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Modeling Dry-Port-Based Freight Distribution Planning[†]

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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 freight distribution 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 ports, logistics, optimization, mixed-integer programming.

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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* [20, 13]. The advantage of introducing one or more dry ports into freight distribution was confirmed by several experiences in terms of logistics integration and port regionalization (e.g., [14, 19]). 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] 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 both 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 will be introduced. The specific features of the considered problem with respect to similar cases previously presented in the literature for different applications will be discussed. In particular, we will 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.

As it will be seen 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, 17]). With respect to advanced approaches recently introduced in the literature on service network design for freight logistics (see [1, 6, 7]), the original 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 chance 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 presence of specific sets of constraints introduced ad-hoc in the model to force the routing and scheduling process to encompass the waiting of shuttles at the terminals needed to permit the loading and unloading of cargo demands;
- 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 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 some 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 and further lines of research 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 briefly 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, whose reflections are widely treated in the literature. 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 [9] 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 advanced logistics platforms, designed to receive containerized goods, 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 additional 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 [19] 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.

Dry ports can rise at a certain distance from seaports as the result of a concurrent effort made by private intermodal operators and public agencies for local development.

They are commonly directly connected to the interested seaports by high capacity lines, most of the times through railway shuttle transportation services. Sometimes referred to as *inland dry ports* as well, they represent advanced logistics macroscopic platforms, designed to provide value-added services such as management, custom, information, storage and manufacturing operations (packaging, labelling, assembly, quality control) before the following shipment of the containers towards the final destinations. These platforms are located in proximity of the seaports and represent a link between manufacturing and service industries.

The features defining the specific nature of dry ports with respect to other logistics nodes and intermodal terminals emerge if one analyzes the definitions provided in the recent literature on this topic. The former introduction of the dry port concept is to be referred to the UNCTAD report [23], 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 [12] 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 [13, 20] is often considered in the scientific literature (see for instance [5, 9, 12]): 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.*

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 [25]). 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.

However, the benefits arising from the presence of dry ports involve several different actors with different goals. A substantial modal shift from the road transport to the more efficient railway transport is obtained, together with the attendant reduction of costs and environmental impact. Seaport cities are somewhat relieved from congestion effects. Advanced services are directly provided to the inland shippers and the transshipment of goods in proximity of the ports becomes more efficient.

According to Notteboom et al. [14], dry ports can assume three main functions within the transport chain. The first function is that of a *satellite terminal*, located very near to a seaport facility to which it is connected, capable of providing services that are not available at the seaports, such as warehousing, storage of empty containers and interface with the local markets. The second function of dry ports as major intermodal facilities is concerned in particular with their role as *load centers* from well defined regional markets, whose area depends on the relevance of the interested railway corridor. The third main function associated to dry ports is that of a *transshipment facility*, linking together different freight distribution systems according to their multimodal (rail-to-rail) and intermodal (road-to-rail) nature, associated to administrative functions for the international traffics and high value-added logistics services. Here the origin or destination of the goods fall outside the terminal's market area. The three main functions are not mutually exclusive and a dry port can serve more than one function at once.

The dry port concept and its role is classified in [20] 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 [20], 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 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. The outcomes of such a configuration include a relevant modal shift towards railway transportation, reducing the port congestions and providing the shippers with a high quality service at low costs. Railway operators take advantage of distant dry ports, together with the shippers, that obtain a lower environmental impact assessment for their products, and the seaport cities, that reduce their congestion load.

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. A midrange dry port assumes the function of a consolidation point for several railway services, and technical equipments for security and custom inspection can be concentrated in a single facility. A midrange dry port can provide services for a high number of shippers, including those located in proximity of the seaports, and there is the possibility to consolidate the loads directed to a container vessel in dedicated trains.

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 [14] and [20].

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. It assumes the function of container buffering and provides the chance to load the containers in sequence on the service shuttles in such a way to synchronize with the vessel loading process.

The classifications presented above are synthetically merged 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.[14]) and its physical distance from the seaports (according to the classification by Roso et al.[20]).

The presence of inland dry ports contributes to push the port development process towards the *regionalization* phase, as described in [15]: 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 multi-level 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 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.

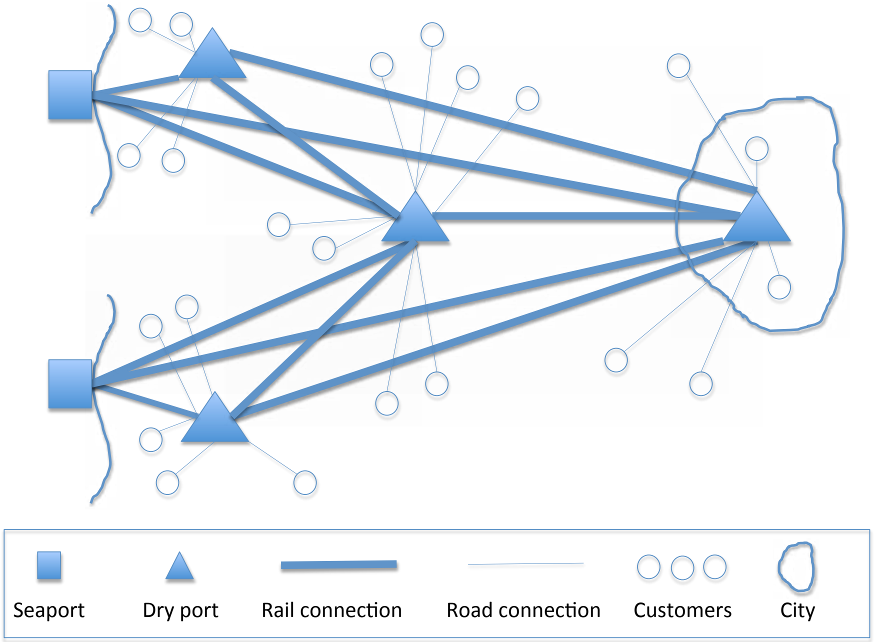

Figure 1: A system with two seaports, two close dry ports, one midrange dry port and one distant dry port.

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 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, 26] 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 [26]. Both approaches are based on a set of factors impacting the location decision and a system of evaluation indicators influencing the locational analysis. 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.

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.

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 [20] 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.

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.

Finally, 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).

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, due to their role as custom service providers, are commonly settled and managed as an initiative of public authorities, ensuring the requested integration and coordination of the activities provided by possibly different service operators. Therefore, 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 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;

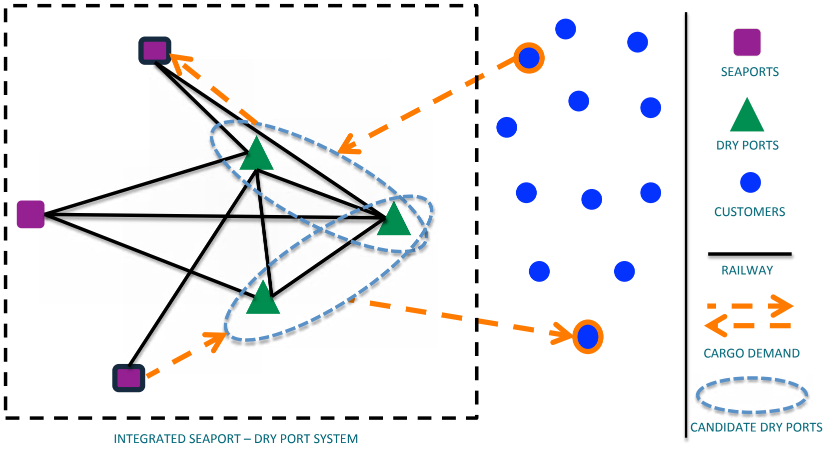

Figure 2: Sketch of the cargo demand within the considered tactical planning problem.

- 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 activation 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 [8] for a wide review of these class of problems). In this Section we present an original SND model designed ad hoc 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 γ 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 γ 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.
- 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 γ. In particular, for each node i in the time expanded network, two dummy arcs (γ, i) and (i, γ) 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.

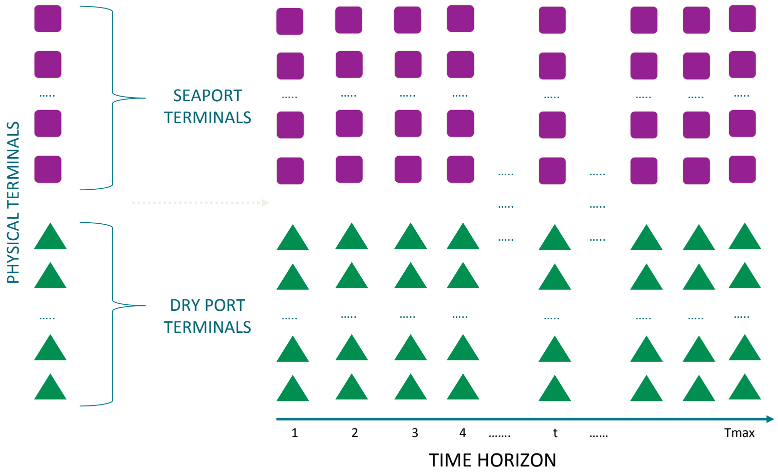

Figure 3: A representation of the time-space network.

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 γ 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 the feasible time window are represented in black. Only the suitable dummy arcs linking the latter nodes to the super-sink γ 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 γ. 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.

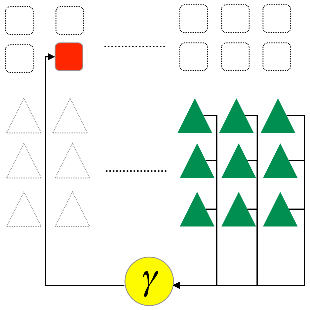

Figure 4: Network representation for a given cargo demand directed from a given seaport node to a set of candidate dry port nodes, represented in black. Only the dummy arcs linking the suitable terminal nodes to the super-sink γ are represented.

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 γ 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.

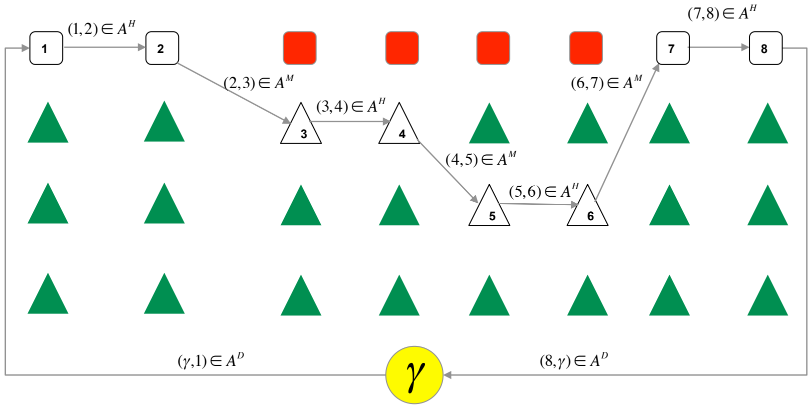

Figure 5: A tour on the time expanded network representing the schedule of a shuttle starting from a seaport, touching two distinct dry ports and then getting back to the origin seaport.

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 γ.

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 [24]. The sum of the capacities of the flat-cars provides the capacity of each shuttle $r \in \mathcal{R}$, denoted by u_r, while π_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 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 ϕ_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 $z^d_r, d \in \mathcal{D}$, assuming a value equal to 1 if the cargo demand d is shipped through shuttle r, and 0 otherwise, $x^d_{ijr}, (i,j) \in \mathcal{A}, d \in \mathcal{D}$, 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 ϕ_r, details on $Q2$ are provided by variables z^d_r, while decisions $Q3$ are associated with variables x^d_{ijr}. Finally, service design variables y_{ijr} define decisions $Q4$, $Q5$, $Q6$ and $Q7$.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 γ 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 realistic size instances for those complex and realistic cases in which more than one dry port and more than one seaport are present in the logistic 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 new 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, that is supposed to be operative in the period 2014-2017, 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 [21, 22]. 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 this case due to the presence of three seaports as well as of the Rivalta Scrivia dry port already operating in the region.

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

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 2 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 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

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

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 3: Nodes in the time expanded network represented in Figure 7.

the time instant 0 until the time instant 12. The meaning of the nodes representation is provided in Table 3 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 γ, which is represented by node 66 in Figure 7.

The testbed for the computational experiments is composed by three sets of instances based on the framework above described representing the Alessandria dry port logistics system. We considered three 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

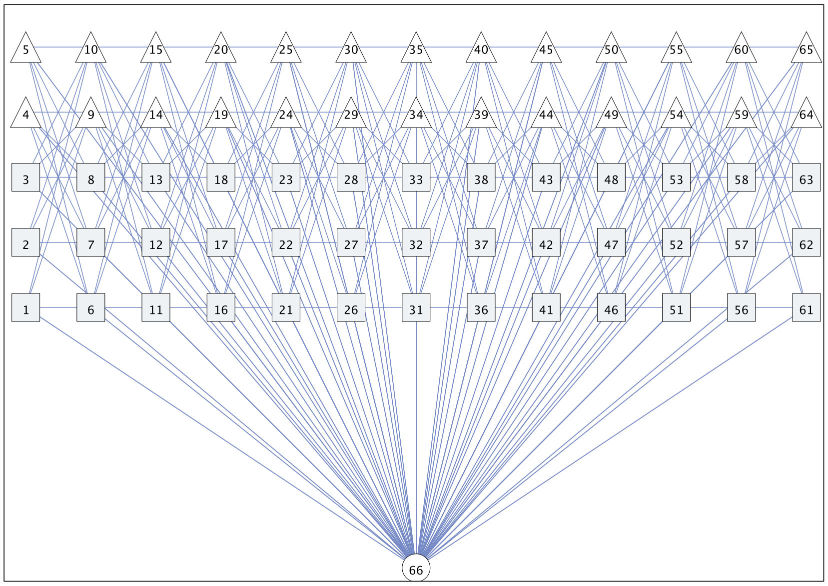

Figure 7: Representation of the whole time expanded network for the case of a time interval equal to 2 hours.

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

Table 4: Description of the time expanded network for each set of instances.

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 $t = 0, t = 1, ..., t = 16$. Finally, 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 $t = 0, t = 1, ..., t = 16$. A description of the time expanded network associated with the three sets of instances in terms of number of nodes and different classes of arcs is presented in Table 4.

We considered three sets of instances and 10 demand scenarios for each set, with an increasing number of cargo demands ranging from 10 to 100. A total number of 30 problem 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 γ 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 12.5 libraries.

The following Cplex parameters and settings were considered. The chosen optimization algorithm was the Branch and Cut algorithm with a time limit of 8 hours of CPU time. MIP emphasis was set to balance optimality and feasibility, and the MIP search method was set to dynamic search.

All the experiments were performed on a server provided with an AMD Opteron 6272 16 Core 2.1GHz L3-16MB Bulldozer skG34 and 37 Gb of RAM running Linux Redhat 6-64 bits as operating system.

5.2 Analysis of the computational results

The numerical results of the computational experiments are shown in Table 5, while in Figure 8 an example of schedule for the two available shuttles is reported, representing the computational results obtained from the instance $1 - 50$. 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 a schedule starting from the Savona seaport, where the shuttle will stay for one time period in order to permit the cargo loading operations (node 3 - node 8). Then the shuttle will reach the dry port of Rivalta (node 8 - node 15) where it will stay for one time period (node 15 - node 20), before moving towards the seaport of Genoa (node 20 - node 21). After waiting for one time period at the Genoa seaport terminal (node 21 - node 26), the shuttle will move towards the Alessandria dry port (node 26 - node 34). Then the shuttle will wait for one time period on the latter terminal (node 34 - node 39), and it will end its schedule in the seaport of La Spezia (node 39 - node 42), where the remaining cargo will be unloaded during the last time interval of the schedule (node 42 - node 47). Similarly, the schedule associated to the second shuttle according to the results starts from the Alessandria dry port where loading operations will be performed (node 4 - node 9), then the seaport of Genoa will be visited (node 9 - node 11) and served (node

11 - node 16). The shuttle will then get back again to the Alessandria dry port (node 16 - node 24), it will hold for one time period at the dry port terminal (node 24 - node 29) before moving to the dry port of Savona (node 29 - node 33), where it will stay for one time period (node 33 - node 38). The shuttle will then reach the Rivalta dry port (node 38 - node 45), where it will hold for one time period (node 45 - node 50) and then it will move towards the seaport of Genoa (node 50 - node 51), ending the schedule with a stop of one time period for the final operations at the seaport terminal (node 51 - node 56). The above described schedules provide an example of the proof of concept obtained through the realized computational experiments on a set of instances based on realistic case studies and validating the original model presented in the previous Section.

Optimal solutions are obtained for instances with a small number of cargo demands for all the sets of instances. From the analysis of the objective function value, it turns out that all of the optimal solutions are related to those cases in which one single shuttle is sufficient to carry all the cargo demands. Higher numbers of cargo demands enable the activation of both the available shuttles, and increase consistently 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. When the number of cargo demands is higher than 70, the optimization code was not able to find a feasible solution for none of the sets of instances.

A smaller time step produces a growth in the number of binary variables in the model, and a related increase in the effort required to process each node of the search tree. Nevertheless, the quality of the obtained solutions is not strongly affected by this growth, and the optimality GAPs obtained for the three sets of instances for the different number of cargo demands are comparable. A possible explanation for this fact lies in the hypothesis that a high number of time intervals for the same time horizon increases the chances for the heuristic algorithm included in the optimization code to find a feasible solution, since the length of the holding arcs to represent cargo loading and unloading operations at terminals is shorter for those cases.

From the analysis of the computational results, it is possible to conclude that the computational effort is very sensitive to the increase in the number of cargo demands and in the number of time intervals in which the time horizon is divided. Therefore the solution of realistic cases in which the tactical planning process must be optimized for hundreds of cargo demands will require the development of metaheuristic algorithms in order to obtain efficiently good quality feasible solutions for the considered problem.

Instance	Cargo demands	Best integer solution	Best bound	GAP (%)	B&C nodes
$1-10$	10	111149	-	optimal	331
$1-20$	20	215449	214202.3831	0.58	42510
$1-30$	30	218578	123256.1161	43.61	14401
$1-40$	40	219706	110529.9533	49.69	8361
$1-50$	50	221794	110396.8857	50.23	4998
$1-60$	60	224059	110740.8143	50.58	1427
$1-70$	70	-	115143.5109	-	1020
$1-80$	80	-	126037.2705	-	629
$1-90$	90	-	127860.1871	-	671
$1-100$	100	-	140278.6256	-	652
$2-10$	10	111203	-	optimal	2237
$2-20$	20	113418	-	optimal	6964
$2-30$	30	220573	110215.9258	50.03	9000
$2-40$	40	219861	77365.1655	64.81	8102
$2-50$	50	224970	79952.5630	64.46	2200
$2-60$	60	226947	110467.3490	51.32	1272
$2-70$	70	230372	111387.4943	51.65	16
$2-80$	80	-	112046.2980	-	476
$2-90$	90	-	112783.9462	-	14
$2-100$	100	-	113599.6415	-	9
$3-10$	10	109161	-	optimal	6934
$3-20$	20	115383	110924.3382	3.86	49008
$3-30$	30	115548	109296.5775	5.41	12226
$3-40$	40	225666	108733.3169	51.82	1081
$3-50$	50	227739	109163.6396	52.07	141
$3-60$	60	242132	110244.1035	54.47	1
$3-70$	70	242152	111150.4990	54.10	2
$3-80$	80	-	65622.9638	-	1
$3-90$	90	-	76642.7093	-	1
$3-100$	100	-	84677.8279	-	1

Table 5: Computational results for the three sets of instances.

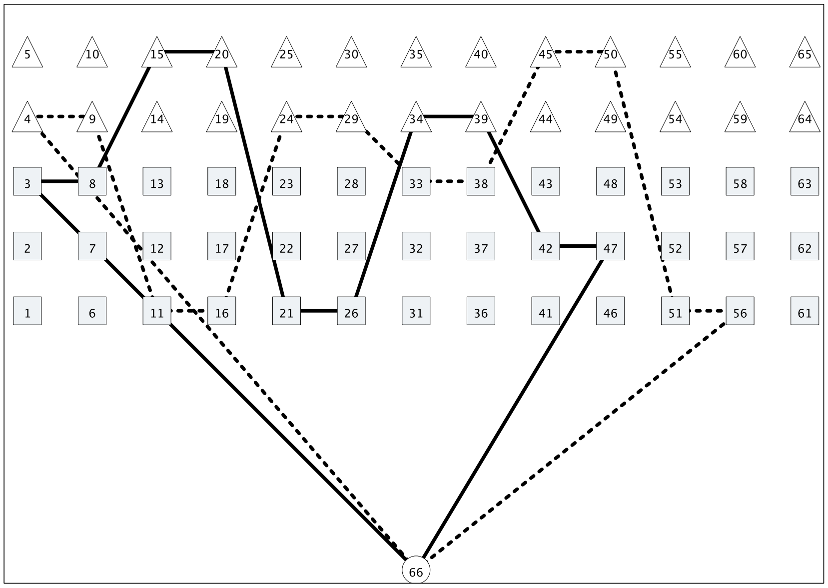

Figure 8: Representation of the schedules for 2 shuttles related to the results of instance 1-50.

6 Conclusions and further research

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 to produce solutions for the considered tactical planning problem. The computational effort required to solve the model is sensitive to the growth in the number of cargo demands and time intervals considered in the instances.

Further research will include the design and implementation of algorithms to solve large size instances of the considered problem. The service network design problem considered in this paper belongs to the class of capacitated multicommodity fixed charge network design problems, and large size instances of such problems are hard to solve to optimality by pure exact methods, while metaheuristic algorithms are widely considered in the literature as suitable methodologies [10, 11, 16, 18].

Even though recent algorithms for CMND problems represent promising algorithmic avenues, a significant novel contribution will be required to develop new approaches and solve large size instances of the faced problem and will be considered in forecoming papers on this topic.

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

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

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

[9] 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.

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

[11] M. Hewitt, G.L. Nemhauser, M.W.P. Savelsbergh, "Combining Exact and Heuristic Approaches for the Capacitated Fixed-Charge Network Flow Problem", *INFORMS Journal on Computing*, 22(2), 314-325, 2010.

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

[13] 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.

[14] 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.

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

[16] M.B. Pedersen, T.G. Crainic, O.B.G. Madsen, "Models and tabu search metaheuristics for service network design with asset-balance requirements", *Transportation Science*, 43(2), 158-177, 2009.

[17] 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.

[18] I. Rodriguez-Martin, J.J. Salazar-Gonzalez, "A local branching heuristic for the capacitated fixed-charge network design problem", *Computers & Operations Research*, 37(3), 575-581, 2010.

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

[20] 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.

[21] Fondazione SLALA - Sistema Logistico del Nord Ovest d'Italia, "Progetto Retroporto di Alessandria", *Relazione di Sintesi*, 2008.

[22] 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.

[23] 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.

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

[25] 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.

[26] 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.