**Article:**

Crainic, T.G., Dell'Olmo, P., Ricciardi, N. et al. (1 more author) (2015) Modeling dry-port-based freight distribution planning. Transportation Research Part C: Emerging Technologies, 55. pp. 518-534. ISSN 0968-090X

https://doi.org/10.1016/j.trc.2015.03.026

# Modeling Dry-Port-based Freight Distribution Planning

**Teodor Gabriel Crainic**
School of Management, Université du Québec à Montréal, Canada
Centre Interuniversitaire de Recherche sur les
Réseaux d'Entreprise, la Logistique et le Transport (CIRRELT)

**Paolo Dell'Olmo, Nicoletta Ricciardi**
Dipartimento di Scienze Statistiche
Sapienza Università di Roma, Italy

**Antonino Sgalambro**
Istituto per le Applicazioni del Calcolo Mauro Picone
Consiglio Nazionale delle Ricerche (CNR), Italy

**Abstract**

In this paper we review the dry port concept and its outfalls in terms of optimal design and management of freight distribution. Some optimization challenges arising from the presence of dry ports in intermodal freight transport systems are presented and discussed. Then we consider the tactical planning problem of defining the optimal routes and schedules for the fleet of vehicles providing transportation services between the terminals of a dry-port-based intermodal system. An original service network design model based on a mixed integer programming mathematical formulation is proposed to solve the considered problem. An experimental framework built upon realistic instances inspired by regional cases is described and the computational results of the model are presented and discussed.

**Keywords:** Service Network Design, Dry port, Logistics, Optimization, Mixed integer programming.

## 1 Introduction

Current trends in maritime logistics often consider the presence of inland freight terminals where consolidation of goods, custom services, information processing activities, short-term storage and value-added manufacturing services for the containerized goods take place before shipment toward the next destinations. In particular, dry ports are defined as inland freight terminals *directly connected to one or more seaports with high-capacity transport means, where customers can drop and pick up their standardised units as if directly at a seaport* [34, 25]. The advantage of introducing one or more dry ports into freight intermodal transport was confirmed by several experiences in terms of logistics integration and port regionalization (e.g., [29, 33]). A significant economic and political effort is currently being undertaken in many countries in order to extend as much as possible the presence, number and suitability of dry ports, especially for the seaports located within the area of congested cities. Despite this increasing interest in dry-port systems, the literature on freight logistics management [4, 11] shows a lack of contributions addressing those optimization problems that arise from the corresponding freight distribution processes, at a strategical, tactical and operational level.

The goal of this paper is to contribute to filling this gap, by introducing and describing the freight distribution systems based on the presence of dry ports from the point of view of optimization challenges at different levels, and then developing an optimization approach for the specific problem of defining tactical plans for these distribution systems. The concurrent presence of high capacity connections among dry ports, seaports, and other terminals, as well as congested road connections between terminals and inland cargo shippers naturally yields a multi-tiered network representation, encompassing different infrastructures and classes of vehicles.

First we present a comprehensive synthesis of the dry port concept as it is presented in the recent literature on freight transportation, identifying and classifying the optimization challenges supporting decisions in the field of optimal design and management of dry-port-based freight transportation systems.

Secondly, we consider the tactical planning problem consisting in the definition of the optimal schedule for the services operated by a fleet of high-capacity vehicles, also referred to as *shuttles* in the rest of the paper, on the railway network connecting seaport terminals and dry ports, in order to address the requested demands of containerized cargoes. An original service network design model representing the above mentioned tactical planning problem and based on a mixed integer programming mathematical formulation is introduced. The specific features of the considered problem with respect to similar cases previously presented in the literature for different applications is discussed. In particular, we consider the integration and consolidation on the vehicles of cargo flows directed from the shippers toward the seaports and vice versa, and the presence of different classes of products with different types of associated administrative and operational requirements.

We adopt a time-space network representation for service network design problems which represents a consolidated method in the scientific literature on network design (see for instance [2, 32]). With respect to advanced approaches recently introduced in the literature on service network design for freight logistics (see [1, 8, 9]), the model proposed in this paper presents further elements of novelty related to the specific features of the considered dry-port-based distribution problem, such as:

- the integration and consolidation on the same vehicles of cargo flows directed from the shippers toward the seaports and vice versa, together with the possibility to model different classes of administrative and operational requirements and operations through the calibration of cost parameters on the dummy arcs, particularly relevant for the case of dry-port-based distribution optimization;
- the possibility to consider several candidate terminals (dry ports, seaports), in space and time, for the pick-up or delivery of each cargo demands, thus leaving the model decide which combination provides better results in terms of the overall logistics cost function.

The paper is organized as follows. In Section 2, a description of dry ports and their role in the intermodal logistics of containerized goods is provided, together with a description of related planning and decisional problems and optimization challenges. In Section 3 we describe an optimization problem introduced to support the tactical planning process for the services operated by a fleet of high-capacity vehicles on the railway network connecting the terminals. In Section 4 we propose an original service network design approach aimed to model and solve the considered optimization problem. In Section 5 an experimental framework built upon realistic instances inspired by regional cases is described and the computational results of the model are presented and discussed. Conclusions complete the paper.

## 2 Dry-port-based intermodal transportation

This Section starts by recalling the relevant role and evolution of the intermodal terminals in freight transportation processes. In particular, the *dry port concept* is revised, emphasizing the specific features differentiating it from a simple inland freight terminal. In the second part of the Section, optimization challenges related to the freight distribution process in presence of dry ports are introduced and discussed.

## 2.1 Concept and role of dry-ports

Starting from the 1960s, the traffic of goods performed through standard containers yielded a progressive increase in the importance and volumes of freight intermodal transportation. With the following impressive increase in the quantities and values associated to freight traffics, several development processes took place, yielding to the expansion and specialization of seaports, the growth of the shipping industry and the empowerment of inland logistics systems respectively, together with the progressive integration among these different components of the intermodal transportation system.

A fundamental consequence of the increase in the worldwide traffic of containers was a growth in the number and size of the vessels operating for the maritime shipping of containerized cargoes. A lot of work was done for the expansion of the seaports capacity and to increase the operational efficiency of the maritime terminals with respect to loading and unloading operations and to the transshipment of freight in proximity of the seaports. The growth in the traffic volumes arising from the development of seaports and maritime shipping industry produced an increased level of congestion in the seaport zones due to the uncontrolled increase in road transportation of containers, which caused in turn the growth of transport times with its negative related economic fallouts, and a higher environmental and social impact interesting the people living in the seaport areas.

Cullinane et al. describe in [14] the development of a seaport as the results of the interactions among the economical system, the port system and the maritime shipping system: the bottleneck of seaport facilities turns out to be the port storage capacity and accessibility to the sea and the land side.

A basic feature in the recent freight distribution networks is represented by the presence of logistics platforms, designed to receive freight and vehicles, provide short-term storage, handling and consolidation, and allow the constitution of value-added loads to be shipped through the next levels of the distribution networks, either to different logistic hubs, or to the respective final customers. An advanced management of such operations, enabled by the growing presence of technologies and information support systems, permits a more efficient use of the overall available transportation capacity, in terms of infrastructures, fleet, load capacity, and consequently a higher environmental and economic sustainability of the activities related to the production and the consumption of goods.

The needs for such advanced logistics facilities yielded to the birth of dry ports as an industrial reality as witnessed by the presence of several examples in the world (see [33] for a review on several cases) much before its theoretical definition and placement within the field of research on transportation, that is still quite limited despite its industrial relevance.

The initial introduction of the dry port concept is to be referred to the UNCTAD report [39], where a dry port is defined as *an inland terminal to which shipping companies issue their own import bills of lading for import cargoes assuming full responsibility of costs and conditions and from which shipping companies issue their own bills of lading for export cargoes.*

A similar definition is provided in [23] where the value-added services component is emphasized as follows: *a dry port is a port situated in the hinterland servicing an industrial/commercial region connected with one or several ports by rail and/or road transport and is offering specialised services between the dry port and the transmarine destinations.*

The description of the dry port concept and the definition provided in [25, 34] is often considered in the scientific literature (see for instance [5, 14, 23]): here a dry port is defined as *an inland terminal directly connected to the seaport(s) with high capacity transport mean(s), where customers can leave/pick up their standardized units as if directly to a seaport.* For a recent update on these topics see also the Special Issue on *The dry port concept - Theory and practice* in [13].

## 2.2 A classification of dry-ports

The role of dry ports as an effective interface for all the hinterland shippers needs implements the concept of *extended gateway* (see for instance [41]). According to the extended gateway concept, the container storage and sorting function, together with custom and other logistics value-added services, can be transferred from congested transhipment points (seaports) to inland locations where more space is available. The connections between seaport and inland terminals are ensured by fast and reliable services, and hence these inland sites can be considered as a real extension of the mainport (gateway). The main relevant positive outfall of the extended gateway concept lies therefore in a substantial decrease in the seaport zones congestion.

According to Notteboom et al. [29], dry ports can assume three main functions within the transport chain: *satellite terminal*, *load centers* and *transshipment facility*. The dry port concept and its role is classified in [34] starting from the location of the dry port terminal with respect to the seaport and on the role that it consequently assumes within the distribution system.

In Figure 1 an integrated logistics system based on the dry ports is depicted, which represents the *fully implemented dry port concept* described in [34], and is composed in this case by two sea ports, two close dry ports, a midrange dry port and a distant dry port.

The *distant dry port* configuration is the most common one: the dry port is located at

| Configuration | Distance from the seaport | Main Function |
|---|---|---|
| Close dry port | $< 50km$ | Satellite Terminal |
| Midrange dry port | $\geq 50km, \leq 500km$ | Load Center |
| Distant dry port | $> 500km$ | Transshipment |

Table 1: Interdependence between the dry port classification schemes in [29] and [34].

a long distance from the interested seaport(s), higher than 500 km. This situation is associated to the maximum economies of scale for the railway operators and provides high-capacity direct connections for a wide geographical area, typically interesting one or more cities. *Midrange dry ports* are located within a distance from the seaport(s) that is commonly covered by road transport (from 50 to 500 km) and are based on the presence of additional railway connections towards conventional inland intermodal terminals. In the *close dry port* configuration, the dry port is located at a short distance (lower than 50 km) from a seaport, whose level of congestion is therefore strongly decreased. It can consolidate the loads collected from and directed to the shippers that are located outside the urban areas. This classification is synthetically represented in Table 1, highlighting the interdependence between the main functions performed in the transport chain by a dry port (according to the classification by Notteboom et al. [29]) and its physical distance from the seaports (according to the classification by Roso et al.[34]).
The presence of inland dry ports contributes to push the port development process towards the *regionalization* phase, as described in [30]: functional interdependency and joint development for a load centre and multimodal logistics platforms in its hinterland takes place, until a *regional load centre network* emerges, thanks to a deep process of logistics integration.

### 2.3 Optimizing dry port logistics: literature review and open issues

The increasing presence of advanced logistic platforms represents a recent and relevant evolution trend in freight logistics, introducing the need to develop specific optimization instruments and methods for planning and managing the distribution of goods on multilevel networks, characterized by hierarchical relationships and mutual influences among the different components of the freight distribution system.
The current scientific literature on freight logistics management presents a lack of contributions addressing the optimization problems arising in dry port based freight distribution processes. Therefore, in the following we introduce some of the optimization challenges

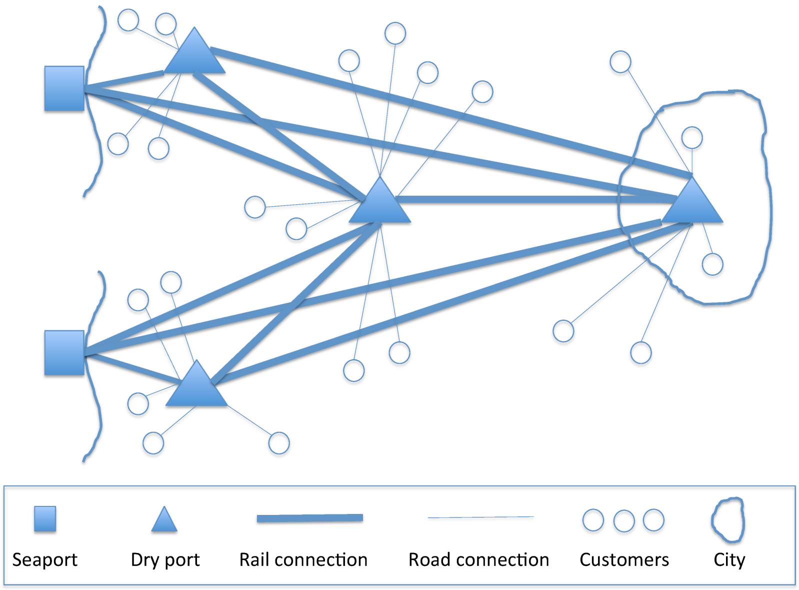


Figure 1: A system with two seaports, two close dry ports, one midrange dry port and one distant dry port.

arising from the presence of dry ports in the containerized goods transportation process, and recall the few scientific contributions presented in the literature on this topic.
To this aim, we consider logistics optimization problems that can be classified according to different planning and decision levels: long term or strategic decisions, mid term or tactical planning, and short-term or operational level. The optimization problems we consider refer to different classes of stakeholders and decision makers. A synthesis of this state of the art is also provided in Table 2.

**Strategic level.** A first relevant example of strategic planning issue for the design of a container distribution network is represented by the location of one or more dry ports. Some contributions were already presented in the literature [5, 43] dealing with the problem of selecting proper locations by using fuzzy methodologies, that is the fuzzy c-Means clustering method in [5] and the fuzzy Analytic Network Process approach in [43]. Both approaches are based on a set of factors impacting the location decision and a system of evaluation indicators influencing the locational analysis. A further contribution is presented in [27] in which the Affinity Propagation Clustering Method is applied to locate dry-ports in South West China area.
Different methods could be considered in order to address the location analysis of dry

ports, for instance those based on mathematical programming and on the development of exact and approximation algorithms to solve the arising optimization problems. For instance, in [16] a Location-Allocation model is considered to optimize the configuration of a Seaport-Dry Port system, solved by a genetic approach.

Dry port location problems could be tackled also in consideration of the concurrent strategical decisions concerning the design of the physical railway network connecting seaports, dry ports and other inland intermodal terminals. The design of a dry-port-based distribution system poses therefore an optimization challenge in the direction of *location-service design* problems. A specific focus on the cost-efficiency when introducing a dry-port system in Finnish transportation network is proposed in [20] adopting a gravitational model solved by integer linear programming.

The choices related to the design and implementation of a dry port system strongly influence the future decisions of the customers, depending on their relative position with respect to the seaport and dry port terminals, as discussed above (see the full implemented dry port concept presented in [34] and depicted in Figure 1). As a consequence, the changes in the configuration of the shipping demand will have to be properly considered when dealing with location and design optimization problems for the dry-port-based intermodal transportation systems.

One more issue for the strategical planning process concerning dry ports falls in the class of the *facility layout design problem*, in consideration of the specific nature of dry ports and of the high and rich variety of different classes of operations that must take place in such inland logistics terminals, that should be properly considered in such a way to optimize the flows of containers and increase the level of efficiency. For a survey on this class of optimization problems, one can refer to [15], while in [38] a focus on concurrent optimization of size and location of public logistics terminals is considered.

**Tactical level.** On the tactical level, some decision problems arising from the presence of dry ports in the distribution process concern the scheduling of the railway shuttle services, the sizing of the operated shuttle fleet, the definition of the routes for the shuttles, and the level of integration of logistics services that can be implemented in a dry port in order to maximize the positive impact for all the shareholders interested by the container distribution process. There is still a lack of optimization contributions at this level, and indeed this reason motivated our paper.

However, we recall a number of papers addressing tactical optimization problems in close fields. In particular, for maritime transportation, a review on ship routing and scheduling

| Strategical | Tactical | Operational |
|---|---|---|
| Location [5], [27], [43] | Scheduling [6] | Berth Allocation [18], [19], [22] |
| Allocation [16], [20] | Train Rout. & Sched. [7] | Berth Scheduling [24], [31] |
| Design [34] | Service Design [10], [26] | Cont. Terminal [21], [28], [37], [42] |
| Layout [15], [38] | Ship Rout. & Sched.[6] | Crane Scheduling [44] |

Table 2: Classification of cited references according to decision levels.

is given in [6]. Concerning railway transport, a survey on train routing and scheduling is proposed in [7]. A specific contribution on Service Design models for railway intermodal transportation is given in [10] while in [26] a general ferry service network design problem is faced.

**Operational level.** A rich set of short term decisions can be considered as an optimization issue for all of the different types of operations that must be correctly managed in a dry port, such as loading and unloading operations, transshipment of containers, detailed vehicles and resource scheduling, custom clearance and inspection, safety procedures, repair of containers, inventory management. More complex problems arise from the need to schedule concurrently transportation services and short term storage and handling activities (see [3] for a review on inventory routing problems). Among the optimization problems at this level, we mention the berth allocation problem, faced in [18], [19] and [22], while berth scheduling is studied in [24] and [31]. Optimization of container terminal operations is widely treated in the literature, see for instance [11], [37] and [42] for a review on this topic. More in particular, container storage and transshipment in maritime terminals is treated in [28], and a model to optimize the container logistics in the port-hinterland is considered in [21]. For the problem of dynamic crane scheduling, a modified Lagrangean relaxation method is applied to find solutions of a MIP formulation in [44].

## 3 Problem setting

The specific aim of this paper is the study of methods for the optimal planning, at a tactical level, of transportation processes on multi-tiered dry-port-based intermodal systems. Tactical planning problems in the field of freight transportation are commonly focused on the need for consolidation processes, aiming to build efficient transportation plans taking concurrently into account the quality of the delivery service and the variability of the demand. We assume the perspective of the shuttle service operator aiming to minimize the overall logistics costs while satisfying the requested transportation demand.

In some cases, more than one operator could provide services on the same physical network. Nevertheless, dry port systems, also because of their role as custom service providers, are commonly settled and managed as an initiative of public port authorities, ensuring the requested integration and coordination of the activities provided by possibly different service operators. Indeed, the idea of public logistics terminals is also motivated by the traffic congestion and social and environmental costs which are not the main objectives where the efforts of private service operators are focused. This concept, seen as a multi-company distribution center, should be seen not as a restriction to the economic distribution activities of private service enterprises in a very competitive market, rather to offer coordinated services allowing the whole system (offered public services and private activities) to be globally and economically efficient. This approach has been followed, for instance in [38] for public logistic platforms in the Kyoto-Osaka area in Japan. For these reasons, also for the case of multiple service operators, tactical planning can be still thought and modeled as an integrated process performed by a single decision maker.

We consider the problem of defining the optimal schedule for the services operated by a fleet of high-capacity shuttles on the railway network connecting seaport terminals and dry ports, in order to address the requested demands of containerized cargoes transportation. The aim is to support the tactical planning process for the considered shuttle services, by defining and optimizing the working plans to be repeated on a daily or weekly basis, in such a way to satisfy most of the regular demand. The time horizon considered in the optimization problem must be therefore defined and calibrated on the base of the expected intensity of the traffic and its variations.

The problem encompasses the concurrent presence on the same services of two types of cargo flows: those generated by the movement of containers from inland shippers to the seaports through the dry ports, and those arising from the containers unloaded from ships at the seaports that are sent to the inland destinations through the dry ports.

We assume that a set of cargo demands are available, each of them being associated to the loading or unloading operation at a fixed seaport at a certain time instant. Moreover, each cargo must be collected from (or delivered to) a certain inland shipper (or consignee) within a time window that is part of the input of our problem.

We are particularly interested in those more complex cases in which the integrated logistics network includes more than one seaport and more than one dry port, as depicted in Figure 1. Solving the problem on simpler networks becomes then straightforward.

It follows that, in general, each cargo demand must be assigned to a dry port that is not fixed a priori, since more than one dry port could be suitable for the shipment. In Figure

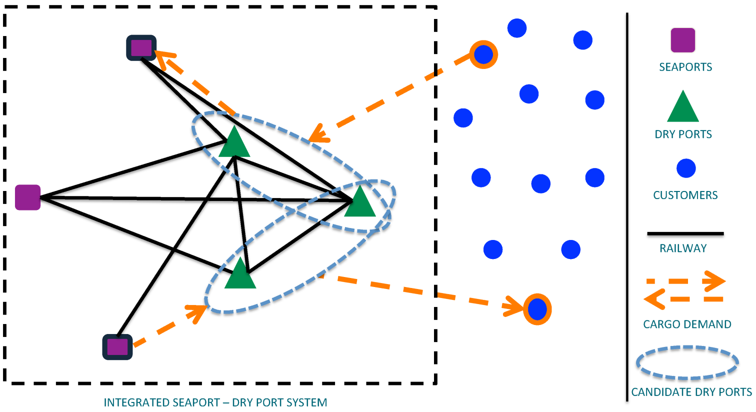


Figure 2: Sketch of the cargo demand within the considered tactical planning problem.

2 an example is illustrated in which we are given an integrated logistics system composed by three seaports and three dry ports. Two cargo demands requiring transportation to a given seaport and from a given seaport respectively are considered, and a set of two candidate dry ports is evaluated for each of the two shipments.

The input of the tactical planning problem therefore includes a set of cargo demands to be satisfied, each one being described by:

- The time instant and the seaport where the cargo transportation has its origin (or destination);
- The set of candidate dry ports and the time window for the delivery (or the pick-up) of the cargo;
- The size of the cargo.

Moreover, the input of the problem includes:

- The size of the available fleet;
- The capacity of each shuttle.

Several classes of costs are considered in the problem, as follows:

a. The shuttle operating costs;

b. The costs required for the movement of a shuttle between each couple of terminals in the integrated network;

c. The costs required for the transportation of a cargo demand between each couple of terminals in the integrated network;

d. The container handling costs at terminals (loading and unloading operations);

e. The dwell times costs (such as demurrage and inventory costs);

f. The costs associated to value-added services, custom clearance, security inspection.

The optimization problem we consider must therefore support the definition of complete tactical plans with detailed information on the following decisions:

Q1. The selection of services: which services must be operated on the base of the set of demands and the size of the shuttle fleet;

Q2. The assignment of cargo demands to the operated services: to which service each cargo demand will be assigned;

Q3. The quantity of cargo demand associated with each operated service;

Q4. The routes on which services will be offered: operated services are associated with a sequence of physical terminals to be served by the shuttles;

Q5. The time schedule of the operated services: at what time instant the shuttle providing a service arrives to a terminal and leaves from the terminal;

Q6. The operations to be performed at each seaport and dry port terminal, in particular with respect to cargo loading and unloading operations;

Q7. Which dry port will be assigned to each cargo demand among the set of suitable terminals.

On the base of the output of the optimization problem we consider, a tactical plan will be built, according to which every cargo demand is assigned exactly to a given service and to a certain dry port among the suitable ones, while minimizing the overall logistics costs.

## 4 A service network design model for dry-port-based intermodal transportation

Service network design (SND) is increasingly used to model tactical planning processes in which the selection and scheduling of the services to operate, the routing of the scheduled service and of the cargoes, and the specification of the terminal operations to be performed must be decided (see [12] for a wide review of these class of problems).
In this Section we present an original SND model designed to represent the problem described above.

**Nodes.** The description of the model starts by considering the set of *physical nodes* that compose the system, and coincides with the set of sea ports and dry ports included in the integrated logistics network. It is represented by the square and triangle nodes in Figure 2.
According to the description presented in the last Section, time is a fundamental element for the considered problem, hence we define a time expanded network in which the set of physical nodes of the logistics system is expanded over a given discrete time horizon as illustrated in Figure 3.
Since the planning of road cargo transportation between the terminals and the customers (shippers and consignees) is not included in the considered problem, customers are not represented individually as network nodes, but a single dummy node $\gamma$ is introduced instead as a concurrent super-sink and super-source for all flows associated to the cargo demands. Therefore, the set of nodes of the network, denoted by $\mathcal{N}$, is composed by:

- a node representing each seaport for each time instant of the considered time horizon.
- a node representing each dry port for each time instant of the considered time horizon.
- a dummy node $\gamma$ on which all the cargo demands are collapsed.

**Arcs.** The set of arcs $\mathcal{A}$ of the time-space network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ is composed of three subsets of arcs, namely:

- the *movement arcs* $\mathcal{A}^{\mathrm{M}}$ that connect nodes representing different terminals, and represent possible shuttle physical movements.

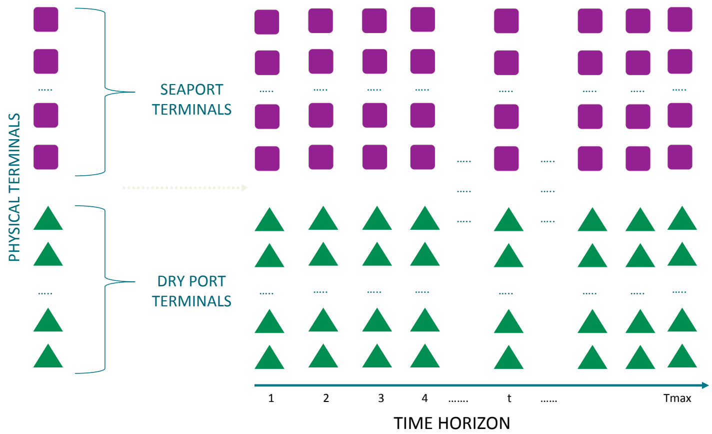


Figure 3: A representation of the time-space network.

- the *holding arcs* $\mathcal{A}^{\mathrm{H}}$ that link couples of nodes representing the same terminal at different time periods and are used to model the loading and unloading of cargo. Shuttles can hold at terminals only for the time strictly needed to load and unload containers.

- the *dummy arcs* $\mathcal{A}^{\mathrm{D}}$ linking the nodes to $\gamma$. In particular, for each node $i$ in the time expanded network, two dummy arcs $(\gamma, i)$ and $(i, \gamma)$ are introduced.

Moreover, for each node $i$, we define the set $\mathcal{N}^+(i) = \{j \in \mathcal{N} : (i,j) \in \mathcal{A}\}$ of successor nodes and the set $\mathcal{N}^-(i) = \{j \in \mathcal{N} : (j,i) \in \mathcal{A}\}$ of predecessor nodes. Similarly, $\mathcal{N}^{\mathrm{H}+}(i) = \{j \in \mathcal{N} : (i,j) \in \mathcal{A}^{\mathrm{H}}\}$ and $\mathcal{N}^{\mathrm{H}-}(i) = \{j \in \mathcal{N} : (j,i) \in \mathcal{A}^{\mathrm{H}}\}$ assume the same meaning limited to the subset of holding arcs.

**Cargo demands.** Define the set of cargo demands $d \in \mathcal{D}$: each customer is associated to a demand $d$ that is characterized by a number of containers $w(d)$, a given time instant and a seaport terminal where the cargo shipment has its origin or destination, and a set of candidate dry ports, together with the time window for the delivery (or the pick-up) of the cargo. One of the main function of the dummy node $\gamma$ and the dummy arcs $\mathcal{A}^{\mathrm{D}}$ is devoted to the mathematical modelling representation of these elements, as depicted in Figure 4. In the picture, the cargo flow must be directed from a given seaport to a set of candidate dry ports. In this case, the nodes representing the candidate dry ports during

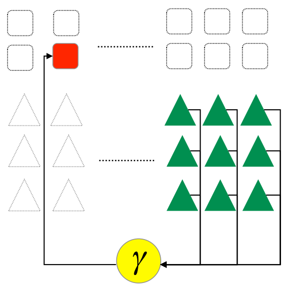


Figure 4: Network representation for a given cargo demand directed from a given seaport node to a set of candidate dry port nodes, represented in black. Only the dummy arcs linking the suitable terminal nodes to the super-sink $\gamma$ are represented.

the feasible time window are represented in black. Only the suitable dummy arcs linking the latter nodes to the super-sink $\gamma$ are represented. Similarly, only the node representing the suitable seaport at the proper time instant for the loading of the cargo on the service shuttle is black, and there is only one dummy arc connecting such a node to the super-source $\gamma$. The use of all the remaining unsuitable dummy arcs is forbidden for that specific cargo demand by associating to them a huge cost $M$.

A symmetrical network representation can be adopted for those cases in which the cargo flow is directed in the opposite direction, namely, from a set of candidate dry ports to a given seaport.

Note that the costs associated to the arcs are differentiated on the base of the service and the demand they refer to, as described in detail in the following.

The total quantity of goods related to each cargo demand is assumed to be shipped on a single shuttle, in order to reduce the effort required by the administrative and information processing tasks.

In order to complete the description of the elements of the proposed SND model, two definitions must be introduced to describe shuttle movements.

**Service leg.** A *service leg* is defined as the activity performed by a shuttle from one node to a different one in the time-expanded network. These nodes can be the time-expanded representation of two different physical nodes when the service leg is the transportation service operated by a shuttle between two different terminals. This first class of activities is represented by the set $\mathcal{A}^{\mathrm{M}}$ of movement arcs already introduced in the network definition. Otherwise, the two nodes could represent the time-expanded representation of the same physical node at two distinct time instants, and in that case the service leg represents the shuttle holding at the associated physical terminal in order to perform loading and unloading services. This second class of activities is represented by the set $\mathcal{A}^{\mathrm{H}}$ of holding arcs introduced above.

**Schedule.** The schedule associated to each of the operating shuttles is represented by a single *tour* passing through the dummy node and composed of consecutive service legs. The tour touches a finite number of nodes in the time-expanded network, representing the shuttle servicing the associated terminal at the corresponding time instant. In Figure 5 an example of schedule is illustrated: the dummy arc between $\gamma$ and the seaport node labelled 1 represents the start of the tour from the seaport, where loading operations take place, represented by the service leg $(1, 2)$. It follows the service leg $(2, 3)$ representing the movement of the shuttle toward a first dry port terminal where loading/unloading operations are performed (service leg $(3, 4)$) before moving, through the service leg $(4, 5)$, and reach a second dry port terminal. After the loading/unloading operations at the second dry port are performed, represented by the service leg $(5, 6)$, a new service leg $(6, 7)$ brings the shuttle again to the seaport, where final unloading operations are performed (service leg $(7, 8)$) before the end of the tour, that is represented by the last (dummy) arc towards $\gamma$.

**Shuttles.** Consider the set $\mathcal{R} = \{r\}$ of available shuttles, with cardinality $|\mathcal{R}|$. Each shuttle is assumed to consist in a locomotive plus a certain number of flat-cars carrying the containers [40]. The sum of the capacities of the flat-cars provides the capacity of each shuttle $r \in \mathcal{R}$, denoted by $u_r$, while $\pi_i$ equals the maximum number of shuttles that can concurrently stop to load or unload at terminal $i \in \mathcal{N}$.

**Costs.** Three sets of cost coefficients are considered in the model: a set of fixed costs $f_r$ for each shuttle $r \in \mathcal{R}$, representing the class $a$ of shuttle operating costs in the problem setting description, a set of service-leg costs $k_{ijr}$ associated with the service leg $(i, j)$ being operated by shuttle $r$, representing the class $b$ of costs in the problem setting description, and a set of variable costs $c^d_{ijr}$ associated with each container of cargo $d$ from node $i$ to

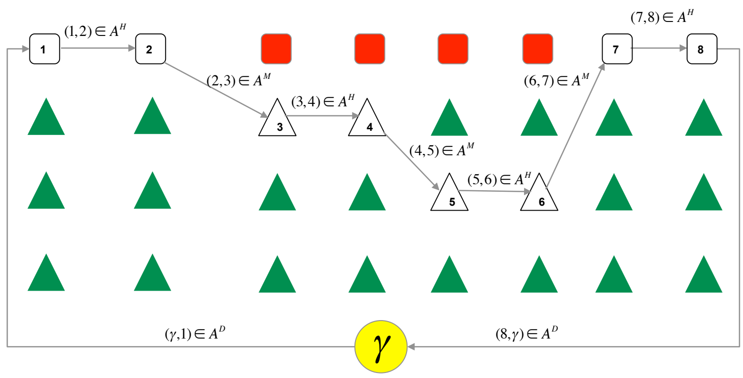


Figure 5: A tour on the time expanded network representing the schedule of a shuttle starting from a seaport, touching two distinct dry ports and then getting back to the origin seaport.

node $j$ on shuttle $r$.

The variable costs $c^d_{ijr}$ permits to represent all the remaining classes of costs presented in the problem setting description in a properly differentiated way, depending on the types of arcs, demands and shuttle they refer to.

*Variable costs associated to movement arcs.* The costs for moving the containers of a given cargo demand (class $c$ of costs in the problem setting description) can be represented by considering the cost coefficients on the movement arcs $\{c^d_{ijr}\} \quad \forall (i,j) \in \mathcal{A}^M, r \in \mathcal{R}, d \in \mathcal{D}$.

*Variable costs associated to holding arcs.* The costs for loading and unloading the containers of a given cargo demand (class $d$ of costs in the problem setting description) can be modelled by calibrating the cost coefficients on the holding arcs $\{c^d_{ijr}\} \quad \forall (i,j) \in \mathcal{A}^H, r \in \mathcal{R}, d \in \mathcal{D}$.

*Variable costs associated to dummy arcs.* We recall as feasible dry ports, sea ports and time instants for the loading and unloading of each cargo demand are considered in our model by properly setting the costs for the dummy arcs associated to each demand and service, that is, $\{c^d_{ijr}\} \quad \forall (i,j) \in \mathcal{A}^D, r \in \mathcal{R}, d \in \mathcal{D}$. All the unfeasible flow assignments for a given demand are excluded forbidding the use of the related dummy arcs by setting the cost as equal to $M$ in the parameter set. Anyway, the presence of costs on dummy arcs is associated to a second main function in our model, namely, that of representing the costs of type $e$ and $f$ in the problem setting description for all those flow assignments that are not forbidden. This way, it is possible to differentiate such costs depending on the shuttle, on the class of product, on the physical terminal and on the time instant they refer to.

**Variables.** For each available shuttle $r \in \mathcal{R}$, we introduce a binary variable $\phi_r$ assuming a value equal to 1 if shuttle $r$ is operated, and 0 otherwise; a set of service design variables $y_{ijr}, (i, j) \in \mathcal{A}$, defining the service legs associated to shuttle $r$: $y_{ijr}$ assumes a value equal to 1 if service leg $(i, j)$ is operated by shuttle $r$, and 0 otherwise; a set of binary variables $z_r^d, d \in \mathcal{D}$, assuming a value equal to 1 if the cargo demand $d$ is shipped through shuttle $r$, and 0 otherwise, $x_{ijr}^d, (i, j) \in \mathcal{A}, d \in \mathcal{D}$, being the corresponding flow variables representing the amount of containers of cargo demand $d$ carried by shuttle $r$ along the service leg $(i, j)$. With respect to the problem setting presented in Section 3, decision $Q1$ is associated with variables $\phi_r$, details on $Q2$ are provided by variables $z_r^d$, while decisions $Q3$ are associated with variables $x_{ijr}^d$. Finally, service design variables $y_{ijr}$ define decisions $Q4$, $Q5$, $Q6$ and $Q7$.

$$\min \sum_{r\in\mathcal{R}} \left[ f_r\phi_r + \sum_{(i,j)\in\mathcal{A}} k_{ijr}y_{ijr} + \sum_{(i,j)\in\mathcal{A}}\sum_{d\in\mathcal{D}} c^d_{ijr}x^d_{ijr} \right] \tag{1}$$

$$\text{s.t.} \sum_{j\in\mathcal{N}^+(i)} x^d_{ijr} - \sum_{j\in\mathcal{N}^-(i)} x^d_{jir} = 0 \qquad d\in\mathcal{D}, r\in\mathcal{R}, i\in\mathcal{N} \tag{2}$$

$$\sum_{j\in\mathcal{N}^+(\gamma)} x^d_{\gamma jr} = w(d)z^d_r \qquad d\in\mathcal{D}, r\in\mathcal{R} \tag{3}$$

$$\sum_{r\in\mathcal{R}} z^d_r = 1 \qquad d\in D \tag{4}$$

$$\sum_{j\in\mathcal{N}^+(i)} y_{ijr} - \sum_{j\in\mathcal{N}^-(i)} y_{jir} = 0 \qquad r\in\mathcal{R}, i\in\mathcal{N} \tag{5}$$

$$\sum_{j\in\mathcal{N}^+(\gamma)} y_{\gamma jr} - \phi_r \le 0 \qquad r\in\mathcal{R} \tag{6}$$

$$\sum_{d\in\mathcal{D}} x^d_{ijr} \le y_{ijr}u_r \qquad (i,j)\in\mathcal{A}, r\in\mathcal{R} \tag{7}$$

$$\sum_{r\in\mathcal{R}} y_{ijr} \le 1 \qquad (i,j)\in\mathcal{A}^{\mathrm{M}} \tag{8}$$

$$x^d_{j\gamma r} - \sum_{i\in\mathcal{N}^{\mathrm{H}-}(j)} w(d)y_{ijr} \le 0 \qquad (j,\gamma)\in\mathcal{A}^{\mathrm{D}}, d\in\mathcal{D}, r\in\mathcal{R} \tag{9}$$

$$x^d_{\gamma ir} - \sum_{j\in\mathcal{N}^{\mathrm{H}+}(i)} w(d)y_{ijr} \le 0 \qquad (\gamma,i)\in\mathcal{A}^{\mathrm{D}}, d\in\mathcal{D}, r\in\mathcal{R} \tag{10}$$

$$\sum_{r\in\mathcal{R}} y_{ijr} \le \pi_i \qquad (i,j)\in\mathcal{A}^{\mathrm{H}} \tag{11}$$

$$\phi_r \in \{0,1\} \qquad r\in\mathcal{R} \tag{12}$$

$$y_{ijr} \in \{0,1\} \qquad (i,j)\in\mathcal{A}, r\in\mathcal{R} \tag{13}$$

$$z^d_r \in \{0,1\} \qquad d\in\mathcal{D}, r\in\mathcal{R} \tag{14}$$

$$x^d_{ijr} \ge 0 \qquad (i,j)\in\mathcal{A}, d\in\mathcal{D}, r\in\mathcal{R} \tag{15}$$

**Mathematical formulation.** The objective function aims at the minimization of the overall cost. Constraints (2) and (3) ensure the conservation of cargo flows at nodes and the satisfaction of the cargo demands, together with constraints (4) assigning each cargo demand to exactly one shuttle. A single unsplit circular route passing through the $\gamma$ node is ensured by constraints (5) and (6). Constraints (7) activate service legs and impose limits on the amount of cargo on each leg, while constraints (8) forbid, for each period in the time horizon, the presence of more than one service leg on the same physical connection. Recalling that two nodes $i$ and $j \in \mathcal{N}^{H+}(i)$ represent the same physical node in different time periods, relations (9) and (10) are introduced to force the shuttles to wait at terminals for the time required to perform the unloading and loading operations, respectively. Constraints (11) impose limits on the number of shuttles that can simultaneously be at a terminal. The proposed arc-based formulation for the considered service network design problem falls into the class of capacitated multicommodity fixed charge network design problems (CMND), which are known to be $NP$-hard [2]. However, this mathematical formulation is solvable for realistic instances as will be seen in Section 5.2.

# 5 Proof of concept for the proposed modeling approach

The purpose of this Section is to perform a computational test for the model proposed previously in order to verify its correctness and suitability to solve the tactical optimization problem introduced in Section 3. The first aim is to provide a proof of concept for the optimization model and its features. Secondly, we want to check the scalability in terms of the computational effort required to solve the model and provide efficient solutions for the freight transportation tactical planning process in presence of dry ports. Third, we want to investigate the possibility to solve instances inspired to those complex and realistic cases in which more than one dry port and more than one seaport are present in the logistics system. To this aim, the testbed for the computational test is inspired on the relevant case of the italian northern logistics platform, in which the presence of a dry port for the city of Alessandria was considered by the authorities in the last years.

## 5.1 Description of the testbed and computational framework

The objective of the Alessandria dry port project is the realization of a large interport hub directly connected to the seaports of Genoa, Savona and La Spezia, in order to increase the potential for development of the ligurian ports with respect to the Northern and Central Italy and enable a strong recovery of competitiveness compared to other ports of the Mediterranean and Northern Europe [36, 35]. The interventions are intended to facilitate the de-congestion of the ligurian seaports, allow a greater operability and integrate activities with the development of port logistics value-added services, as well as the establishment of new enterprises and a growth in the logistics and transport employment. The modeling of the tactical planning process turns out to be particularly challenging in

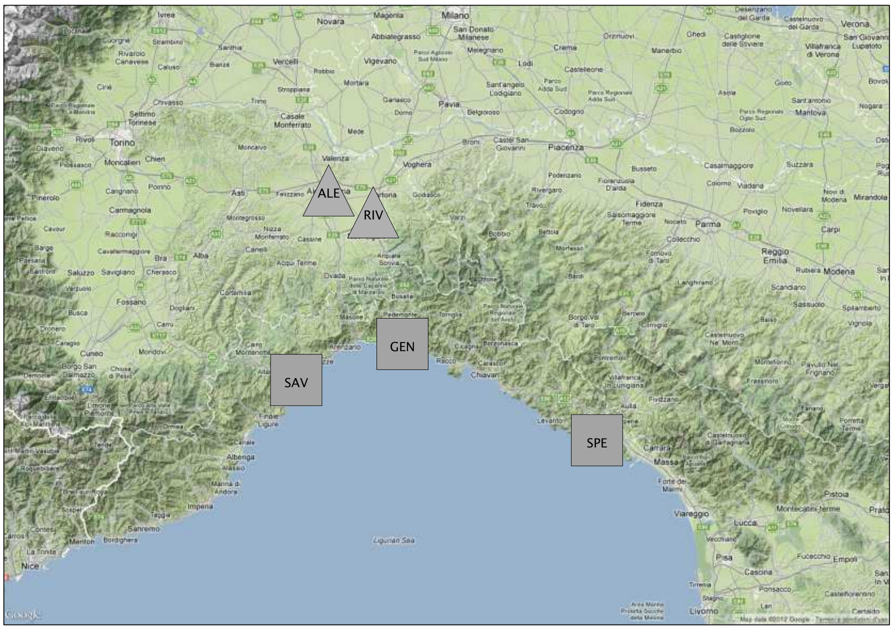


Figure 6: GIS representation of the physical nodes for the considered logistics network.

this case due to the presence of three seaports as well as of the Rivalta Scrivia dry port already operating in the region.
The testbed for the computational test was built under the hypothesis that the overall logistics network is composed of five physical nodes, that is, three ligurian seaports: Genoa ($GEN$), Savona ($SAV$) and La Spezia ($SPE$), and two dry ports in the region of Piemonte: Alessandria ($ALE$) and Rivalta Scrivia ($RIV$). The set of physical nodes considered in the testbed is represented in Figure 6, obtained by means of a Geographical Information System implemented within the free open source Quantum Gis (http://www.qgis.org/) environment. We assume direct railway connections exist between each seaport and the two dry ports, and between the two dry ports. The set of physical movement arcs is reported in Table 3 in which the tail and head of each arc is expressed through the code name of the related node, and the length, expressed in $km$, is computed starting from the geographical coordinates of the nodes in the GIS system. In the testbed we assume a mean speed for the shuttles of 60 km/h while the number of time steps required for performing the movement is equal to the integer approximation of the physical distance divided by the product of the mean shuttle speed times the length of the time interval.

An example of graphical representation of the time expanded network is depicted in Figure 7. In this example we assume a discrete time interval of two hours. Since the

| Arc ID | Tail Node | Head Node | Length (km) |
|---|---|---|---|
| 1 | GEN | ALE | 66 |
| 2 | GEN | RIV | 49 |
| 3 | SPE | ALE | 162 |
| 4 | SPE | RIV | 139 |
| 5 | SAV | ALE | 70 |
| 6 | SAV | RIV | 71 |
| 7 | ALE | GEN | 66 |
| 8 | ALE | SPE | 162 |
| 9 | ALE | SAV | 70 |
| 10 | RIV | GEN | 49 |
| 11 | RIV | SPE | 139 |
| 12 | RIV | SAV | 71 |
| 13 | ALE | RIV | 24 |
| 14 | RIV | ALE | 24 |

Table 3: List of the physical movement arcs for the considered logistics network.

Alessandria dry port logistics system is planned to work on a 24 hours-a-day basis, the time expanded representation of the network is obtained by exploding the set of physical nodes on a time horizon composed by 13 time instants and 12 time intervals, starting from the time instant 0 until the time instant 12. The meaning of the nodes representation is provided in Table 4 where each node presented in Figure 7 is described according to the following classification: *type*=0 if the node represents a seaport ($GEN$, $SAV$, $SPE$), while *type*=1 if the node represents a dry port ($ALE$, $RIV$).

In this case the set of arcs is composed by 144 movement arcs, 60 holding arcs and 130 dummy arcs linking the nodes of the time expanded network to the additional dummy node $\gamma$, which is represented by node 66 in Figure 7.

The testbed for the computational experiments is composed by four sets of instances based on the framework above described representing the Alessandria dry port logistics system. We considered four different values for the time step parameter defining the number of time intervals in which the 24 hours time horizon is divided. The first set of instances is based on a time step equal to 120 minutes, corresponding to 12 time intervals and 13 time instants, namely $t = 0, t = 1, ..., t = 12$. The time step for the second set of instances equals 90 minutes, giving rise to 16 time intervals and 17 time instants, namely $t = 0, t = 1, ..., t = 16$. The third set of instances is based on a time step equal to 60 minutes, that corresponds to 24 time intervals and 25 time instants, with $t = 0, t = 1, ..., t = 24$. Finally, the fourth set of instances has a time step of 45 minutes, with 32 associated time intervals and 33 time instants, namely $t = 0, t = 1, ..., t = 32$. A description of the time expanded network associated with the four sets of instances in terms of number of nodes and different classes of arcs is presented in Table 5.

We considered four sets of instances and 5 demand scenarios for each set, with an increasing number of cargo demands ranging from 20 to 100. A total number of 20 problem

| Node ID | Physical Node | Type | Time Instant | Node ID | Physical Node | Type | Time Instant |
|---|---|---|---|---|---|---|---|
| 1 | GEN | 0 | 0 | 34 | ALE | 1 | 6 |
| 2 | SPE | 0 | 0 | 35 | RIV | 1 | 6 |
| 3 | SAV | 0 | 0 | 36 | GEN | 0 | 7 |
| 4 | ALE | 1 | 0 | 37 | SPE | 0 | 7 |
| 5 | RIV | 1 | 0 | 38 | SAV | 0 | 7 |
| 6 | GEN | 0 | 1 | 39 | ALE | 1 | 7 |
| 7 | SPE | 0 | 1 | 40 | RIV | 1 | 7 |
| 8 | SAV | 0 | 1 | 41 | GEN | 0 | 8 |
| 9 | ALE | 1 | 1 | 42 | SPE | 0 | 8 |
| 10 | RIV | 1 | 1 | 43 | SAV | 0 | 8 |
| 11 | GEN | 0 | 2 | 44 | ALE | 1 | 8 |
| 12 | SPE | 0 | 2 | 45 | RIV | 1 | 8 |
| 13 | SAV | 0 | 2 | 46 | GEN | 0 | 9 |
| 14 | ALE | 1 | 2 | 47 | SPE | 0 | 9 |
| 15 | RIV | 1 | 2 | 48 | SAV | 0 | 9 |
| 16 | GEN | 0 | 3 | 49 | ALE | 1 | 9 |
| 17 | SPE | 0 | 3 | 50 | RIV | 1 | 9 |
| 18 | SAV | 0 | 3 | 51 | GEN | 0 | 10 |
| 19 | ALE | 1 | 3 | 52 | SPE | 0 | 10 |
| 20 | RIV | 1 | 3 | 53 | SAV | 0 | 10 |
| 21 | GEN | 0 | 4 | 54 | ALE | 1 | 10 |
| 22 | SPE | 0 | 4 | 55 | RIV | 1 | 10 |
| 23 | SAV | 0 | 4 | 56 | GEN | 0 | 11 |
| 24 | ALE | 1 | 4 | 57 | SPE | 0 | 11 |
| 25 | RIV | 1 | 4 | 58 | SAV | 0 | 11 |
| 26 | GEN | 0 | 5 | 59 | ALE | 1 | 11 |
| 27 | SPE | 0 | 5 | 60 | RIV | 1 | 11 |
| 28 | SAV | 0 | 5 | 61 | GEN | 0 | 12 |
| 29 | ALE | 1 | 5 | 62 | SPE | 0 | 12 |
| 30 | RIV | 1 | 5 | 63 | SAV | 0 | 12 |
| 31 | GEN | 0 | 6 | 64 | ALE | 1 | 12 |
| 32 | SPE | 0 | 6 | 65 | RIV | 1 | 12 |
| 33 | SAV | 0 | 6 | 66 | DUMMY | 2 | |

Table 4: Nodes in the time expanded network represented in Figure 7.

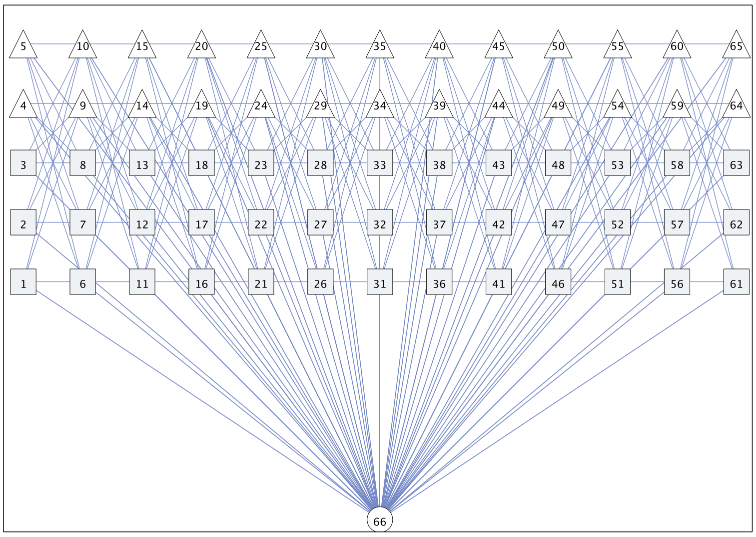


Figure 7: Representation of the whole time expanded network for the case of a time interval equal to 2 hours.

| Instance set | Time step (minutes) | Time intervals | Nodes | Movement Arcs | Holding arcs | Dummy arcs | Total arcs |
|---|---|---|---|---|---|---|---|
| 1 | 120 | 12 | 66 | 144 | 60 | 130 | 334 |
| 2 | 90 | 16 | 86 | 192 | 80 | 170 | 442 |
| 3 | 60 | 24 | 126 | 284 | 120 | 250 | 654 |
| 4 | 45 | 32 | 166 | 377 | 160 | 330 | 867 |

Table 5: Description of the time expanded network for each set of instances.

instances was generated. The size $w(d)$ associated to each cargo demand $d \in \mathcal{D}$ was set at pseudorandom with a uniform distribution in the range $1, ..., 5$ TEUs. Each cargo demand was associated to a seaport at pseudorandom with a uniform distribution among those available, and the geographical location of the customer was set at pseudorandom as well. The available fleet was considered as composed of 2 shuttles, each one with a maximum load parameter $u_r$ equal to 50 TEUs. The cost $f_r$ associated with the activation of a shuttle was fixed to 100000, while the fixed cost for the activation of each service leg was set equal to 1000. Concerning the variable costs, the parameters $\{c^d_{ijr}\}$ were set to 10 for the transportation of each unit of cargo between two different terminals (movement arcs). The variable costs associated to the holding arcs are supposed to include the handling costs, and therefore were set at pseudorandom with a uniform distribution in the range $1, ..., 50$. The variable costs associated to the dummy arcs linking the dry port nodes to the dummy node $\gamma$ in both directions represent the costs for dwell times and value-added services at terminals, and were set at pseudorandom with a uniform distribution in the range $1, ..., 100$.

An optimization code was designed and written in ANSI C++ language in order to load and process the instances, build the time expanded networks and create and solve the associated model by recalling the IBM ILOG Cplex 12.6 libraries.

The following Cplex parameters and settings were considered. The chosen optimization algorithm was the Branch and Cut algorithm with a final time limit of 12 hours of CPU time, also providing intermediate results after 6, 8 and 10 hours of CPU time. MIP emphasis was set to balance optimality and feasibility, the MIP search method was set to dynamic search with 20 parallel running threads.

All the experiments were performed on a workstation with an Intel Xeon CPU E5-2680 v2 @ 2.80GHz, 64 Gb of RAM and running Linux Ubuntu 14.04 64 bits as operating system.

### 5.2 Analysis of the computational results

The numerical results of the computational experiments are shown in Table 6, while in Figure 8 an example of schedule for the two available shuttles is reported, representing the computational results obtained from an instance with 12 time intervals. The dashed line represents the schedule for shuttle 1 while the solid line represents the schedule for shuttle 2. The structure of the schedules obtained from the computational results confirms the correctness and the suitability of the model to provide solutions for the tactical optimization problem introduced in Section 3. In particular, the first shuttle is associated with the following schedule: Savona seaport - Rivalta dry port - Genoa seaport - Alessandria dry port - La Spezia seaport. Between each couple of terminals, holdover arcs are correctly activated in order to permit the required loading/unloading operations, as requested by the model. Similarly, the schedule associated to the second shuttle according to the results is as follows: Alessandria dry port - Genoa seaport - Alessandria dry port - Savona dry port - Rivalta dry port - Genoa seaport. Also in this schedule the required holdover arcs are correctly activated by the model at each schedule leg to represent the associated loading/unloading operations.

The above described schedules provide an example of the proof of concept obtained through the computational experiments performed on a set of instances based on realistic case studies and validating the original model presented in the previous Section.

With respect to the quality of the computational results, a feasible solution is found by the solver for all the considered instances within the time limit of 6 hours. Additional CPU time enables better results in most cases, but the difference is often very limited, in particular for those instances with a higher number of cargo demands.

Optimal solutions are obtained for instances with a limited number of cargo demands for the first two sets of instances. Higher quantities of cargo demands increase considerably the computational effort required to solve the instances, as confirmed by an increase in the values of the optimality GAP and the decrease in the number of analysed nodes in the search tree. Shorter time steps correspond to a growth in the number of intervals for the considered time horizon and therefore in the number of binary variables. A related increase in the required computational effort can be observed in the results, in particular for large size instances where the number of analysed nodes in the search tree is reduced. On smaller instances, a more dense time resolution permits sometimes to find better solutions in terms of objective function value and optimality GAP, since the available time horizon can be exploited in a more flexible and efficient way.

More in general, the results obtained from the computational test confirm the suitability of the proposed model for practical purposes, even in the case of a complex dry port logistics system.

| INSTANCE SET | CARGO DEMAND | BEST INTEGER SOLUTION | | | | BEST BOUND | | | | GAP % | | | | B&C NODES | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 6h | 8h | 10h | 12h | 6h | 8h | 10h | 12h | 6h | 8h | 10h | 12h | 6h | 8h | 10h | 12h |
| 1 | 20 | 215449 | - | - | - | - | - | - | - | optimal | - | - | - | 24191 | - | - | - |
| 1 | 40 | 218720 | 218720 | 218716 | 218716 | 129728.8138 | 137285.6743 | 149908.6608 | 161210.7033 | 40.69 | 37.23 | 31.46 | 26.29 | 17796 | 24333 | 31578 | 39118 |
| 1 | 60 | 219098 | 219098 | 219098 | 219098 | 113650.8283 | 113650.8283 | 119267.8543 | 124169.2123 | 48.13 | 48.13 | 45.56 | 43.33 | 6093 | 7906 | 9835 | 11993 |
| 1 | 80 | 220725 | 220725 | 220725 | 220671 | 110291.8144 | 110330.8703 | 110598.7865 | 110598.7865 | 50.03 | 50.01 | 49.89 | 49.88 | 4361 | 6016 | 6488 | 7067 |
| 1 | 100 | 224914 | 224914 | 224914 | 223808 | 111482.2859 | 112016.8847 | 112729.0261 | 112729.0261 | 50.43 | 50.20 | 49.88 | 49.63 | 809 | 1192 | 1794 | 2350 |
| 2 | 20 | 113418 | - | - | - | - | - | - | - | optimal | - | - | - | 11564 | - | - | - |
| 2 | 40 | 221842 | 221842 | 221842 | 221842 | 110491.7358 | 110524.4047 | 110524.4047 | 110644.9857 | 50.19 | 50.18 | 50.18 | 50.12 | 7298 | 9198 | 11214 | 13481 |
| 2 | 60 | 226955 | 226955 | 225955 | 225955 | 110535.9766 | 110581.4358 | 110993.7556 | 110993.7556 | 51.30 | 51.28 | 50.88 | 50.88 | 3144 | 4872 | 7261 | 8010 |
| 2 | 80 | 225553 | 225553 | 222563 | 222563 | 109901.7403 | 109901.7403 | 109901.7403 | 109901.7403 | 51.27 | 51.27 | 50.62 | 50.62 | 426 | 596 | 1034 | 1360 |
| 2 | 100 | 233737 | 233737 | 233737 | 233737 | 113691.5575 | 113691.5575 | 113691.5575 | 113691.5575 | 51.36 | 51.36 | 51.36 | 51.36 | 420 | 591 | 1110 | 1194 |
| 3 | 20 | 115399 | 115399 | 115383 | 115383 | 109165.3953 | 109362.6987 | 112535.8936 | 113142.5473 | 5.40 | 5.22 | 2.47 | 1.94 | 34224 | 47430 | 58521 | 70059 |
| 3 | 40 | 118600 | 118600 | 118600 | 117696 | 111646.4954 | 111646.4954 | 111646.4954 | 111646.4954 | 5.86 | 5.86 | 5.86 | 5.14 | 9227 | 12687 | 20614 | 25319 |
| 3 | 60 | 235987 | 235987 | 235987 | 233077 | 110411.4671 | 110411.4671 | 110411.4671 | 110411.4671 | 53.21 | 53.21 | 53.21 | 52.63 | 499 | 714 | 928 | 1263 |
| 3 | 80 | 236125 | 236125 | 236125 | 228237 | 111423.0848 | 111423.0848 | 111423.0849 | 111423.0849 | 52.80 | 52.80 | 52.81 | 51.18 | 86 | 155 | 234 | 287 |
| 3 | 100 | 242750 | 242750 | 242750 | 242750 | 113656.4995 | 113656.4995 | 113656.4995 | 113656.4995 | 53.18 | 53.18 | 53.18 | 53.18 | 20 | 34 | 165 | 208 |
| 4 | 20 | 115441 | 115441 | 115441 | 115389 | 109971.4168 | 110184.4411 | 110305.3063 | 110510.5942 | 4.74 | 4.55 | 4.45 | 4.23 | 31294 | 41993 | 52088 | 64204 |
| 4 | 40 | 120892 | 120862 | 119851 | 119851 | 109338.7014 | 109338.7117 | 109338.7117 | 109339.2914 | 9.56 | 9.53 | 8.77 | 8.77 | 6960 | 7434 | 10974 | 13303 |
| 4 | 60 | 238923 | 238923 | 238923 | 238923 | 110136.3264 | 110136.3264 | 110136.3264 | 110136.3264 | 53.90 | 53.90 | 53.90 | 53.90 | 41 | 67 | 81 | 207 |
| 4 | 80 | 250595 | 250595 | 249267 | 249267 | 111742.1477 | 111781.9434 | 111783.2848 | 111783.2848 | 55.41 | 55.39 | 55.39 | 55.16 | 1 | 15 | 53 | 87 |
| 4 | 100 | 245863 | 245863 | 245863 | 245863 | 112362.5303 | 112738.0365 | 113053.9311 | 113081.4334 | 54.30 | 54.15 | 54.02 | 54.01 | 1 | 1 | 1 | 1 |

Table 6: Computational results for the four sets of instances.

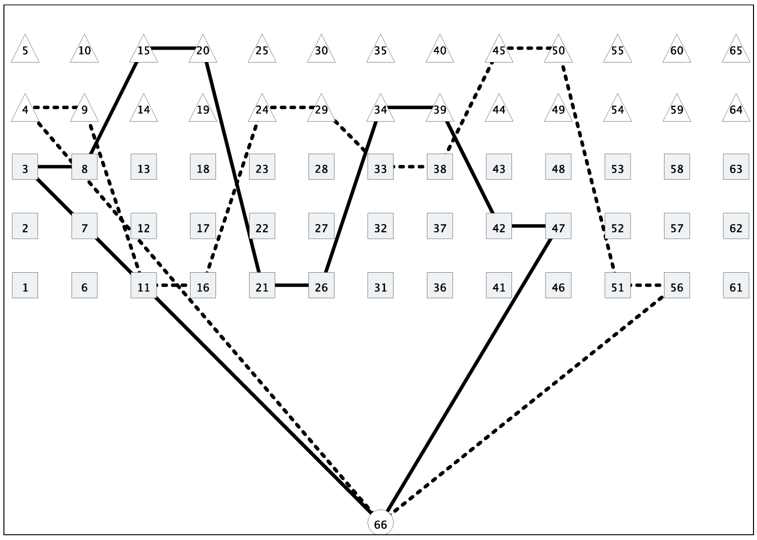


Figure 8: Representation of the schedules for 2 shuttles related to the results obtained on an instance with 12 time intervals.

## Conclusions

Dry ports are defined in the literature as inland freight terminals directly connected to one or more seaports with high-capacity transport means, where customers can drop and pick up their standardised units as if directly at a seaport. The goal of this paper was to provide a contribution for addressing the optimization problems frequently arising from the recent introduction of dry ports in the freight transportation processes.

To this aim, we presented a review of the dry port concept as it is presented in the scientific literature on freight transportation, identifying and classifying the optimization challenges supporting decisions in the field of optimal design and management of dry-port-based freight transportation systems.

We introduced a tactical planning problem consisting in the definition of the optimal schedule for the services operated by a fleet of shuttles on the railway network connecting seaport terminals and dry ports, in order to address the requested demands of containerized cargoes.

An original service network design model representing the considered optimization problem was presented, in which the integration and consolidation on the shuttles of cargo flows directed from the shippers toward the seaports and vice versa is encompassed, and a number of different classes of costs and operational constraints are considered.

A quite complex dry port system was considered as a computational testbed for the model,

based on an italian regional case: the Alessandria logistics system, linking the ligurian seaports with the hinterland by means of high capacity railway connections.
The results of the computational test confirmed the correctness and suitability of the proposed service network design model and good quality feasible solutions were produced for the considered tactical planning problem on realistic instances within a limited amount of computational time.

## Acknowledgements

Partial funding for this project has been provided by the Natural Sciences and Engineering Council of Canada (NSERC), through its Industrial Research Chair and Discovery Grants programs, and by the Sapienza University of Rome, through the "Ricerche Universitarie" program C26A09AT9W.

## References

[1] J. Andersen, T.G. Crainic, M. Christiansen, "Service network design with asset management: formulations and comparative analyses", *Transp. Res. Part C*, 17, 197-207, 2009.

[2] A. Balakrishnan, T.L. Magnanti, P. Mirchandani, "Network design". In *Annotated Bibliographies in Combinatorial Optimization*, M. Dell'Amico, F. Maffioli, S. Martello (Eds.), John Wiley & Sons, New York, NY, 311-334, 1993.

[3] L. Bertazzi, M.W.P. Savelsbergh, M.G. Speranza, "Inventory Routing". In *The Vehicle Routing Problem: Latest Advances and New Challenges*, B.L. Golden, E. Wasil, R. Raghavan (eds.), 49-72, 2008.

[4] M. Caramia, P. Dell'Olmo, *Multi-objective Management in Freight Logistics*, Springer-Verlag, 2008.

[5] Z. Chang, T. E. Notteboom, "Location analysis of dry ports using Fuzzy c -Means (FCM) clustering: a case study of the port of Dalian", WCTR 2012, Antwerp, Belgium, 21-22 May 2012.

[6] M. Christiansen, K. Fagerholt and D. Ronen, "Ship routing and scheduling: Status and Perspectives", *Transportation Science*, 38(1), 1-18, 2004.

[7] J.F. Cordeau, P. Toth, and D. Vigo,"A Survey of Optimization Models for Train Routing and Scheduling", *Transportation Science* 32(4), 380-404, 1998.

[8] T.G. Crainic, A. Sgalambro, "Service Network Design Models for Two-tier City Logistics", *Optimization Letters*, 8(4), 1375-1387, 2014.

[9] T.G. Crainic, N. Ricciardi and G. Storchi, "Models for Evaluating and Planning City Logistics Transportation Systems", *Transportation Science*, 43(4), 432-454, 2009.

[10] T.G. Crainic, "Service design models for Rail Intermodal transportation". In B. et al. (ed.), Innovations in Distribution Logistics, Lecture Notes in Economics and Mathematical Systems 619. Springer Verlag, 2009.

[11] T.G. Crainic, K.H. Kim, "Intermodal Transportation" (Chapter 8). In: C. Barnhart, G. Laporte (Eds.), Handbooks in Operations Research and Management Science: 14 Transportation, Elsevier, North-Holland, Amsterdam, 467-537, 2007.

[12] T.G. Crainic, "Service network design in freight transportation", *European Journal of Operational Research*, 122, 272-288, 2000.

[13] K. Cullinane, R. Bergqvist and G. Wilmsmeier,"The dry port concept - Theory and practice", *Maritime Economics & Logistics* 14, 1-13. doi:10.1057/mel.2011.14 , 2012.

[14] K. Cullinane, G. Wilmsmeier, "The Contribution of the Dry Port Concept to the Extension of Port Life Cycles", In: J. W. Böse (ed.), *Handbook of Terminal Planning*, Operations Research/Computer Science Interfaces Series 49, LLC 2011.

[15] A. Drira, H. Pierreval, S. Hajri-Gabouj,"Facility layout problems: A survey", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 35, Issue 3, 207-222, 1999.

[16] X. Feng, Y. Zhang, Y. Li, and W. Wang, "A Location-Allocation Model for Seaport-Dry Port System Optimization" in *Discrete Dynamics in Nature and Society* Volume 2013, Article ID 309585, http://dx.doi.org/10.1155/2013/309585, 2013.

[17] I. Ghamlouche, T.G. Crainic, M. Gendreau, "Cycle-Based Neighbourhoods for Fixed-Charge Capacitated Multicommodity Network Design", *Operations Research*, 51(4), 655-667, 2003.

[18] Y. Guan, Y. and R.K. Cheung, "The berth allocation problem: Models and solutions". *OR Spectrum* 26(1): 75-92, 2004.

[19] P. Hansen, C. Oguz, C. and N. Mladenevic, "Variable neighborhood search for minimum cost berth allocation", *European Journal of Operational Research* 191(3): 636-649, 2008.

[20] V. Henttu, L. Lttil and O-P. Hilmola,"Optimization of Relative Transport Costs of a Hypotetical Dry Port Structure", *Transport and Telecommunication*, Vol. 12, No 2, 12-19, 2011.

[21] F. Iannone, "A model optimizing the port-hinterland logistics of containers: The case of the Campania region in Southern Italy". In: K.P.B. Cullinane, R. Bergqvist and G. Wilmsmeier (eds.) *Maritime Economics and Logistics*, Special Issue on Dryports 40: 33-72, 2011.

[22] A. Imai, E. Nishimura, and S. Papadimitriou, "The dynamic berth allocation problem for a container port", *Transportation Research B*, 35(4): 401-417, 2001.

[23] A. Jaržemskis, A.V. Vasiliauskas, "Research on dry port concept as intermodal node", *Transport* 22(3), 207-213, 2007.

[24] K.H. Kim and K.C. Moon, "Berth scheduling by simulated annealing", *Transportation Research B*, 37: 541-569, 2003.

[25] P. Leveque, V. Roso, "Dry Port concept for seaport inland access with intermodal solutions", Master thesis. Department of Logistics and Transportation, Chalmers University of Technology, 2002.

[26] M.F. Lai, and H.K. Lo,"Ferry service network design: optimal fleet size, routing and scheduling". *Transportation Research part A: Policy and Practice* 38, 305-328, 2004.

[27] F. Li, X. Shi, Hao Hu,"Location selection of dry port based on AP clustering - the case of southwest China", ISSN 1816-6075 (Print), 1818-0523 (Online) *Journal of System and Management Sciences* Vol. 1, No. 5, 93-105, 2011.

[28] E. Nishimura, A. Imai, G.K. Janssens, S. Papadimitriou, "Container storage and transshipment marine terminals", *Transportation Research Part E*, 45, 771-786, 2009.

[29] T. Notteboom, J.P. Rodrigue, “Dry ports and the maritime hinterland: gaining momentum”, *Port technology international: the review of advanced technologies for ports and terminals world-wide*, 50, 21-24, 2011.

[30] T. Notteboom, J.P. Rodrigue, “Port Regionalization: Towards a New Phase in Port Development”, *Maritime Policy and Management*, 32(3), 297-313, 2005.

[31] Y.M. Park and K.H. Kim, ”A scheduling method for berth and quay cranes”, *OR Spectrum* 25: 1-23, 2003.

[32] W. Powell, P. Jaillet and A. Odoni, “Stochastic and Dynamic Routing and Networks”, in M.O. Ball et al. (Eds.), *Handbook of Operations Research*, 8, 141–295, 1995.

[33] V. Roso, K. Lumsden, “Review of Dry Ports”, *Maritime Economics & Logistics*, 12(2), 196-213, 2010.

[34] V. Roso, J. Woxenius and K. Lumsden, “The dry port concept: connecting container seaports with the hinterland”, *Journal of Transport Geography*, 17(5), 338-345, 2008.

[35] Regione Piemonte - Assessorato ai Trasporti e Infrastrutture, “Accessibilità e mobilità in Piemonte: la gestione del processo di pianificazione”, *Documento consuntivo delle azioni e attività della VIII legislatura*, 2010.

[36] Fondazione SLALA - Sistema Logistico del Nord Ovest d’Italia, “Progetto Retroporto di Alessandria”, *Relazione di Sintesi*, 2008.

[37] D. Steenken, S. Voss, R. Stahlbock, “Container terminal operation and operations research - a classification and literature review”, *OR Spectrum* 26 (1), 3-49, 2004.

[38] E. Taniguchi, M. Noritake, T. Yamada, T. Izumitani,“Optimal size and location planning of public logistics terminals” *Transportation Research Part E*, 35, 207-222, 1999.

[39] UNCTAD [United Nations Conference on Trade and Development] (ed) Multimodal Transport and Containerisation (TD/B/C.4/238/Supplement 1, Part Five: Container and Depots), Geneva, 1982.

[40] UNCTAD [United Nations Conference on Trade and Development] (ed) Handbook on the management and operation of dry ports (UNCTAD/RDP/LCD/7), Geneva, 1991.

[41] A. Veenstraa, R. Zuidwijka and E. van Asperen, “The extended gate concept for container terminals: Expanding the notion of dry ports”, *Maritime Economics & Logistics*, 14, 14-32, 2012.

[42] I.F.A. Vis, and R.D. Koster, “Transshipment of containers at a container terminal: An overview”, *European Journal of Operational Research*, 147, 1-16, 2003.

[43] J. Wei, A. Sun, J. Zhuang, “The Selection of Dry Port Location with the Method of Fuzzy-ANP”, in Q. Luo (ed.): *Advances in Wireless Networks and Information Systems*, LNEE 72, 265-273, 2010.

[44] C.Zhang, Y. Wan, J. Liu, and R.C. Linn, ”Dynamic crane deployment in container storage yards”. *Transportation Research B* 36(6), 537-555, 2002.