned to the corresponding link in the full network, while a demand equal to 1 TEU is associated with the same link in the partially full network.

When decomposing the network as described above, two further set of trips are identified, namely \( N_f \), which is the set of trips related to the full network and \( N_p \), gathering trips included in the partially full network.

Fig. 2 provides an example of decomposition of the simple demand network shown in Fig.1. As it can be noticed, the demand on links belonging to the full network is represented by numbers multiple of 2, while the partially full network is made of links associated only with values equal to 1.

Once the demand on the network is decomposed, all the possible combinations of partially full trips must be defined. This is realized by applying on each couple of trip a specific rule among a pre-defined set, as shown in Fig. 3. More specifically, for each couple of trips, one of the following conditions may occur:

1) they have the same origin;
2) they have the same destination;
3) they have different origins/destinations;
4) the origin of the first trip corresponds with the destination of the second trip;
5) the destination of the first trip coincides with the origin of the second trip.

The performing of a trip separately (i.e. not in combination with another one) means that the truck starts its trip from the depot, arrives at the origin point of the trip, performs the trip getting to its destination and then comes back to the depot.
It must be underlined that, the necessity of enumerating all the possible pairs of trips and of defining the corresponding paths, makes the present approach effective when small networks (related to small geographical areas) are taken into account. Anyway, by considering that the present methodology is referred to the activity of a single carrier, this is not a significant limitation since either a small network is typically covered by one single carrier or a possible extended network can be easily decomposed in smaller areas where combining trips is actually reasonable.

B. Optimization phase a

The objective of the first optimization phase is to maximize the cost saving by coupling, two by two, all the trips of the partially full network (consisting of the trips belonging to \( N^p \)). In other words, the goal of this stage is to minimize empty and partially empty trips. The outcome of this phase is a modified network, in which the combined trips increase the capacity usage of trucks.

With reference to a pair of combined trips \((n, k), n, k \in N^p\), \( n \neq k \), the following notation must be introduced:
- \( t_{nk} \) is the time for serving the pair of trips \((n, k)\);
- \( S_{nk} \) is the cost saving by coupling trip \( n \) and trip \( k \);
- \( C_{nk} \) is the cost of combining trip \( n \) and \( k \);
- \( \rho_l^{nk} \) is the utilization factor of link \( l \in A \) when serving the pair of trips \((n, k)\);
- \( \rho_M \) is the maximum capacity of a truck, equal to 2 TEUs;
- \( E_{nk} \subset A \), is the set of links that must be covered to serve the pair of trips \((n, k)\); as for single trips, such a set of links includes the links connecting the depots to the nodes that are origin or destination of trips.

The decision variables of this first optimization problem are represented by \( y_{nk} \in (0, 1) \), \((n, k), n, k \in N^p\), which assume value equal to 1 if trips \( n \) and \( k \) must be combined and 0 otherwise. The mathematical formulation of the optimization problem follows.

**Problem 1:**

\[
max U = \sum_{n \in N^p} \sum_{k \in N^p, k \neq n} S_{nk} y_{nk} \tag{1}
\]

subject to

\[
t_{nk} = \sum_{l \in L_{nk}} t_l \quad \forall (n, k), n, k \in N^p, n \neq k \tag{2}
\]

\[
t_{nk} y_{nk} < T \quad \forall (n, k), n, k \in N^p \tag{3}
\]

\[
C_n = \sum_{l \in L_n} c_l \ast (\rho_M - \rho_l^{nk}) \quad \forall n \in N^p \tag{4}
\]

\[
C_{nk} = \sum_{l \in L_{nk}} c_l \ast (\rho_M - \rho_l^{nk}) \quad \forall (n, k), n, k \in N^p, n \neq k \tag{5}
\]

\[
S_{nk} = C_n + C_k - C_{nk} \quad \forall (n, k), n, k \in N^p \tag{6}
\]

\[
\sum_{k \in N^p} y_{nk} + y_{nk} \leq 1 \quad \forall n \in N^p \tag{7}
\]

\[
y_{nk} \in (0, 1) \quad \forall (n, k), n, k \in N^p, n \neq k \tag{8}
\]

The resulting problem is a mixed-integer linear programming problem in which the objective function (1) is a sum of the cost savings of the combined trips.

Constraints (2) make sure that the time necessary to cover a pair of trips \((n, k)\) is given by the sum of the times necessary to cover each link composing the combined path. Constraints (3) ensure that the time required by a truck for performing a certain number of trips is not exceeding the total availability of the truck. The cost needed to execute a single trip \( n \) is provided by Constraints (4); this cost is calculated by summing the cost of each link multiplied by the residual capacity on that link. Analogously, constraints (5) define the cost of executing the generic couple of combined trips \((n, k)\). Constraints (6) define the cost saving of combining a pair of trips \((n, k)\) as the sum of the costs of each single trip performed individually and the two trips executed together. Constraints (7) make sure that each trip is not combined more than once and, finally, constraints (8) define the decision variables of the problem.

By solving Problem 1, a new set of trips that maximize the trucks capacity usage is achieved. Let us denote this set with \((N)^p\). This means that we obtain a new network, better than the previous one but maybe still not completely full.

C. Optimization phase b

The goal of the second optimization phase is to minimize the cost of assigning trips to trucks for serving the carrier demand. This assignment is made on the overall set of trips belonging to the full network and on the ones composing the new partially full network. Then, the considered set of trips is \( \tilde{N} = N^f \cup N^p \), being \( \tilde{N} = \text{card}(\tilde{N}) \).

Moreover, let us denote with \( C_{nm} \), \( n = 1, \ldots, \tilde{N}, m = 1, \ldots, M \) the cost of assigning trip \( n \) to truck \( m \) on the basis of its travel time (or travel distance). The decision variables of Problem 2 are defined by \( x_{nm} \in (0, 1) \), \( n = 1, \ldots, \tilde{N}, m = 1, \ldots, M \), assuming a value equal to 1 if trip \( n \) is assigned to truck \( m \) and 0 otherwise.

The problem statement, resulting in a mixed integer programming structure, follows.

**Problem 2:**

\[
min Z = \sum_{m=1}^{M} \sum_{n=1}^{\tilde{N}} C_{nm} x_{nm} \tag{9}
\]

s.t.
where \( n = 1, \ldots, M \) (10)

\[
\sum_{m=1}^{M} x_{nm} = 1 \quad \forall n \in \tilde{N} \quad (11)
\]

\[x_{nm} \in (0, 1) \quad \forall (n, m), n \in \tilde{N}, m = 1, \ldots, M \quad (12)
\]

Constraints (10) avoid that a truck overcomes its time availability while performing the trips which are assigned to it. Constraints (11) make sure that each trip is served by one truck. Finally, constraints (12) determine the nature of the decision variables.

The solution of Problem 2 provides the assignment of all the trips to the available trucks by minimizing the operating costs for performing them.

IV. EXPERIMENTAL RESULTS

In order to test the effectiveness of the proposed heuristic, it has been applied to the simple case study provided in Fig. 1. So, the original network is composed of 4 nodes, 14 links (also the 4 links drawn with dashed lines and connecting the nodes of the network with the depot must be considered) and 10 trips to be executed. The demand to be served is specified near each arch and is expressed in terms of TEU. Firstly, the pre-processing phase has been carried out: the original network has been divided into a full network, composed of links allowing to make full trucks, and a partially full one, made up of links with only one TEU per link. Making reference to the partially full network provided in Fig. 2 and denoting with \( D \) the depot node, 18 possible links can be defined as shown in Table I.

<table>
<thead>
<tr>
<th>Trip Number</th>
<th>Single path</th>
<th>( \rho_l^\text{FR} )</th>
<th>( (\rho_M^l - \rho_l^\text{FR}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-5-7-14</td>
<td>0-1-0</td>
<td>2-1-1-2</td>
</tr>
<tr>
<td>2</td>
<td>2-7-14</td>
<td>0-1-0</td>
<td>2-1-1-2</td>
</tr>
<tr>
<td>3</td>
<td>3-9-13</td>
<td>0-1-0</td>
<td>2-1-1-2</td>
</tr>
<tr>
<td>4</td>
<td>2-8-15</td>
<td>0-1-0</td>
<td>2-1-1-2</td>
</tr>
<tr>
<td>5</td>
<td>4-11-12</td>
<td>0-1-0</td>
<td>2-1-1-2</td>
</tr>
</tbody>
</table>

Then, by applying the five combination rules presented in Fig. 3, all the possible paths for combined trips have been derived, as shown in Table III.

| Combined trips | Combined path | \( \rho_l^\text{FR} \) | \( (\rho_M^l - \rho_l^\text{FR}) \) |
|----------------|---------------|----------------|----------------|----------------|----------------|
| 1+2            | 1-5-7-14      | 0-1-0           | 2-1-1-2         |
| 1+3            | 1-6-9-13      | 0-1-2-0         | 2-1-0-2         |
| 1+4            | 1-5-8-15      | 0-1-1-0         | 2-1-1-2         |
| 1+5            | 1-5-8-12      | 0-1-1-0         | 2-1-1-2         |
| 2+3            | 2-7-9-13      | 0-1-1-0         | 2-1-1-2         |
| 2+4            | 2-7-10-15     | 0-2-1-0         | 2-1-1-2         |
| 2+5            | 2-7-10-11-12  | 0-1-0-1-0       | 2-1-1-2         |
| 3+4            | 3-9-8-15      | 0-1-1-0         | 2-1-1-2         |
| 3+5            | 3-10-11-15-13 | 0-1-2-1-0       | 2-1-0-1-2       |
| 4+5            | 2-8-11-12     | 0-1-1-0         | 2-1-1-2         |
| 2+1            | 2-7-16-5-13   | 0-1-0-1-0       | 2-1-2-1-2       |
| 3+1            | 3-16-5-13     | 0-1-2-0         | 2-1-0-2         |
| 4+1            | 2-8-11-15-13  | 0-1-0-1-0       | 2-1-2-1-2       |
| 5+1            | 4-11-5-13     | 0-1-1-0         | 2-1-1-2         |
| 3+2            | 3-9-7-14      | 0-1-1-0         | 2-1-1-2         |
| 4+2            | 2-8-17-14     | 0-2-1-0         | 2-0-1-2         |
| 5+2            | 4-11-5-7-14   | 0-1-0-1-0       | 2-1-2-1-2       |
| 4+3            | 2-8-17-9-13   | 0-1-0-1-0       | 2-1-2-1-2       |
| 5+3            | 4-17-9-18-12  | 0-1-2-1-0       | 2-1-0-1-2       |
| 5+4            | 4-11-5-8-15   | 0-1-0-1-0       | 2-1-2-1-2       |

Table III also provides, for each link of two combined trips, the related capacity utilization factor and residual capacity utilization one (in columns 3 and 4 respectively). The two problems have been implemented utilizing the Lingo software. By solving Problem 1 considering the trips combined as in Table III, we obtain that the maximum cost saving is realized when trips \((3, 5)\) and \((4, 2)\) are executed in combination, while trip 1 is performed individually (Table IV). The value of the objective function of the solution found is equal to 30. As it is clear from Table III, the number of full trucks (with 2 TEU per links) increases when combining trips.

As it can be easily calculated by looking at Table IV, in case of serving each demand individually, the total cost is
TABLE IV
RESULTS OF PHASE TWO (FIRST OPTIMIZATION PROBLEM)

<table>
<thead>
<tr>
<th>Trips</th>
<th>Links</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-5-13</td>
<td>350</td>
</tr>
<tr>
<td>2</td>
<td>2-7-14</td>
<td>290</td>
</tr>
<tr>
<td>3</td>
<td>3-9-13</td>
<td>280</td>
</tr>
<tr>
<td>4</td>
<td>2-8-15</td>
<td>340</td>
</tr>
<tr>
<td>5</td>
<td>4-11-12</td>
<td>290</td>
</tr>
<tr>
<td>(3+5)</td>
<td>3-10-11-5-13</td>
<td>360</td>
</tr>
<tr>
<td>(4+2)</td>
<td>2-8-17-14</td>
<td>470</td>
</tr>
</tbody>
</table>

equal to 1550, while in case of combined trips (1, 3+5 and 4+2), the total cost decreases to 1180, with a saving of 370.

Finally, the second optimization problem (phase three) of the heuristic, whose goal is to assign trucks to trips, considers the combined trips (regarded as a single trip with a longer duration) derived from the first optimization phase with not combined ones.

Table V provides the results obtained by solving Problem 2, in which 15 trucks are considered, each one having different time availability (working time spans, expressed in minutes), and different associated costs (expressed in cost per Kilometre). More specifically, the assignment of trips to trucks is shown in the last column of Table V. As it can be seen, only trucks number 2, 3, 13 and 15 are activated; moreover, it is worth noting that trucks number 8, 9 and 10 are not chosen despite their higher time availability and this is due to their higher operating costs.

TABLE V
RESULTS OF PHASE THREE (SECOND OPTIMIZATION PROBLEM)

<table>
<thead>
<tr>
<th>Trucks</th>
<th>Trucks availability</th>
<th>Truck cost</th>
<th>Links assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>3</td>
<td>4-3; 1-2</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>4</td>
<td>1-4; 3-4; 3-4-1</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>1</td>
<td>1-5-13</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>2</td>
<td>3-9-13</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>3</td>
<td>2-8-15</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>4</td>
<td>4-11-12</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>5</td>
<td>(3+5)</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>7</td>
<td>(4+2)</td>
</tr>
<tr>
<td>9</td>
<td>1000</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1200</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>500</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>500</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>500</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>500</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1000</td>
<td>4</td>
<td>2-1; 2-3; 2-4; 4-2</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

This paper proposes a heuristic approach with the goal of serving a container transportation demand of a single truck carrier by minimizing its costs. In order to do that, trips which do not allow to compose full trucks are combined in an optimal way and the optimal combination of trucks-trips is determined.

The heuristic is formulated as three phase algorithm: firstly, decomposition of the demand and definition of combination of trips based on a set of pre-defined rules, subsequently a first optimization problem allows to combine possible trips with the goal of increasing trucks capacity usage and, finally, a second optimization problem permits to assign trucks to trips with the goal of minimizing operating cost.

The proposed heuristic has demonstrated to be effective in serving all the required demand while minimizing the total costs and optimizing trucks capacity utilization. The methodology has been tested on numerous example of similar size and the results are good in all the analyzed cases. Future research will be devoted to apply the proposed heuristic to bigger instances utilizing real network data and to enlarge the problem to multiple carriers. Moreover, further efforts will be dedicated to properly model negotiation mechanisms among carriers in order to improve the solutions found.

REFERENCES