Cooperation among truck carriers in seaport containerized transportation

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Claudia Caballini[a], Simona Sacone[a], Mahnam Saeednia[b]

[a] *DIBRIS-Department of Informatics, BioEngineering, Robotics and Systems Engineering*
University of Genova, Italy
[b] *IVT-Institute for Transport Planning and Systems*
Swiss Federal Institute of Technology, Zurich, Switzerland

Abstract

Nowadays the majority of goods passing through seaports are transported by road, resulting in a large number of empty movements and high total costs. This paper proposes an optimization model for the cooperative planning of multiple truck carriers operations in a seaport environment for maximizing the total profit derived from their cooperation. A compensation mechanism is introduced for motivating carriers to share their trips. Time windows, trips deadlines and fleet sizes are considered. The planning approach is evaluated using real data sets of the Italian port of Genoa. Numerous scenarios are tested and an extensive computational analysis is reported.

Keywords: Road freight transportation, drayage operations, horizontal cooperation, mathematical programming

1. INTRODUCTION

Today, the negative impacts resulting from road freight transportation is of major concern. It contributes to road congestion and environmental pollution ([1] [2]). This issue is more significant in areas surrounding ports which are the origin and destination of high and increasing volumes of containers moving on a daily basis [3].

[1] Email:claudia.caballini@unige.it,simona.sacone@unige.it,mahnam.saeednia@ivt.baug.ethz.ch.

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As a matter of fact, seaports represent areas where high volumes of containers originate or end, giving rise to a significant number of transportation operations to/from the hinterland. These short distance movements are also denoted as drayage operations and are mainly realized by road [4]. Usually, a truck that picks up/delivers a full container in a port must return the empty container at/to its point of pick up, thus generating an empty movement, which decreases the carrier's profit and also contributes to increasing congestion on roads [5].

In this perspective, a beneficial action both for trucking companies (from an economic point of view) and for the social community (from congestion and pollution viewpoints) is represented by an effective planning of road transport operations. Such planning aims at maximizing the profit gained by the different actors, which is equivalent to the reduction of unproductive (i.e. empty) movements. One of the approaches to achieve this goal is not only the proper organization (possibly through optimization) of trips belonging to the same carrier (i.e. the trucking company) but also the definition of cooperation schemes in which different carriers share their demands to find the most suitable combination of trips in a broader context [6].

To further analyze the considered port context, the occurrence of inefficient trips in case of drayage transport is due to commercial and operational reasons, some of which are stated in the following:

- lack of planning tools or skills by road carriers (or freight forwarders in case they own the trips), especially considering that in many countries the majority of trucking companies are of small size and run at a domestic level;
- unwillingness of leasing trips to other carriers due to concerns related to the possibility of losing customers;
- imposition, by shipping companies - which are the usual owners of containers - to leave or pick up empty containers in specific empty depots located near to the origin of trips (which is usually represented by the

port for what concerns the import cycle and by an area near the inland node for what regards the export one) or in locations that do not allow the truck to travel full. This is due to the inclination of shipping companies to dominate the inland transportation.

Then, it is important to design methods and realize tools for road transport operators to make them aware and convinced of the advantages of effectively planning their trips. Moreover, it is also crucial to define collaboration schemes making single carriers act as a network, thus gaining competitiveness in their market. Finally, an effective planning of road trips is also beneficial as a whole, both for reducing congestion and for decreasing the social impacts resulting from a high presence of trucks on road networks.

Considering the high potential of improving trucking operations connecting seaports to their hinterlands as described above, the present paper studies one form of collaboration among multiple carriers serving their container demand to/from a seaport. The proposed collaboration scheme is a centralized one in which all the trips constituting the demand of carriers acting in the scheme are considered as a whole, and such trips are effectively organized. The goal is to optimally combine import and export trips (possibly related to the demand of different carriers) in order to maximize the total profit obtained by carriers. The proposed scheme ensures that the profit obtained in the cooperative scheme is higher than the the carriers initial income (i.e. without collaboration). A compensation mechanism is introduced which motivates carriers to share their trips with their competitors. Various constraints such as the time windows of port terminals and companies as well as the deadlines of trips are taken into account.

The paper is organized as follows: in the following Section, the most relevant previous research is mentioned along with the major gaps covered by the present study. In Section 3 the problem under consideration is described and in Section 4 the optimization model for planning the cooperation among multiple carriers is presented. Section 5 analyzes the results obtained by applying the model to a real case study; more specifically, in this section, 27 different scenarios have been compared and analyzed, and a deep insight into the compensation mechanism is provided. In Section 6 a computational analysis has been carried out in order to further test the efficiency of the proposed approach. Finally, some concluding remarks and highlights on future research are addressed in Section 7.

2. PREVIOUS RESEARCH

Drayage operations are the short-haul transportation of containers by trucks between seaports and inland terminals (customers/shippers) [7]. High numbers of such operations pose port management issues especially related to the organization of road gates procedures. The problem has been tackled in some studies by defining and analyzing port appointment systems [8], [9]. Actually, port appointment systems aimed at organizing the arrival and departure flows of trucks at port gates, finally succeed in improving the port management but do not yield significant benefits to the whole circulation of trucks in the hinterland.

As regards road freight transportation, the problem of planning trips for a single carrier dates back to three decades ago [10, 11]. Later, other authors have addressed this issue [12], [13]. This problem has been solved both for static and dynamic cases considering different objective functions, such as maximizing the total costs of deadheading or the total distribution costs. For instance, the work by Zhang et al. [14] formulates the truck scheduling problem with multiple depots and terminals considering inbound, outbound, full and empty trips. They optimize trucks operating times considering time windows of origin and destination nodes. The same objective is pursued in [7] where the sharing of trips within a single trucking firm is studied. Sterzik et al. [15] solved a comprehensive form of this problem considering vehicle routing and scheduling and empty container repositioning using an efficient Tabu Search Heuristic. Lai et al. [16] proposed a model for combining import and export trips related to a seaport assuming that trucks and containers are not separated during the service. This model minimizes the truck operating costs and is solved by using a variant of the Clarke-and-Wright algorithm improved by a sequence of local search phases.

More recent studies shift attention from single carrier cases to the possibility of fostering collaboration among two or more actors (i.e. carriers or shippers). Two main research streams defined as vertical collaboration and horizontal collaboration exist when dealing with cooperative schemes in transportation. In the case which a form of collaboration is established among decision makers acting at different levels in the logistic chain (for instance shippers, carriers and even customers), vertical collaboration takes place. Instead, collaboration schemes among actors belonging to the same level are denoted as horizontal collaboration. Being the objective of the paper that of defining an horizontal collaboration framework, some approaches of this kind are outlined here. Horizontal collaborations have been studied both among shippers ([17],[18], [19]) and among carriers ([20],[21]). In the second case, the aim is mainly that of reducing costs and competing with larger carrier companies while the main goal of collaboration among shippers is to negotiate better rates with the carriers. Ergun et al. [18] study how carriers can collaborate to minimize asset repositioning, thereby reducing deadhead trips. They formulate the problem in terms of a lane covering problem, in which a set of constrained cycles that cover a subset of arcs in a directed graph are found. The same authors in [22] aim at decreasing transportation costs through the definition of repetitive movements in which repositioning is reduced by exploiting the collaboration among carriers. Yilmaz and Savasaneril [17] study another form of this problem. They assume that shippers transport truckload shipments and have contracts with the carriers dedicating some of their fleet to the shipper.

As regards the collaboration among carriers and focusing on the topic of cost and benefit sharing in the coalitions, the work by Krajewska et al. [20] studied the distribution of both costs and savings arising from horizontal cooperation using cooperative game theory. Maximizing the total cost saving is the objective of a study by Caballini et al. [21] where the authors propose a simple planning approach for collaboration among multiple carriers.

These last works introduce a key aspect in cooperation schemes, i.e. the fact that a proper form of collaboration ensures a fair division of costs and savings among actors, preventing each actor to lose the customers related to the orders shared with the other carriers. Some works exist dealing with suitable ways of distributing costs and profits among the coalition participants and the majority of such works adopt simple game theory concepts. In particular, in [20] the computation of the Shapley value is just used to allocate costs among carriers and coalitions of carriers. Again game theory is adopted in [23] for the cost allocation in a vehicle routing problem.

As regards the adopted methodology, the studies that target the optimization of drayage operations through collaboration among carriers have utilized both simulation approaches (such as in [24], [25], [26]) and optimization methods. Since this paper uses optimization models as the main tool, here we focus on the second type of studies. Such studies differ in the objective function, the mechanism of sharing as well as the constraints. Xue et al.[27] minimize the total costs assuming that tasks are assigned to tractors which can be separated from trailers and assigned to new trips. In a comprehensive study, Sterzik et al. [28] study two main variants of this problem where the containers may or may not be shared within the seaport-hinterland transportation with the objective of minimizing the vehicles total operating time. Their study shows the potential benefits of sharing empty containers and it highlights the importance of developing motivating mechanisms so that the companies remain in the collaboration.

Based on the mentioned research, the main contribution of the present paper can be summarized as below:

- it maximizes profit which ensures the sustainability of the cooperation. In this case, a carrier does not participate in the coalition unless it is profitable for it;

- it provides a novel and effective compensation mechanism for the collaboration among a certain number of carriers;

- it considers the importance of a trip (and consequently that of a customer) for the related carrier;
- it considers specific and realistic features such as time windows of operations at the port/terminals/customers, the deadlines of trips to be served, and the maximum number of available trucks for each carrier.

Then, the present paper presents a novel form of modeling collaboration, which is simple and straightforward. Also, from a managerial insight, this can be useful for the trucking industries to simply implement it with a low level of technological competence.

3. PROBLEM DESCRIPTION

The problem of effectively organizing drayage operations performed by several carriers acting in the same geographical area is considered in this paper. The problem addressed here, which has been inspired by real case studies, presents several features which are described in this section.

First of all, the type of network taken into account is a “star-type” network (see Figure. 1) in which a logistic node, typically a port, takes on a central role in a sense that all the considered transportation operations are either generated by this node or have the node as their destination. By specifically considering containerized transportation, the kind of operations is also referred to as drayage operations. Drayage operations are defined as short-distance transport operations typically realized by road and aimed at moving containers between ports and inland terminals, logistics platforms, consolidation centres or company sites in the hinterland. The star-type network was firstly introduced by Clarke and Wright [29] for routing trucks in delivery operations, considering the port as a central node.

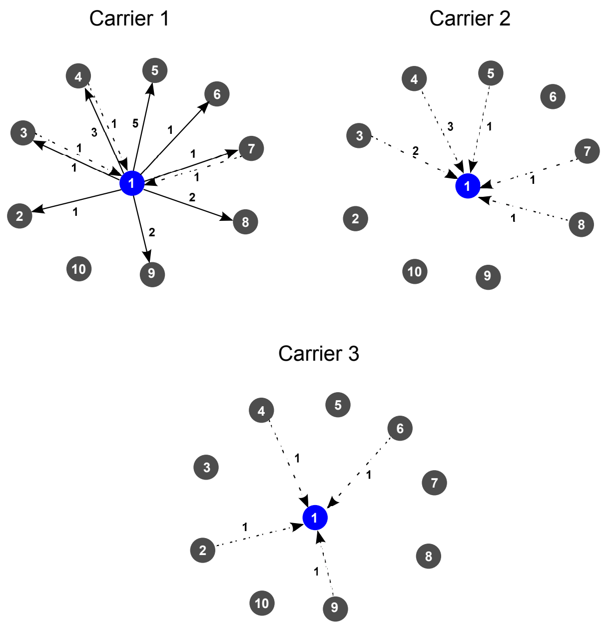

Figure 1: A star-type trip demand network for 3 carriers (a real example).

A major feature of the considered context lies in the presence of several carriers operating in the network for realizing the drayage operations. During the considered time horizon each carrier has to fulfill a specific transportation demand consisting in a set of trips to be performed on the network. The network structure and, specifically, the centrality of the port, implies that a trip can be carried out as a part of either the import or the export cycle, depending on whether goods arrive from sea to land (i.e. they are imported) or from land to sea (i.e. they are exported).

Moreover, each carrier is characterized by a unitary management cost, owns a certain number of trucks and, as already mentioned, has a certain amount of import and export trips to be fulfilled. Each trip has an origin, a destination, a deadline and it is characterized by a specific level of importance in relation to the customer that has ordered it.

When import and export cycles are taken into account, it is possible to distinguish between the case in which the import and export trips are performed separately, denoted as *Round Trips* (RT) and, the case in which import and export trips are combined in the so-called *Street Turns* (ST) or *backhaul* modality.

In a generic import RT, the following operations must be performed by a truck (Fig. 2, left side):

1. it picks up a full container in the port (node C);
2. it travels with the full container to the inland node where the container is stripped (link C-A);
3. it brings the empty container to a depot for empty containers pointed out by the shipping company and located inside or near the port (link A-C).

Taking into account a generic export RT, the operations to be executed by the haulier are the following ones (Fig. 2, left side):

1. the truck picks up an empty container from the depot of empty containers indicated by the shipping company, located inside or near the port (node C);
2. the truck travels to the inland node where the container is stuffed (link C-B);
3. the truck travels back to the port with the full container, where it is released to continue its trip by ship (link B-C).

In the ST modality (Fig. 2, right side), instead, import and export trips are combined. Specifically an import-export ST trip is composed of the following steps:

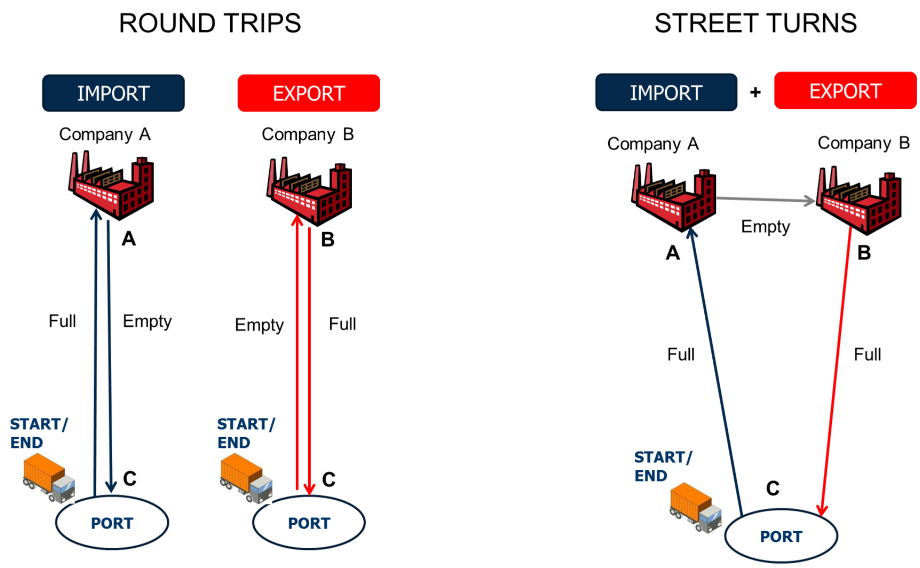

Figure 2: Scheme of a typical import and export Round Trip (left side) and a Street turn trip (right side).

1. the truck picks up a full container at the port (node C);
2. the truck travels with the full container to the inland node and waits for the container to be stripped (link C-A);
3. if the import company does not coincide with the export one, the truck travels with the empty container to another inland node where the container is stuffed for the export cycle (link A-B);
4. the truck travels with the full container to the port for delivering it (link B-C). The container continues its journey by ship.

An export-import ST trip is analogous to the import-export one; in both cases, the truck travels full on the two main links (C-A and B-C in Fig. 2, right side).

As a result, it is effective to consider the combination of no more than two trips due to the specific typology of the network. Moreover, if the planning is realized on a daily basis, it is again adequate to schedule few trips for each truck again which justifies to combine two trips for each truck cycle.

Regarding the usage of containers, two main cases are possible: the first one is the case in which one single container is used, assuming that the shipping line agrees to let the carrier use the same container for both import and export trips. In this first case, the driver has to wait a certain time at the inland node for the stuffing and stripping (unstuffing) of the container. In the second case, two different containers are used for the two cycles, so inland nodes should be provided with equipments for loading/unloading containers on/from trucks. Note that, in this latter case the circulation of empty containers should be faced. In this paper, we are considering the first case; however, from the modeling point of view these two cases differ only in the value of the time delay related to the waiting of the truck at the company. In addition, it is assumed that only one container is transported at a time (either 20' or 40' container), which is what happens in reality in the majority of cases, especially for what concerns full containers, due to weight constraints. Another assumption, which has a negligible impact on the model formulation, neglects the distance to be covered from empty depots to trips origins.

The goal of the present study is to optimally plan the activity of the different carriers in a cooperative environment in which carriers accept to share some trips. The adopted objective function considers the total carriers' profit which is maximized by suitably exploiting the capacity of trucks, i.e. by combining the import and export trips shared by the carriers involved in the collaboration. A compensation mechanism is designed to take into account the competitive nature of the trucking industry and to encourage carriers to share some of their trips with others.

4. MATHEMATICAL FORMULATION

In this section, the problem described above is furtherly detailed and stated as a mathematical programming problem. In order to properly formalize the problem, let us consider a generic network represented by the graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$, where the set of nodes and the set of links are represented by $\mathcal{V}$ and $\mathcal{A}$, respectively. Nodes represent the points where containers are stuffed and stripped while links represent portions of the road network that connect these points (which are assumed to be the shortest paths connecting each pair of nodes).

An optimization model is formulated for matching the trips shared by all carriers. The assignment is based on the revenues and costs sustained by each carrier taking into account compensation fees received by the carriers that give their trips to the others. Fig. 3 shows the proposed optimization scheme.

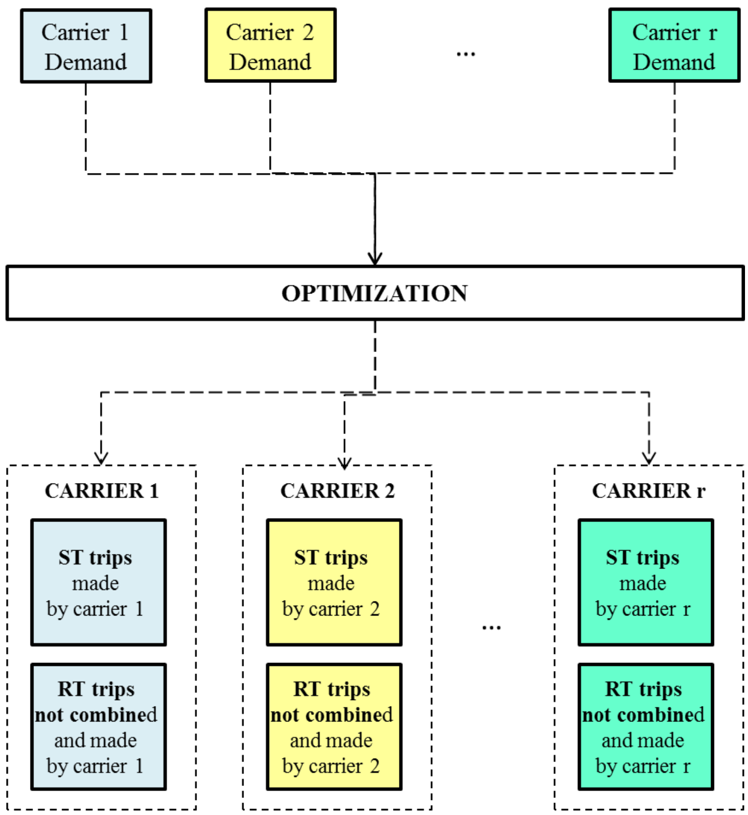

Figure 3: The proposed optimization scheme.

The objective of the mathematical model is to maximize the total profit of all carriers by coupling the shared RTs, two by two, resulting in an increase in the number of ST trips. Therefore, the number of empty trips is substantially reduced while the trucks utilization increases.

For modeling purposes, let us apply the following notation:

- $\mathcal{N}$, the set of import and export trips; N is its cardinality ($N = card(\mathcal{N})$);
- $\mathcal{R}$, the set of all carriers.

As regards the trips, the following notation is defined:

- $o_n, n \in \mathcal{N}$, the origin of trip n;
- $w_n, n \in \mathcal{N}$, the destination of trip n;
- $d_n, n \in \mathcal{N}$, the distance - expressed in kilometers - between the origin and destination of trip n;
- $t_n, n \in \mathcal{N}$, the required time for serving trip n. It comprises two terms, one depends on the distance to be covered and on the average speed v of a truck, and the other one considers the time β_n for stuffing and stripping the container in the nodes. So $t_n = \frac{d_n}{v} + \beta_n$;
- $\delta_n, n \in \mathcal{N}$, the compensation cost related to trip n. This value changes depending on the importance of each customer related to the carrier that owns it;
- $q_n, n \in \mathcal{N}$, the starting time of trip n;
- $f_n, n \in \mathcal{N}$, the finishing time of trip n; defined as: $f_n = q_n + t_n$;
- $h_n, n \in \mathcal{N}$, the deadline of trip n.

The notation referring to carriers is:

- $\mathcal{N}^r \in \mathcal{N}$, $r \in \mathcal{R}$, the set of trips owned by carrier r;
- $c^r, r \in \mathcal{R}$, the unitary cost of carrier r for performing its trips. It is expressed in euro/kilometre;

- $z_n^r \in \{0,1\}$, $n \in \mathcal{N}^r$, $r \in \mathcal{R}$, a parameter known in advance which assumes a value equal to 1 if trip n is performed by carrier r and 0 otherwise;

- $S_0^r, r \in \mathcal{R}$, the initial profit of carrier r for performing its trips autonomously;

- $S^r, r \in \mathcal{R}$, the final profit of carrier r which is composed of four terms: a profit obtained for performing single trips; a profit coming from the execution of combined trips; a profit related to the compensation costs that the carrier receives for giving some of its trips to other carriers; finally, a negative profit term related to the cost sustained by the carrier for compensating other carriers that gave their trips to it;

- $V^r, r \in \mathcal{R}$, the number of trucks available for carrier r.

Finally, e is the unitary revenue received by a carrier for executing a trip (euro/kilometre) and T is the total time available for a truck.

With reference to a pair of combined trips (n,k), $n,k \in \mathcal{N}$, the following notation is introduced:

- $d_{nk}, n,k \in \mathcal{N}$, the distance to be covered for serving the pair of trips (n,k); $d_{nk} = d_n + d_k$;

- $t_{nk}, n,k \in \mathcal{N}$, the total required time for serving the pair of trips (n,k) which includes the stuffing and stripping time at nodes as well as the repositioning time;

- $C_{nk}^d, n,k \in \mathcal{N}$, the eventual cost of delay arising in case of performing the combination of trips (n,k) and violating the deadline of trip k;

- c^d, the unitary cost of delay. The calculation of this time is described in the following;

- $\epsilon_{nk}, n,k \in \mathcal{N}$, the eventual repositioning distance needed to be covered by the truck when combining trips n and k (when the destination of trip n coincides with the origin of trip k there is no need for repositioning).

Moreover, soft and hard time constraints related to the deadline of trips and opening/closing times of nodes, respectively, are considered. So, let us introduce the following additional notation for defining time constraints:

- $f_{nk}, n, k \in \mathcal{N}$, the finishing time of the couple of trips (n, k);
- $P_n^o, n \in \mathcal{N}$, the opening time of the terminal/company where trip n starts;
- $\acute{P}_n^o, n \in \mathcal{N}$, the closing time of the terminal/company where trip n starts;
- $P_n^d, n \in \mathcal{N}$, the opening time of the terminal/company where trip n ends;
- $\acute{P}_n^d, n \in \mathcal{N}$, the closing time of the terminal/company where trip n ends.

Referring to a single ST trip, Fig. 4 provides a sketch of the proposed time window framework. In the upper diagram, the timing of not combined RT trips is reported whereas, in the lower diagram, the same timing in case the trips are combined is depicted.

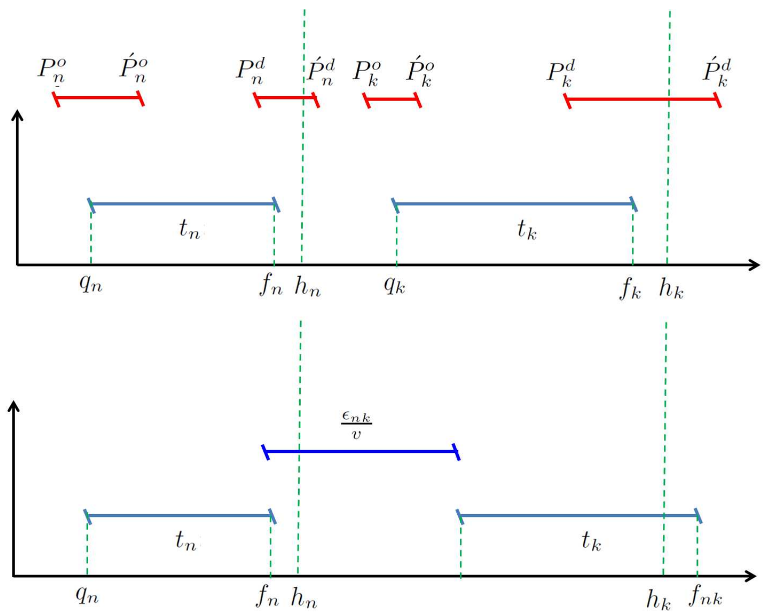

Figure 4: The time window framework.

It is assumed that, when combining two trips, the first one (e.g. trip n) is organized in order to respect its deadline h_n but, depending on the finishing time of the first trip (f_n) and the repositioning distance (ϵ_{nk}), the second one (e.g. trip k) may violate its deadline h_k (Fig. 4). In other words, coupling the trips can cause a delay to the second trip with the consequence that its deadline h_k is not respected anymore.

A pre-processing phase is necessary to calculate the finishing time of all the possible couples (n, k) and the eventual generated time delays. If trips n and k are combined, their finishing time f_{nk} is given by (1).

$$f_{nk} = f_n + \frac{\epsilon_{nk}}{v} + t_k \qquad n, k \in \mathcal{N}, n \neq k \tag{1}$$

In case the second trip ends after its deadline h_k, a delay cost incurs. The delay cost C^d_{nk} assumes different meanings, depending on whether the trip is an import or an export one: a potential delay related to the import trip n affects the deadline imposed by the inland node and may generate a penalty to be paid. On the other hand, a delay related to the export trip k may cause a "late arrival" fee or, even worse, a "change of vessel" fee if the delay causes the loss of the ship departure. Equation (2) expresses the calculation of the delay cost.

$$\begin{cases} C^d_{nk} = c^d(f_{nk} - h_k) & \text{if} \quad f_{nk} > h_k \\ C^d_{nk} = 0 & \text{if} \quad f_{nk} < h_k \end{cases} \tag{2}$$

As it can be noticed, we compute a delay cost only if the second trip is delayed with respect to its deadline, while if it arrives earlier no additional costs are considered. However, it may happen that a truck arrives at a company in advance with respect to its deadline. In this case, it has to wait for its turn which results in a wasted time; analogously, if it arrives at a large port terminal earlier than the "yard opening time" for its departure ship, the truck is not allowed to leave its container immediately or it has to pay an extra fee. Consequently, in such cases, an early arrival should be minimized as well and C^d_{nk} would be computed as $|f_{nk} - h_k|$. This can be easily introduced in the subsequent problem formulation.

Moreover, in order to exploit the unused capacity of trucks as much as possible, it is assumed that only an import and an export trip can be combined together. Therefore, two attributes o_{nk} and w_{nk} (whose definitions are shown in equations (3) and (4)) have been defined to prevent the combination of two import or two export trips:

$$o_{nk} = \begin{cases} 1 & \text{if} \quad o_n \neq o_k \\ M & \text{if} \quad o_n = o_k \end{cases} \tag{3}$$

$$w_{nk} = \begin{cases} 1 & \text{if} \quad w_n \neq w_k \\ M & \text{if} \quad w_n = w_k \end{cases} \tag{4}$$

being M a very large number.

The decision variables of the optimization problem are represented by:

- $y^r_{nk} \in \{0, 1\}$, $n, k \in \mathcal{N}, r \in R$, assuming a value equal to 1 if trips n and k are combined together and executed by carrier r, and 0 otherwise;
- $x^r_n \in \{0, 1\}$, $n \in \mathcal{N}, r \in R$, assuming a value equal to 1 if trip n is performed singularly by carrier r, and 0 otherwise.

The initial profit of each carrier, i.e. the one without street turns, is provided by equation (5).

$$S^r_0 = \sum_{n \in \mathcal{N}_r} 2 z^r_n d_n (e - c^r) \qquad \forall r \in R \tag{5}$$

The problem statement follows.

Problem

$$max \quad U = \sum_{r \in R} S^r \tag{6}$$

subject to

$$
\begin{aligned}
S^r = &\sum_{n \in \mathcal{N}^r} 2 d_n x_n^r (e - c^r) \\
&+ \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{N}} y_{nk}^r (e(d_n + d_k) - c^r(d_{nk} + \epsilon_{nk}) - C_{nk}^d) \\
&+ \sum_{r' \in R, r \neq r'} \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{N}} \Big(y_{nk}^{r'} (\delta_n z_n^r + \delta_k z_k^r) + x_n^{r'} (\delta_n z_n^r) \Big) \\
&- \sum_{r' \in R, r \neq r'} \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{N}} \Big(y_{nk}^r (\delta_n z_n^{r'} + \delta_k z_k^{r'}) + x_n^r (\delta_n z_n^{r'}) \Big) \\
& \qquad \forall r \in \mathcal{R} \qquad (7)
\end{aligned}
$$

$$
S^r \geq S_0^r \qquad \forall r \in \mathcal{R} \qquad (8)
$$

$$
M - M \sum_{r \in R} (y_{nk}^r + y_{kn}^r) \geq \sum_{r \in R} (x_n^r + x_k^r) \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad (9)
$$

$$
\sum_{r \in \mathcal{R}} \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{N}} (x_n^r + 2 y_{nk}^r) = N \qquad (10)
$$

$$
\sum_{r \in \mathcal{R}} x_n^r \leq 1 \quad \forall n \in \mathcal{N} \qquad (11)
$$

$$
t_{nk} y_{nk}^r \leq T \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \qquad (12)
$$

$$
\sum_{n \in N} \sum_{k \in N} (y_{nk}^r + y_{kn}^r + x_n^r) \leq V^r \qquad \forall r \in \mathcal{R} \qquad (13)
$$

$$
\sum_{k \in \mathcal{N}} (y_{kn}^r + y_{nk}^r) \leq 1 \qquad \forall n \in \mathcal{N} \qquad \forall r \in \mathcal{R} \qquad (14)
$$

$$
\sum_{r \in R} (y_{nk}^r + y_{nk}^r) \leq 1 \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad (15)
$$

$$q_k y^r_{nk} + M(1 - y^r_{nk}) \geq f_n + \frac{\epsilon_{nk}}{v} \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{16}$$

$$(f_{nk} - P^d_k) y^r_{nk} \geq 0 \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{17}$$

$$f_{nk} y^r_{nk} \leq \acute{P}^d_k \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{18}$$

$$(f_{nk} - t_k - P^o_k) y^r_{nk} \geq 0 \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{19}$$

$$(f_{nk} - t_k) y^r_{nk} \leq \acute{P}^o_k \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{20}$$

$$o_{nk} y^r_{nk} \leq 1 \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{21}$$

$$w_{nk} y^r_{nk} \leq 1 \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{22}$$

$$x^r_n \in \{0, 1\} \qquad \forall n \in \mathcal{N} \qquad \forall r \in \mathcal{R} \tag{23}$$

$$y^r_{nk} \in \{0, 1\} \qquad \forall n, k \in \mathcal{N}, n \neq k \qquad \forall r \in \mathcal{R} \tag{24}$$

The resulting problem is a Binary Linear Programming (BLP) problem in which the objective function (6) is the sum of the profits of all carriers.

Constraints (7) define the profit of each carrier while constraints (8) assure that the final profit of each carrier is bigger than/equal to its initial profit.

Constraints (9) define the relations between coupled and single trips, whereas constraints (10) makes sure that the whole demand of trips is executed.

Each single trip must be performed by no more than one carrier, as defined by constraints (11). Constraints (12) ensure that the time required by a truck for performing a certain number of trips is not exceeding its total time availability, while constraints (13) avoid assigning to each carrier more trips than the maximum number of its available trucks. Constraints (14) make sure that each trip is not combined more than once, while constraints (15) grant that each pair of combined trips is executed only by one carrier. The respecting of timing of trips in a combination is assured by constraints (16), while constraints (17), (18), (19) and (20) are related to the respect of terminals and companies time windows. The combination of an import and export trip is assured by constraints (21) and (22). Finally, constraints (23) and (24) define the nature of the decision variables of the problem.

By solving Problem 1, a set of combined ST trips and RT trips are obtained and assigned to the carriers. This output maximizes their profit as well as their trucks' capacity usage and, consequently, it reduces the number of empty trips performed.

Note that, in case carriers are not willing to share some of their trips with their competitors, the model is still valid and it is sufficient to preassign some variables, i.e. to fix the x_n^r values to zero to prevent it from assigning trips to the carriers which do not own them.

5. EXPERIMENTAL RESULTS

In order to evaluate the effectiveness of the proposed methodology, the BILP optimization model described in Section 4 has been implemented in Visual Studio 2012 ♯ by using Cplex 12.3 as ILP solver. An extensive experimental campaign is carried out based on real data regarding the daily truck trips related to the port of Genoa, in Italy. In order to analyze the performance of the model and the effect of various factors on the efficiency of collaboration, first, a real case is studied by analyzing 27 different scenarios. Then, a computational analysis is carried out to test the efficiency of the model using extensive case studies with larger numbers of trips as well as carriers.

5.1. Case Study Description

The primary case includes a total of 30 daily trips, which are carried out by three carriers whose demand is shown in Fig. 1. It is assumed that each carrier is serving the same area composed of 10 nodes: a seaport and 9 companies spread in the North-West area of Italy, near Milan. The number of trips to be served is specified near each link and is expressed in terms of the number of containers to be transported between each pair of nodes. It is assumed that the trucks take the shortest route connecting the port and the companies (as shown by direct arrows).

Table 1 reports the input data related to trips' features and, more specifically, the trip reference number, the distance to be covered in order to execute it, the origin and destination nodes, the carrier that owns the trip and the deadline of each trip. Table 2 provides all features related to the nodes of the considered network. The time window of the port (node number 5) is between 6 a.m. and 10 p.m. which corresponds to the gate opening hours, whereas all other nodes corresponding to companies are supposed to open at 8 a.m and close at 6 p.m.

Table 1: Case study - data related to trips.

Trip	Distance	Origin	Destination	Carrier	Deadline
1	215	1	4	1	10 a.m.
2	160	1	5	1	11 a.m.
3	124	1	8	1	9 a.m.
4	247	1	9	1	10 a.m.
5	116	1	4	1	10 a.m.
6	146	1	6	1	8 a.m.
7	220	1	8	1	11 a.m.
8	166	1	5	1	9 a.m.
9	133	1	5	1	11 a.m.
10	101	1	4	1	11 a.m.
11	214	1	5	1	8 a.m.
12	104	1	3	1	8 a.m.
13	101	1	9	1	11 a.m.
14	176	1	7	1	11 a.m.
15	157	1	5	1	9 a.m.
16	141	3	1	1	10 a.m.
17	205	4	1	1	9 a.m.
18	135	7	1	1	11 a.m.
19	209	8	1	2	9 a.m.
20	113	3	1	2	10 a.m.
21	112	5	1	2	11 a.m.
22	150	7	1	2	11 a.m.
23	149	4	1	2	11 a.m.
24	209	4	1	2	9 a.m.
25	234	3	1	2	11 a.m.
26	221	4	1	2	11 a.m.
27	198	2	1	3	10 a.m.
28	239	9	1	3	9 a.m.
29	114	6	1	3	9 a.m.
30	203	4	1	3	8 a.m.

Table 2: Case study - data related to network nodes.

Node	Opening time	Closing time	Type of node
1	8 a.m.	6 p.m.	company
2	8 a.m.	6 p.m.	company
3	8 a.m.	6 p.m.	company
4	8 a.m.	6 p.m.	company
5	6 a.m.	10 p.m.	port terminal
6	8 a.m.	6 p.m.	company
7	8 a.m.	6 p.m.	company
8	8 a.m.	6 p.m.	company

Table 3 provides the features of all the scenarios that have been run and analyzed: they differ in terms of time windows ("standard" refers to the framework provided in Table 2 while "extended" refers to a situation in which all nodes are open from 6 a.m. to 8 p.m.), unitary carrier cost c^r (expressed in *euro/km*), compensation factor δ_n (expressed in *euro*. Note that letter "a" in scenario 10 means that δ_n is equal to 100 for the first 24 trips and 50 for the remaining 6; letter "b" in scenario 11 means that δ_n is equal to 100 for the first 18 trips and 50 for the remaining 12, while letter "c" in scenario 12 means that the δ_n is equal to 50 for the first 9 trips and 100 for the remaining 11 ones), number of available trucks per carrier V^r, unitary delay cost c^d, repositioning distance ϵ_{nk}, initial assignment of trips to carriers z_{nr} and split between import (I) and export (E) trips. Note that, regarding δ_n and ϵ_{nk}, when considering, for instance, the notation (50,100), we indicate a random value between 50 and 100. The average truck speed has been set to 50 km/h for all the trucks.

Table 3: Features of analyzed scenarios.

Sc.♯	**Time w.**	c^r	δ_n	V^r	c^d	ϵ_{nk}	z_{nr}	**I/E**
1	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	18-8-4	18-12
2	extended	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	18-8-4	18-12
3	standard	1-1-1	(50,100)	10-7-5	10	(10,40)	18-8-4	18-12
4	standard	1.1-0.8-1.1	(50,100)	10-7-5	10	(10,40)	18-8-4	18-12
5	standard	1.2-1.1-0.8	(50,100)	10-7-5	10	(10,40)	18-8-4	18-12
6	standard	0.8-1.1-1.2	(0,10)	10-7-5	10	(10,40)	18-8-4	18-12
7	standard	0.8-1.1-1.2	0	10-7-5	10	(10,40)	18-8-4	18-12
8	standard	0.8-1.1-1.2	50	10-7-5	10	(10,40)	18-8-4	18-12
9	standard	0.8-1.1-1.2	100	10-7-5	10	(10,40)	18-8-4	18-12
10	standard	0.8-1.1-1.2	a	10-7-5	10	(10,40)	18-8-4	18-12
11	standard	0.8-1.1-1.2	b	10-7-5	10	(10,40)	18-8-4	18-12
12	standard	0.8-1.1-1.2	c	10-7-5	10	(10,40)	18-8-4	18-12
13	standard	0.8-1.1-1.2	(50,100)	8-7-10	10	(10,40)	18-8-4	18-12
14	standard	0.8-1.1-1.2	(50,100)	1-5-10	10	(10,40)	18-8-4	18-12
15	standard	0.8-1.1-1.2	(50,100)	10-7-5	20	(10,40)	18-8-4	18-12
16	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(50,100)	18-8-4	18-12
17	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	30-0-0	18-12
18	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	0-30-0	18-12
19	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	0-0-30	18-12
20	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	18-8-4	18-12
21	standard	1.2-1.1-0.8	0	10-10-10	10	(10,40)	18-8-4	18-12
22	standard	0.8-1.1-1.2	100	0-7-5	10	(10,40)	30-0-0	18-12
23	standard	1-1-1	100	10-7-5	0	(10,40)	30-0-0	18-12
24	standard	1-1-1	100	6-7-7	0	(10,40)	30-0-0	18-12
25	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	12-9-9	18-12
26	standard	0.8-1.1-1.2	(50,100)	10-7-5	10	(10,40)	18-8-4	15-15
27	standard	1-1-1	100	6-7-7	0	(10,40)	30-0-0	15-15

5.2. Analysis of Results: Carriers Profit

In this subsection we analyze how the profit of carriers changes by varying both the strategies of sharing trips and the scenarios. The initial profit of carriers is calculated assuming that a carrier does not share trips with the other ones, so executing all of them individually. In reality, there is a further consideration to be made: since the maximum number of trips that a carrier can receive from others is limited by the available number of trucks that it owns, it might be beneficial if a carrier shares also the single trips that have not been paired during the optimization process. This possibility is already considered in the BLP model that has been stated in the paper. In real case studies, it can also happen that carriers are available for sharing trips with others in order to combine them but they prefer to maintain the single trips that they own, without sharing also single trips. Therefore, two possible strategies can be implemented:

- *Strategy A*: single trips that are not combined are shared with other carriers;
- *Strategy B*: single trips that are not combined have to be performed by the carrier that initially owns them.

Note that *strategy A* is implemented by using exactly the BLP model (equations (6)- (24)) presented above. As regards *strategy B*, a slightly different version of the BLP model is used; specifically, the first term of equation (7) (i.e. $\sum_{n\in\mathcal{N}^r} 2d_n x_n^r (e-c^r)$) is replaced by the following term:

$$\sum_{n\in\mathcal{N}^r} 2d_n x_n z_n^r (e-c^r) \tag{25}$$

This term ensures that each carrier performs all the single trips that he initially owns, in case they are not combined with any other trip.

A comparison between the two different strategies has been carried out and the obtained results are shown in Figures 5 and 6. In all scenarios and in both strategies, the final profit of carriers increased significantly, highlighting the importance of collaboration. It can be noted that the continuous red line illustrating the profit of carriers in strategy A is always higher than/equal to the dotted blue line related to strategy B. This is due to the fact that, when considering strategy A, there is a higher degree of freedom to find more optimal solutions by better matching the supply (available trucks) with the demand (trips) of all carriers. Note also that, when applying strategy B to scenario 14, no feasible solution is found because the number of available trucks of carrier 1 is not sufficient to satisfy all the single trips that he should perform. So, in the following analysis, only strategy A is considered.

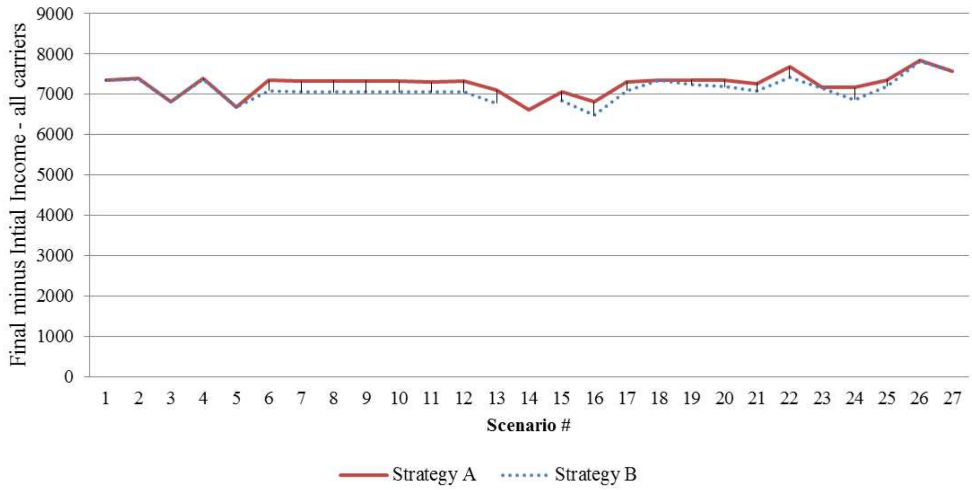

Figure 5: Final minus initial profit - sum over all carriers. Comparison between strategies A and B.

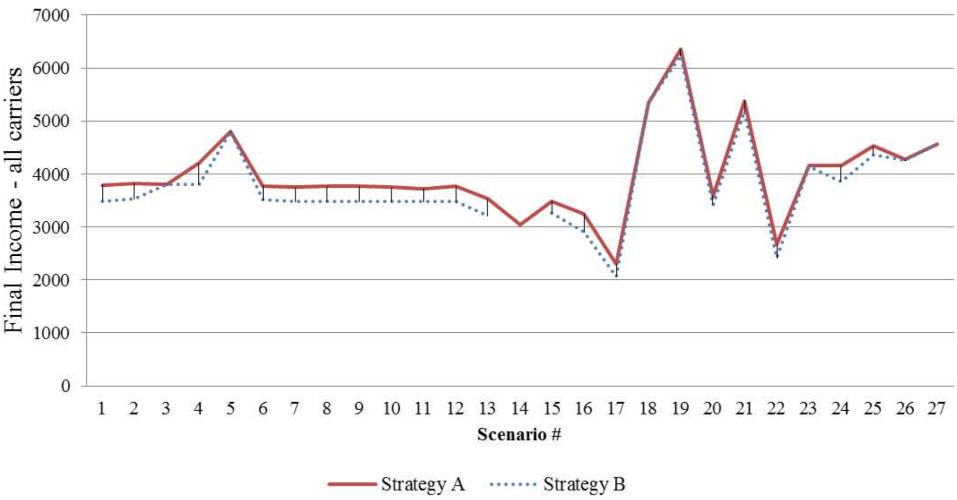

Figure 6: Final profit - sum over all carriers. Comparison between strategies A and B.

Figures 7, 8, and 9 provide an overview of the final and initial profits of carriers (red and blue bars, respectively) as well as the number of trips (yellow dotted lines) that each of them performs in various scenarios, by applying strategy A which provides better results, as demonstrated above. Carrier 1 executes the highest number of trips (Figure 7) and has the highest final profit; this is due to the fact that, except for scenarios 18 and 19, in all the other ones carrier 1 owns the highest number of trips. Moreover, in most scenarios this carrier has the lowest unitary cost c^r which makes it a profitable choice for executing trips.

By comparing the results obtained in scenarios 17, 18 and 19, it can be seen that in case all trips are owned by carrier 2 (scenario 18), still carrier 1 continues to get the highest profit and the largest number of trips. This is due to the fact that it owns a higher number of trucks and has the lowest operational cost. This effect is even amplified in scenario 19 where carrier 3 has got the highest unitary cost and owns the lowest number of trucks.

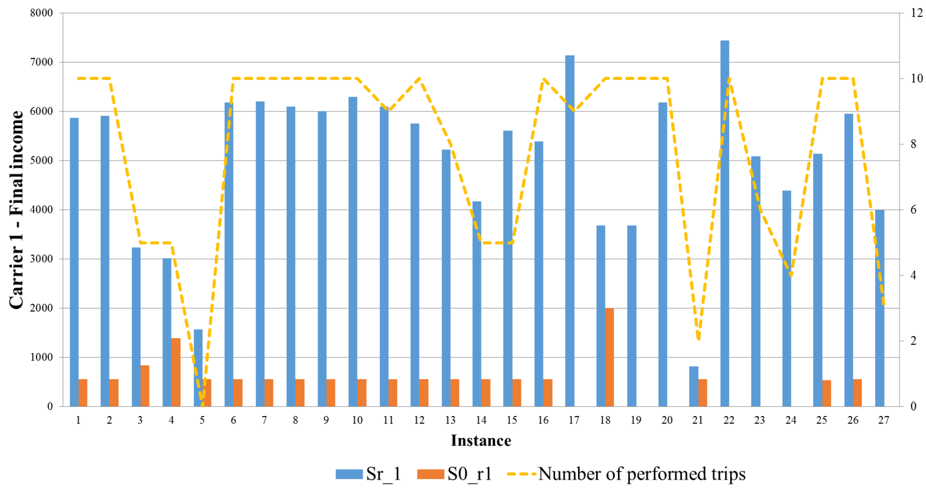

Figure 7: Carrier 1 - final profit, initial profit and number of trips performed.

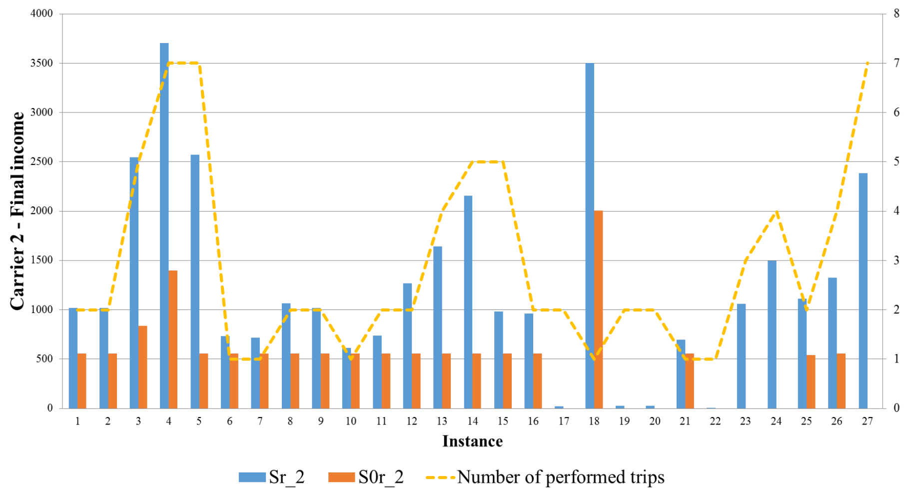

Figure 8: Carrier 2 - final profit, initial profit and number of trips performed.

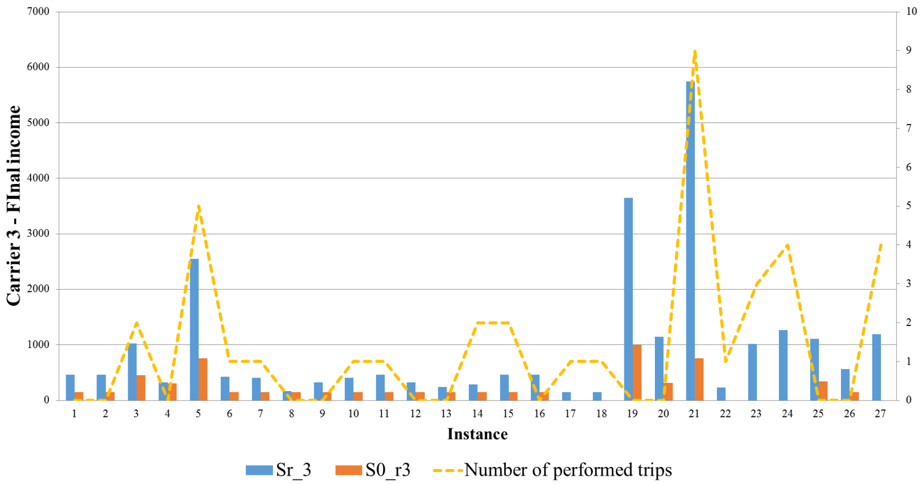

Figure 9: Carrier 3 - final profit, initial profit and number of trips performed.

Moreover, Figure 10 shows the assignment of Round Trips (x_n^r) to different carriers. In this analysis, it is assumed that the carriers follow Strategy A, i.e. single trips that are not combined can be shared with other carriers.

In scenarios 1 to 17 single trips are owned by carrier 1, in scenario 18 all trips are owned by carrier 2, and in scenario 19 carrier 3 owns all trips. In the three remaining scenarios, trips initially belong to various carriers: in scenario 20, 4 trips are owned by carrier 1 and 2 trips belong to carrier 3;in scenario 25, 5 trips are owned by carrier 1 and 1 trip by carrier 2, and in scenario 26, 1 trip is owned by carrier 1 and 1 trip by carrier 2. Note that these results must be jointly analyzed with the ones presented in Figures 7, 8 and 9. Lower operational costs and the fact that each carrier owns a limited number of trucks (which may prefer to assign them to ST trips) are the reasons for sharing RT trips among carriers. For instance, considering scenario #5, carrier 1 performs all single trips which it owns. This can be analyzed as follows: referring to Figure 7, it can be noticed that carrier 1 performs the lowest number of ST trips in scenario #5. This is related to the higher operational unitary cost ($c^r = 1.2$) of this carrier in comparison to others (table 3). Therefore, it is not profitable for other carriers to share their trips with carrier 1. As a result, due to the limited number of trucks available for performing trips, carrier 1 has the possibility to perform its own RT trips. On the contrary, considering scenarios # 6 and # 7, carrier 1 has the lowest operational costs making it a profitable option for performing shared trips. Therefore, having a limited number of vehicles, carrier 1 will not have the possibility to execute its RT trips. It can be noticed in Figure 7, that carrier 1 has its highest profit in these two scenarios.

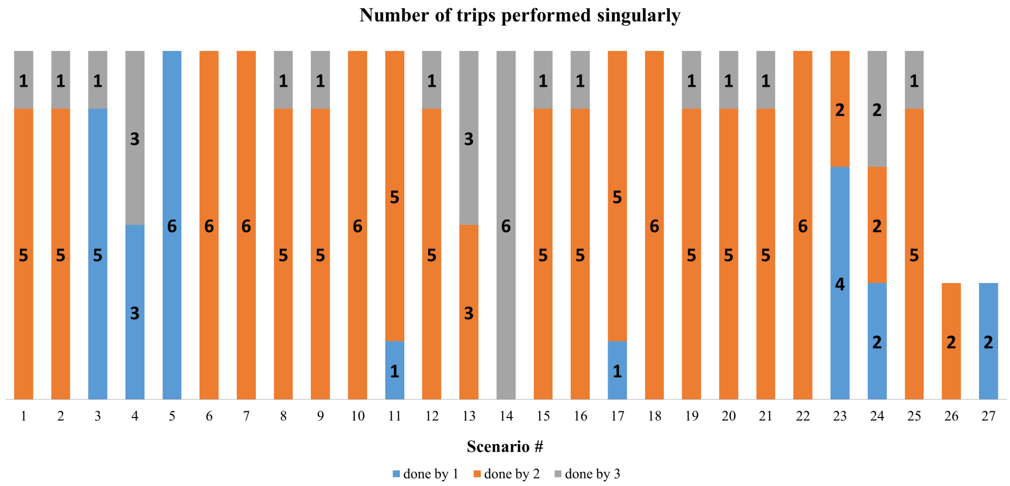

Figure 10: Distribution of single trips among carriers per each scenario.

Moreover, figure 11 depicts the increase in the profit of carriers with and without cooperation in relation to a different number of trips and carriers (see instances in Table 4). The red bars show the objective function of the model stating the earning of carriers. The blue bars show the initial profit of carriers referring to a situation when each of them serves its own trips and does not share them with other carriers. As it is quite well depicted by this graph, the profit of all carriers increases by forming a coalition, provided that the profitability of the cooperation is ensured for each individual carrier.

Table 4: Instances with varying number of trips and carriers.

Ins. #	Import trips #	Export trips #	Carriers #
1	30	30	6
2	40	40	6
3	50	50	6
4	60	60	6
5	70	70	6
6	80	80	6
7	90	90	6
8	100	100	6
9	110	100	6
10	110	110	6
11	30	30	8
12	30	30	10
13	30	30	12
14	30	30	20

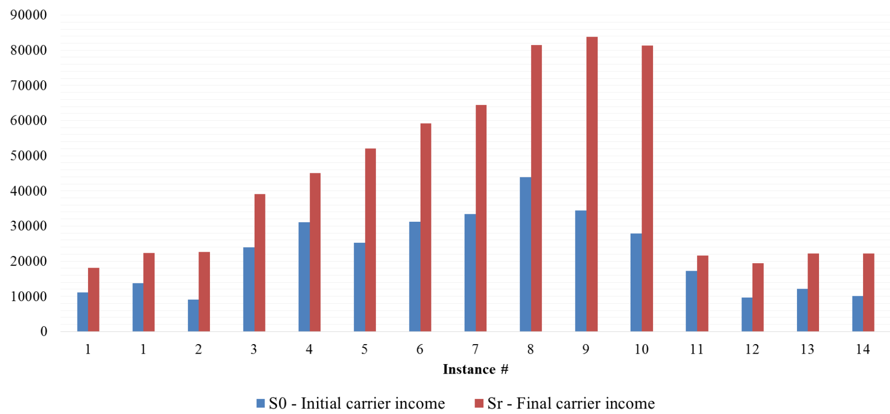

Figure 11: The initial - without cooperation - and final profit of carriers (in Euro) in relation to different number of trips (instances 1-10) and carriers (instances 11-14).

525 *5.3. Analysis of Results: δ Values*

In this section, the compensation mechanism developed in this paper is further analyzed and commented on. A first analysis that has been done with respect to the value of the compensation factor δ_n, refers to the impact that the choice of such a value has on the carriers' profit. In the above defined 27 scenarios, trip ownership distribution is selected according to the base scenario (i.e. scenario # 1), carriers' unitary costs c^r are assumed to be the same for all, and also the compensation factor is considered the same for all carriers and all trips, but its value changes between 100 and 450 for each trip. The effect of changes in δ_n values on the final profit of carriers is shown in Figure 12.

Carriers terminate sharing their trips for δ_n values higher than 450. When this happens, the final profit of at least one carrier drops below its initial profit (i.e. S_0) and it is no more available to share its trips with other carriers, thus terminating the cooperation.

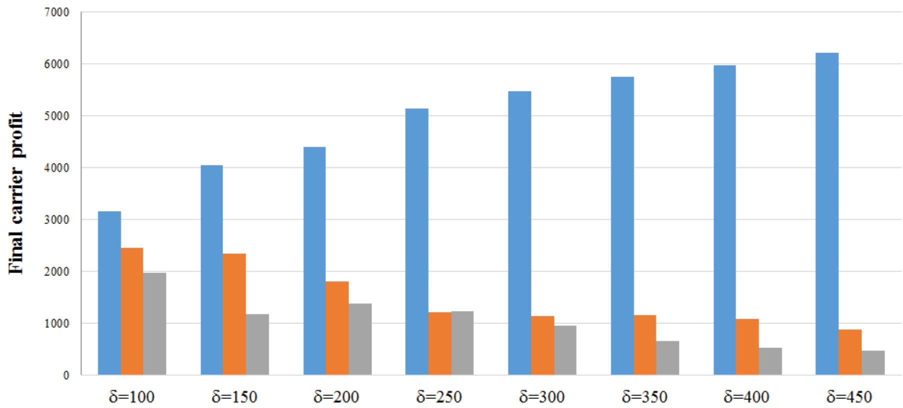

Figure 12: The effect of δ variation on carriers' final profit.

This analysis further confirms that a proper choice of the compensation value is crucial, being the compensation factor δ_n a key issue in enabling or disabling cooperation among carriers.

In order to carry out a deeper analysis, to understand which are suitable values of the compensation factor, we focus our attention on each carrier and on any possible pair of trips that the carrier could realize. The profit of the carrier in case two trips are assigned to it, can be calculated using equation (7), which is composed of four terms. Specifically, to make it convenient for a carrier r to borrow a generic couple of trips (n, k) initially belonging to other carriers, its revenue deriving from the execution of the couple of trips (i.e. the second term of equation (7)) has to be greater than the cost derived from the compensation given to the carriers who owned the two trips (i.e. the fourth term of equation (7)). This means that the inequality (26) must be satisfied for any couple of trips (n, k).

$$e(d_n + d_k) - c^r(d_{nk} + \epsilon_{nk}) - C^d_{nk} \geq \delta_n + \delta_k \quad (26)$$

assuming that $z^r_n = 0$ or $z^r_k = 0$, i.e. at least one of trips n and k is initially owned by a carrier different from r. Note that the third term of equation (7) is not considered since it refers to a pure profit term present in the case in which trips already belong to carrier r and are performed by another one.

Any carrier can use equation (26) to determine ranges of variation of the compensation factor to be provided to other carriers. Actually this implies the solution of sets of inequalities that are not very complex to be analysed. The main concern regards the number of pairs to be considered that actually grows with the number of trips involved, but the structure of the inequalities is very simple. The same ranges can also be analyzed by a more qualitative analysis as the one reported in the following. It consists in analyzing effective values of the compensation factors by varying only some terms of equation (26).

The surface in Fig.13 corresponds to the value of the left hand side of equation (26) obtained by varying the value of the trip distances d_n and d_k and, consequently the one of d_{nk}, and by fixing ϵ_{nk} and C^d_{nk} to 20 and 0 respectively. This surface provides the upper bound to the sum of the two compensation factors $\delta_n + \delta_k$ in order to satisfy the inequality (26), thus making it convenient for carrier r to get trips n and k.

In this case, it is always possible to find values of the two compensation factors satisfying equation (26). The same reasoning is done with reference to the surface shown in Fig.14 which, instead, provides the value of the left hand side of equation (26) when varying the unitary revenue e and the unitary cost c^r.

In such case, it can be noted that there are some values of the unitary revenue e and the unitary cost c^r making it impossible to find positive compensation

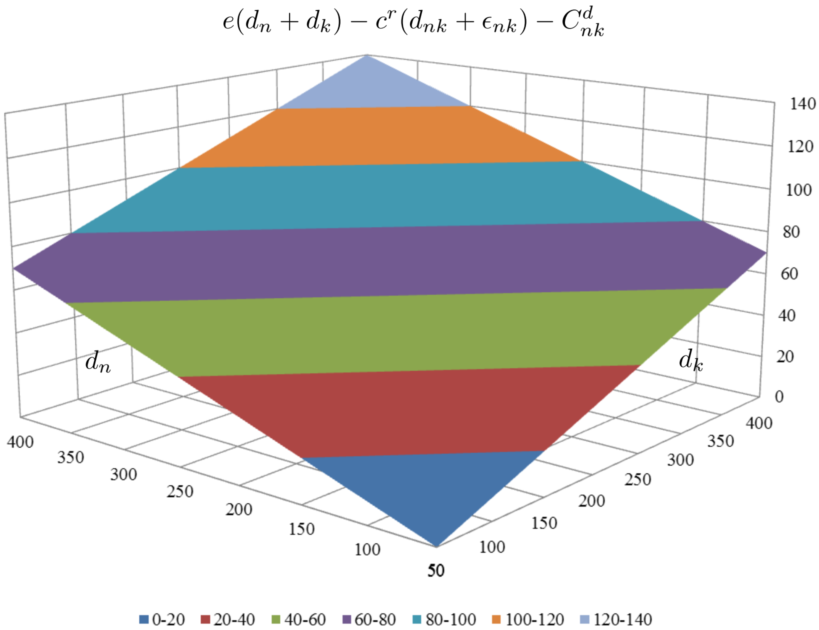

Figure 13: The value of the compensation factors by varying the distances of trips.

factors thus making it ineffective to share the trips. This simple analysis can be carried out by carriers to identify the least effective values of the compensation factors to be provided to other carriers in order to make the cooperation useful. Specifically, carriers can analyze the compensation factors by considering the above surfaces depending on the ranges of values of the left hand side terms of equation (26) including all the possible features of trips that they would borrow from others. So, by simply analyzing the two surfaces, each carrier is able to identify ranges of the compensation factors.

6. Computational Analysis

In order to evaluate the model's efficiency from the computational point of view, an extensive computational analysis has been carried out. Numerous instances, whose specifications are mentioned in Table 5 were tested and

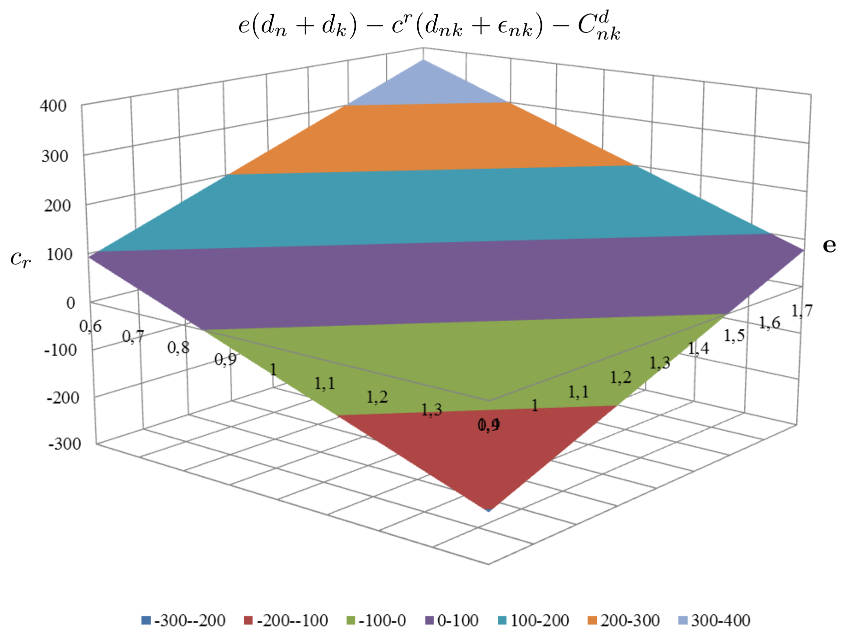

Figure 14: The value of the compensation factors by varying the distances of trips.

analyzed. In instances 1 to 10, the number of trips was gradually increased, while in instances 11 to 14 the number of carriers was raised in order to analyse the effect of the growth in the number of variables and constraints on the run time.

The calculations were carried out using a laptop having the following features: Intel Core i5 - 1.80 GHz with 8 GB of RAM. The maximum number of trips that can be handled with these hardware specifications was 220 trips, which can be increased using a more powerful hardware. However, it must be pointed out that this number is more than acceptable given the real average number of truck trips serving a standard port area on a daily basis.

Table 5 shows the results of the computational performance - in terms of the number of variables, the number of constraints, CPU time (seconds) and gap (%)- obtained as the average of 10 replications.

Table 5: Computational performance.

Ins. #	Import trips #	Export trips #	Carriers #	Variables #	Constraints #	CPU time	Gap
1	30	30	6	21966	71647	1000.30	0.01
2	40	40	6	38886	128615	1000.63	0.00
3	50	50	6	60606	200421	1000.88	0.07
4	60	60	6	87126	290515	3602.58	0.08
5	70	70	6	118446	399383	3602.25	0.07
6	80	80	6	154566	514089	3602.40	0.04
7	90	90	6	195486	656071	3602.82	0.06
8	100	100	6	241206	811157	3603.63	0.04
9	110	100	6	265866	894916	3604.51	0.06
10	110	110	6	291726	982689	3604.59	0.03
11	30	30	8	27384	87356	1000.39	0.05
12	30	30	10	34230	109596	1000.55	0.04
13	30	30	12	41076	129504	1000.58	0.04
14	30	30	20	68460	214136	1001.00	0.06

The computational time for solving instances 1-3 is around 1000 seconds, while it increases significantly (to about one hour) as the number of trips is higher than 100 (instances 4-10). On the contrary, as shown in figure 15, the effect of increasing the number of carriers proved not to be significant.

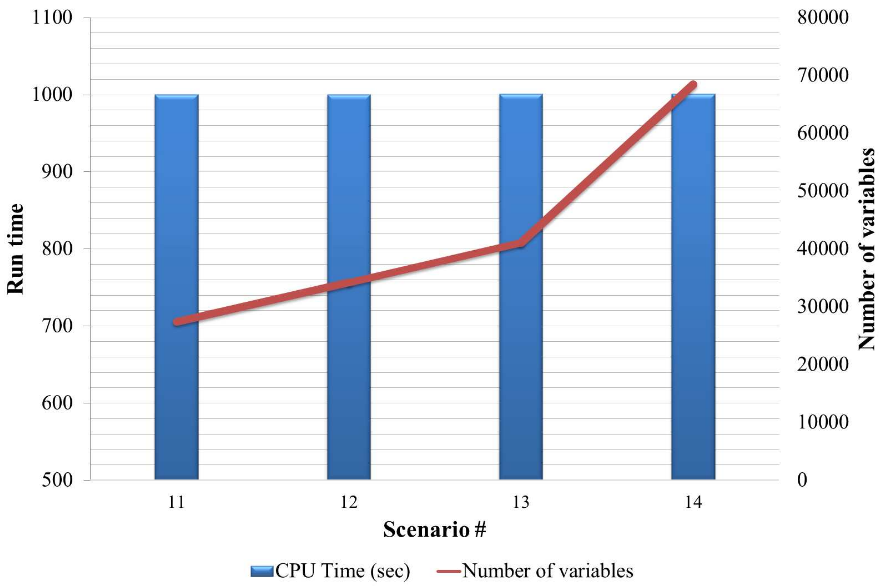

Figure 15: The effect of increasing the number of carriers on the run time

Overall, the problem faced in this paper needs to be solved off-line, for instance some hours before the starting time of trips. Therefore, the run time of the program is not of great concern.

The time limit imposed to the solver of the program (i.e. the maximum elapsed time) was set to 3600 seconds. However, the gap tolerance decreases significantly within a very short time, enabling us to obtain a “good solution” within few minutes. Figure 16 shows the changes in the gap over time with a reasonable solution obtained within 200 seconds.

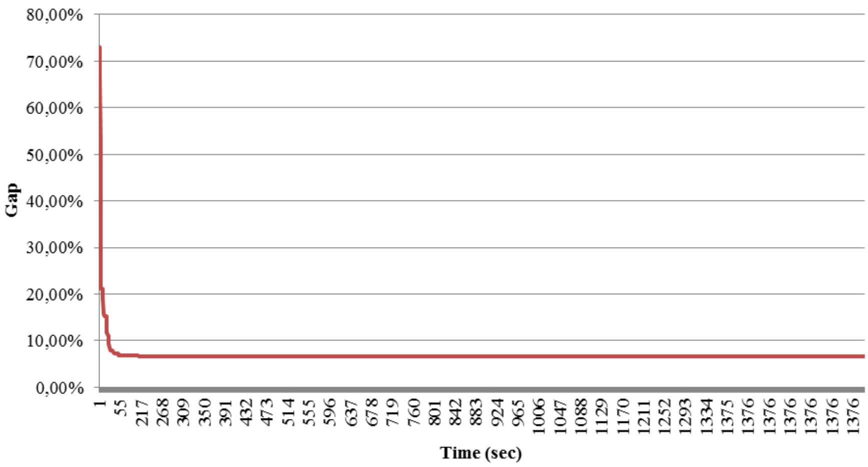

Figure 16: Changes in the gap over time

7. Conclusions

In this paper a cooperative framework was proposed for truck carriers serving the hinterland area of a port. The goal of each carrier is to satisfy its demand of import and export trips while maximizing its profit. The cooperation is valid as long as the final profit of carriers exceeds their initial profit. This form of cooperation, in addition to economic advantages for the collaborating carriers, results in positive environmental impacts in terms of reduction of congestion and pollution.

The main contributions of this paper with respect to the obtained conclusions can be summarized as follows:

- it considers a star-type network where the port is the central node. This enables considering import and export trips belonging to the port area;

- it proposes a novel compensation mechanism for sharing trips among carriers. Based on this mechanism, a carrier receives a compensation for giving its trip to another carrier depending on the importance of that trip and the related customer. The choice of the compensation factor is of a high level of importance since it may facilitate or hinder the collaboration;

- the collaboration, as proposed by this paper, ensures an increased profit with respect to the overall initial profit (i.e. without collaboration).

The proposed BLP model was successfully tested on a real case study related to trips to/from the port of Genoa in Italy and it demonstrated to be effective in serving all the required demand while maximizing the total final profit of the coalition. The computational performance of the model was satisfactory as well as the run time which increases significantly only when the number of trips is over 220 (considering both import and export trips).

Future research will take into account other constraints such as drivers' maximum working hours and the presence of depots where trucks start/end their trips. Moreover, further efforts will be dedicated to improving negotiation mechanisms for enhancing the cooperation.

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