

# DRY PORT AS A LEAN AND GREEN STRATEGY IN A CONTAINER TERMINAL HUB: A MATHEMATICAL PROGRAMMING MODEL

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**ABSTRACT**

Maritime freight transport represents an effective solution, allowing to ensure a low-impact service both under an economic and a sustainable perspective. As a consequence, in the last ten years, an increasing trend of goods transported by sea has been observed. In order to improve the terminal containers' performance, recently published scientific studies shown the applicability of the 'lean logistic' concept as a strategic key for ensuring a continuous improvement of the logistic chain for inter-/intra terminal containers' activities. According to this approach, the adoption of a dry port can positively affect terminal containers' performance, but this requires resources and investments due to inter-terminal activities (e.g. transport of the container from port to dry port and vice versa). The purpose of the study is to develop a mathematical programming optimization model to support the decision making in identifying the best containers' handling strategy for intermodal facilities, according to lean and green perspectives. Numerical experiments shown the effectiveness of the model in identifying efficient material handling strategies under lean and green perspective.

**KEYWORDS**

lean logistic, container terminal, material handling, container relocation problem, dry port.

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## Introduction

Nowadays the maritime freight transport has a key role in the international trade, and a growing number of industries require an effective and efficient service in order to meet the 5R's of lean logistic: The Right product in the Right quantity and Right condition, at Right place in the Right time, pursuing a low-cost strategy focused on the minimization of the 'Total cost' due to all logistic activities. In this context, the terminal container hub and its facilities play a fundamental role in the global supply chain. The effectiveness of a terminal container hub depends on several factors, like the number of available bays, material handling systems, personnel, turnaround time, strategic and operational planning of hub resources. If on one hand most of ports, by careful management of these aspects, allows ensuring

a high productivity, evaluated in terms of number of containers handled in a time interval. On the other hand the increasing demand of the international containerized cargo freight transportation makes it more difficult the perfect fitting of the seaports in logistic chains. One of the important phenomena preventing to match the ports with their logistic chains is represented by congestion issues [1–3]. A strong indication of high congestion probability is given by the terminal Capacity Utilization (CU), evaluated as the rate between the average number of TEU handled in one year by the terminal and the capacity of the same terminal (maximum number of storable TEU). According to the last Corporate Partnership Board report by OECD [4], the average CU of the worldwide terminal container in 2013 is about 0,65 with peak of value of 0.75–0.80 in countries like China, South-east Asia, Middle east and North Africa (Table 1).

In relative terms these data seems not to be cause of alarm but if these information are crossed with the data related to container traffic forecast in next years, the scenario will drastically worsen in many worldwide countries.

Table 1  
Terminal CU in worldwide countries (estimates obtained from OECD Report [4]).

Country	CU 2013 [#]	Estimated CU 2030 [#]
China	0.79	0.76
Southeast Asia	0.71	0.83
Western Europe	0.58	0.63
North Asia	0.61	0.68
East Coast North America	0.56	0.56
West Coast North America	0.58	0.56
East Africa	0.63	0.46
South Asia	0.66	1.06
East Mediterranean & Black Sea	0.61	0.36
Middle East	0.72	0.36
Gulf Coast North America	0.63	0.40
Southern Africa	0.60	0.57
Oceania	0.65	0.68
Central America/Caribbean	0.66	0.27
East Coast South America	0.69	0.41
West Africa	0.61	0.31
North Africa	0.74	0.49
West Coast South America	0.56	0.33

According to OECD prediction, based on the worldwide TEU trading per year from 2000 to 2016 (Fig. 1), the overall container traffic related to international trade will double by 2030 (an average increase of TEU traffic corresponding to 73% is estimated) while by 2050 the additional traffic will nearly 300% of that today [4].

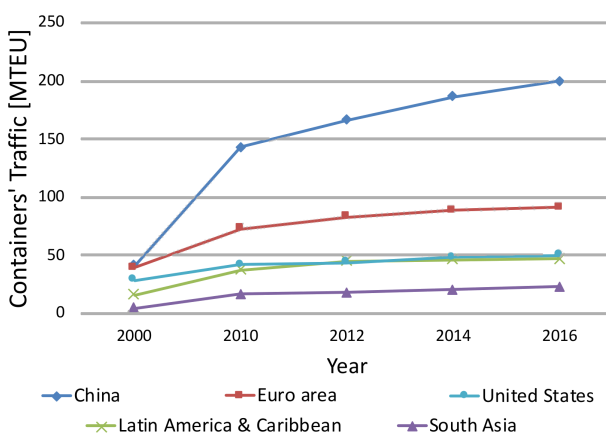


Fig. 1. Containers' port traffic per country from 2000 to 2016, <https://data.worldbank.org/indicator/is.shp.good.tu> (accessed on November 2018).

The containers' traffic showed in Fig. 1, is evaluated according to the classification of the aggregate countries identified by OECD in 2011 [5].

Looking at the traffic by 2030, considering the current port terminals' infrastructure, it is possible to observe that ports in Asia, Western Europe, as well as Oceania, will operate in condition very close to their capacity limits ( $CU \approx 1$ ), and in many cases they will not be able to manage the containers' flow since the number of TEU to be handled, will exceed the port capacity ( $CU > 1$ ).

In order to solve the containers handling performance due to a limited terminal area, in 2009 Roso et al. [6] introduced a new concept of inland port (dry port) directly connected to terminal container structured like an intermodal area where customers could leave or pick up the containers. The dry port concept was certainly not new, but Authors in [6] extend the idea of the dry port as a way to jointly reduce the problem of congestion in terminal hub and improve container logistics. The implementation of the dry port radically changes the traditional handling process of the terminal. Indeed, is possible to transfer and storage the containers from terminal hub to dry port avoiding, in this way, the terminal area's congestion and facilitate the containers' stocking in an inland area, where more space is available [7]. The connection between port and dry port are ensured by fast and reliable services (by road or by rail) allowing to consider the inland sites as a real extension of the seaport liable to cause a substantial decrease of the seaport zone congestion [8].

Under this perspective, it is not possible considering the seaport like just a transferring point between different nodes, but it can be identified like an integrated center in the seamless transport chain, therefore an internal supply chain approach is required for servicing the needs and for satisfying the users' demand [9]. Consistently with this target, Chandrakumar et al. proposed an approach based on lean tools applied to the port sector, already available in scientific literature, to face the internal issue of terminal container. The model developed, based on lean techniques, allows to maximize the customer value, minimizing the resource consumption, the non-value addition operations, as well as the idle times [10].

The Lean principles were born as a concept based on working process of the Toyota Production System, generally defined in terms of the five lean principles: elimination of the waste, standardization, visualization, synchronized flow, and continuous improvement [11]. The term lean thinking was coined by Womack et al. [12], according to authors the Lean thinking is a business methodology that aims to cre-

ate an enterprise able to align the customers satisfaction with employee satisfaction. This aim can be pursued by offering innovative products and minimizing the overall manufacturing costs; according to lean philosophy, the specific activities, from concept to launch of a specific product, require detailed design able to ensure a final product very close to customer's needs, according to best production strategies (low cost, high efficiency, and minimum waste). Olesen et al., proposed to adopt the same framework, referred to as lean terminalization, in container terminal hub, in this case the following key principles are identified:

- waste elimination: the reduction of the time required for loss time activities (e.g. time for containers' re-handling, time for gate access, time for communications, etc.);
- standardization: the reduction or the elimination of unnecessary communications by implementation of logical information based on 'easy-to-interpret' techniques (e.g. pre-printed tickets, barcodes, RFID, etc.);
- visualization: the continuous monitoring of inbound, outbound and transshipment containers flows, generally these activities can be supported by advanced ICT infrastructure to be implemented in terminal container;
- synchronized flow, understood as 'levelling': the improvement of the containers' coordination flows, in order to increase the utilization of terminal resources (e.g. cranes, bays, employees, etc.);
- continuous improvement (CI): the deployment of a CI program finalized to optimize the materials and the information flow through the terminal (e.g. PDCA cycle adoption, seek and reward value added activities, reducing the number of KPIs).

As a consequence, the lean terminalization allows to identify the most critical elements of lean that should be applied in the context of the intermodal container facilities, in order to improve the flow of goods and materials, reducing the issues related to bottleneck-derived terminalization [13]. An approach based on lean terminalization is proposed by Notteboom, that introduced the concept of bottleneck-derived terminalization, considering the operational issues related to storage space, demand and frequency gate access. According to author, these aspects affect the effective performance of the terminal and its facilities, therefore is required a lean approach allows to face the most of challenges related to the efficiency of terminal container, including the communication issues between external and internal players, the utilization of terminal resources and its facilities, the coordination of internal move-

ments, as well as the strategy for containers' storage [14].

According to Garza-Reyes the lean paradigms are not focused only on organizational target such as profitability and efficiency but also on contemporary objectives that comprise customer satisfaction, quality, and responsiveness [15]. In particular, two other researchers in 2016 highlight the importance, in lean paradigms, of the environmental impacts due to industrial activities. This sentence is supported by recently evidences that have raised significant concerns amongst firms and their stakeholders [16]. In order to evaluate the scientific researches on lean initiatives related to environmental aspects, a survey analysis, on most widespread scientific database, is conducted. It is very interesting note that only the works of Parveen et al. (2011) and Mason et al. (2008), focused on manufacturing industries, have integrated lean and green aspects, merging their fundamentals and principles, within the context of supply chains [17–19]. This suggests that further researches are needed to propose a method to integrate the applicability of lean terminalization in order to enhance the environmental performance of supply chains in terminal containers.

As a result of this lack, the follows research questions are proposed in this paper:

RQ1: It is possible considering jointly economic and environmental aspects, for increase the productivity of container terminal hub, according to a lean terminalization approach?

RQ2: The lean terminalization approach can be adopted for optimizing the intra-/inter-terminal handling activities?

RQ3: The dry port can be a good solution, according to lean perspective, for reducing the congestion of the terminal hub and increase its productivity?

In order to reply on RQs above mentioned, in this study it is proposed a mathematical programming optimization model to support decision making in identifying the best containers' handling strategy for intermodal facilities, according to lean and green perspectives is proposed. The adoption of a dry port leads to many benefits on terminal congestion, but the transport of the containers from port to dry port requires resources and generate extra costs. In order to select the optimal strategy under both economic and environmental perspective, a reliable model of the logistic system is required, and many variables and criteria have to be considered. For this reason, mathematical programming has been adopted to define the optimization model.

The model proposed ensures, on one hand, the optimization of the lean performance due to intra-/inter-terminal handling activities and, on the other hand, identifies the best handling strategy to minimize the carbon footprint due to containers transportation. Results are obtained given the number of containers to be stocked, type of available ‘road’ and ‘non-road’ material handling equipment, and presence of one or more dry-port area/s.

The rest of the paper is structured as follows: in second section a literature review on the optimization models for congested terminal hub is proposed; in third section, materials and method of developed model are presented; results obtained in case of a full-scale numerical experiment are in fourth section; finally, conclusions of this work are in the last section.

## Literature review

Traditionally, in scientific literature many studies appeared on both the planning and management of container terminals, with the aim of jointly increasing efficiency and reducing operational costs. In the past, planning and management of operations in container terminals have been studied separately and independently for the seaside (berth and quay), the landside (yard and gates), and the transport area (between quay and yard) of terminals.

In the seaside research field, three main problems have been investigated: the Berth Layout Problem (BLP), the Berth Assignment Problem (BAP) and the Quay Crane Assignment Problem (QCAP), and the Quay Crane Scheduling Problem (QCSP). A review of studies on seaside operations appeared in scientific literature in the period 2004-2015 is in [20, 21]. In both papers, Authors classify studies by means of the assumptions and performance measurements adopted. In the first review, it is found that less than 20% of papers considered dealt with studies on integrated problems (at least two of BLP/BAP/QCAP/QCSP), while in the second one a growing number of studies striving for a combined solution of seaside and landside (yardside) problems in order to minimize yard congestion is observed. In the recent contributions appeared in scientific literature it is quite common the attempt to solve an integrated problem: in [22] the BAP and QCAP are jointly faced (BACAP); in [23], the BAP, QCAP, and QCSP are jointly solved considering cranes setup times; The BAP/QCAP/QCSP problem is faced in [24]; in [25] a multi BAP with vessel speed optimization is proposed.

As far as concern the transport area, the main problems investigated in scientific literature deal

with the selection of the MHE to be adopted and the number of vehicles to be adopted as well as their routing and dispatching. In this research area also collision and deadlock problems are investigated, since in many terminals automated vehicles (Automated Guided Vehicles – AGVs or Automated Lifting Vehicles – Vs) are often adopted. A review of scientific contributions on this topic is in [26, 27].

With reference to the landside area, storage yard layout, yard MHE selection and scheduling, storage allocation problem, container re-shuffling, and truck arrivals management are the main problems investigated in scientific literature. Reviews of scientific contributions on these topics are in [28, 29]. More recent contributions can be found in [30] (on integrated schedules of MHEs), in [31] (integrated schedules of QCs, Yard Trucks (YTs), and YCs), in [32] (YCs scheduling minimizing the energy consumption), in [33] (vehicles scheduling, yard crane scheduling and container storage location), and in [34] (scheduling of twin (non-passing) automated stacking cranes in presence of a temporary containers storage location shared by the two cranes). In the landside research field, often the MHE selection problem is faced also jointly considering the container allocation problem. Recent scientific contributions on this topic are in [35] (optimal yard trucks schedules and container storage allocation strategy), [36] (storage allocation problem), in [37] (Storage Space Allocation Problem (SSAP) in presence of stacking constraints and arrival data uncertainty), and in [38] (integrated Problem of Location Assignment and Straddle Carrier scheduling – IPLASS).

Many studies appeared in scientific literature aiming at improving stack layout organization, since it proves to deep affect the performance of a terminal. The search for an optimal stack layout is performed with the main objective of reducing the reshuffling of containers, that is the process of removing and relocating interfering containers to access a desired one as well as to reduce MHEs process time. Recent scientific contributions can be found in [39], (exact and heuristic solution procedures identifying the optimal stacking policy minimizing), [40] (MIP model to identify the optimal stacking strategy of containers), [41] (queuing network model to evaluate the optimal parallel stack layout), [42] (discrete-event simulation model to evaluate the optimal configuration of the storage yard in case of perpendicular stack layout), [43] (mathematical model to minimize containers reshuffling on the base of a shared stacking policy – location of containers of different types in the same stockpile). Truck arrival management policy also proves to improve service quality, in terms of



reduction of container retrieval time from the storage yard. Recent contributions on this topic are in [44] (decentralized decision making model to support the negotiation process between trucks companies and the terminal operator with the aim of smoothing trucks arrivals), [45] (multiple trucks companies involved in the decentralized decision making process of trucks arrival management), [46] (model to optimize truck appointment system with the aim of minimizing waiting times of both external – at gate and yard – and internal – in yard – trucks).

In many cases, however, the main limit in the increase of a terminal productivity (number of handled containers per working hour) is in the lack of available space. In such cases, the only solution is a physical expansion of the terminal and/or a (re)building of logistic infrastructures. This requires considerable costs and efforts, and often is not feasible because in-city or near-city port location. The concept of dry port defined in [6] can be considered an effective solution for reducing terminal congestion and hence to increase terminal productivity. In their work, authors classify dry ports into three categories: close, mid-range and distant dry ports, and discuss potential benefits and negative implications for each of them. Starting from the work in [6], many studies appeared in scientific literature aiming at solving dry port location problem and at evaluating the potential benefits from the dry port adoption. A review of scientific contributions appeared in the period 2007–2013 is in [47]. Recent contributions are in [48] (a conceptual framework for the inclusion of multiple criteria in the evaluation of dry port location in developing Countries), [49] (hybrid model – CFA/MACBETH/PROMETHEE – for solving the dry port location problem).

The environmental impact of logistic activities has been widely investigated in scientific literature, and both in terms of internal logistic [50–54] and of external logistic [55, 56]. Environmental implications of container terminal operation have been also investigated. A comprehensive review of contributions appeared in scientific literature until 2012 on the port sustainability issue is in [57]. Recent contributions on this topic are in [58] (COPERT based evaluation model of Heavy Duty Vehicles – HDV – emissions adopted in terminals for the transport of containers), [59] (queuing theory based model for evaluating CO<sub>2</sub> emissions from yard tractors during the loading of export containers), [60] (review of existing model for the evaluation of trucks emissions in terminal operations), [61], (system dynamic approach based model for the evaluation of the CO<sub>2</sub> emissions due to all processes operated in a terminal for the handling

of the containers), [62] (simulation model to quantify carbon emissions of a container terminal and to evaluate the effect of the allocation of facilities on the overall emissions), [63] (green vessel scheduling problem in presence of Emission Control Areas – ECAs), [64] (feasibility study of cold ironing system installation in a medium sized port), and [65] (different clean energy technologies for the reduction of energy consumption and emissions in container terminals).

Few researches have been published on the effects of dry port adoption on the environmental performances of container terminals. In [66] the authors investigate the factors influencing the location of dry ports, jointly considering location, accessibility, economic and social, and environmental factors. They propose a methodology based on Multicriteria Decision Analysis (MCDA) and Bayesian Networks (BNs) to assess the sustainability of locations, and apply it to the case study of the existing dry ports in Spain. In [67] the dry port location problem is formulated considering the optimization of the hinterland dry port-seaport logistic network jointly taking into account the cost concession partnership between dry port and seaport as well as environmental factors. A MILP model is defined in order to solve the problem, and results of its application to the case study of dry ports in the Henan Province (China) are discussed.

One of the first attempts to investigate on the applicability of lean principles in port operations appeared in scientific literature in 2003 [68]. In their work, Authors stressed out the need for a traditional sector as the port one to adopt leanness and agility in order to cope with the high level of market uncertainty. Starting from the consideration that unlike manufacturing industries characterized by continuous unidirectional flow of materials regulated in order to provides the shortest flow path without unnecessary activities [69], ports are bi-directional systems, and hence characterized by a double-derived demand, Authors discuss some limits in the application of lean principles in ports operation management, and identify in the reduction of the inventory, in the decreasing of transit time and lead time, in the creation of new value-added services as well as in the reduction of fixed costs per units handled the key factors able to increase ports' competitive edge and profitability. In [70], authors propose a set of new port performance indicators allowing measuring lean port performance and sustain the subsequent development of agile ports. Authors propose qualitative performance indicators in order to overcome the limits of traditional quantitative measures adopted to assess ports' performances. In [71], the efficiency

of 104 European container terminals is investigated. Results obtained show how significant inefficiency characterized most of the terminals considered in the study and that large-scale production tends to be associated with higher efficiency. Authors underline the need for the port industry to understand and adapt itself to meet the frequently changing demands of its customers. In [9], authors stressed out the new role of ports in the international supply chain, as integrated centres unlike simple transferring points, and suggest the adoption of an internal supply chain approach for servicing the needs and satisfy the demand of the users ensuring a high efficiency. With reference to a leading Turkish container terminal in the Marmara region, in their work Authors developed a conceptual model covering both the lean and the green dimension of the port. In [13], authors investigate the application of lean practices to improve material flow within intermodal terminals and to develop an overarching framework for lean terminalization. The lean terminalization allows identifying the most fundamental and critical elements of lean that should be applied in the context of the intermodal container facilities, in order to improve the flow of goods and materials optimizing the issues related to bottleneck-derived terminalization. In [10], Authors define a simulation model to optimize terminal operations by adopting a lean and green approach. Results obtained show the potential benefits of a lean and green based optimization approach resulting in a minimization time (and related emissions) of non-value added operations.

In Author's knowledge, very few researches have been published yet (December 2018) focusing on a lean and green approach for the increase of container terminal productivity. In this study a mathematical programming optimization model is defined in order to support decision makers in identifying the best containers' handling strategy for intermodal facilities, according to lean and green perspectives. The model is detailed in the next session.

## Materials and method

### Problem description

Containers' terminal hubs are complex systems characterized by different functional areas in which the loading and discharging process of vessels runs smoothly. Generally, two kind of containers' flows are managed inside the terminal hub: the (export) Outbound Containers Flow (OCF) including the containers shipped by customers of the terminal, through the port, to another destination port in the world, and

the (import) Inbound Containers Flow (ICF) including the containers that comes on a vessel from other ports in the world, to be unloaded in port and kept in temporary storage until the customer for whom it is destined picks it up [72]. The same material path, information flow as well as Material Handling Equipment (MHE) are adopted for the management of inbound and outbound containers, the only substantial difference is represented by start and destination point: vessel-customers and customer-vessel for inbound and outbound containers, respectively.

The first step in case of management of ICF (last step for OCF) consists to unload containers from the vessel docked on the berth, and place them on quayside. This handling procedure requires the adoption of a Ship-To-Shore gantry crane (so-called "STS crane") able to load and unload the containers from/to vessel at the same time (Fig. 2), or in other cases is adopted a traditional quay crane. From quayside, the containers are picked (one for each MHE per trip) and transferred to container yard (also known as staking area) where is stored. In this step can be adopted two different MHE, one for container' transport and one for stacking the container within container yard, or only one MHE able to transport and stacking the container (e.g. straddle carrier, Reach Stacker, Rubber-Tyred Gantry crane, Rail-Mounted Gantry crane, etc.). The container can remain from a couple of hours to some weeks in container yard, the dwell time (the time in which the container remains within the terminal area) depends by the agreement with container's recipient. There are different alternatives for identify the layout of container yard, generally this choice is affected from the features of the available area and from kind of the MHE adopted. The block stack and the linear stack, shown in Fig. 3, are the layouts more widespread [73].

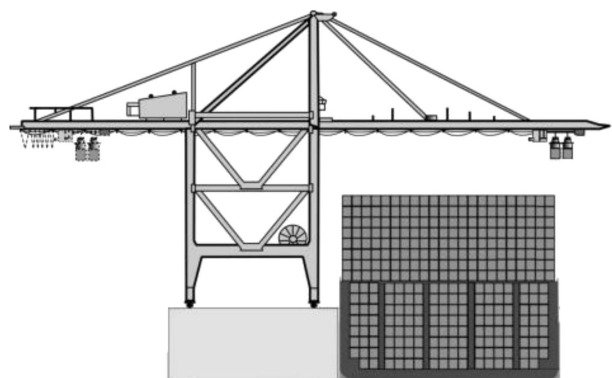
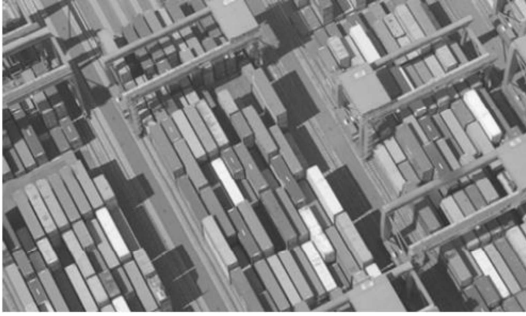


Fig. 2. Typical structure of the current STS crane (picture adapted from Bartosek A. and Marek O., Quay Cranes in Container Terminals, 2013, in Transaction on Transport Sciences).

a)



b)



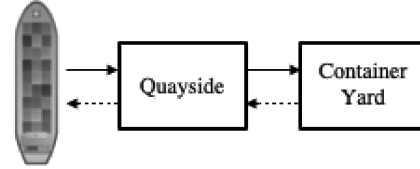
Fig. 3. Layout of container yard according to block stacking (a) and linear stacking (b), (picture adapted from reference [18]).

In case of dry port implementation, the containers' flow inside to terminal hub radically change, since there are two different areas where the containers can be stocked. Therefore, a part of containers stocked in quayside will be transfer to container yard and the other part will be loaded, by intermodal facilities, on transport units (truck or more generally freight train) that will ensure the containers' handled from terminal hub to dry port. In most of cases the dry port is an effective solution also for containers sorting functions as well as for the hinterland shippers. The general framework of containers' flow for both scenarios (with and without dry port) is shown in Fig. 4.

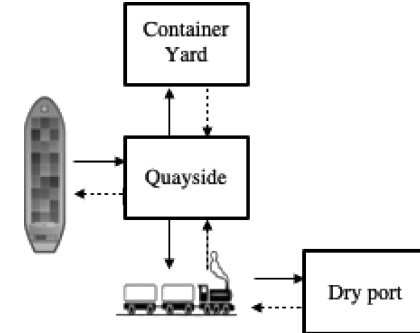
It is clear that the adoption of a dry port, if on one hand leads to benefits on terminal congestion (reducing the number of containers stored in container yard), on the other hand requires resources and investments due to handling of the containers in dry port, rent of the dry port area, as well as to the transport of the container from port to dry port, and vice versa. Therefore, the solution of the problem consists to identify the number of containers to be stored in container yard, their blockstructure configuration (number of containers to be stocked according to bays, rows and tiers), as well as the number of containers to be transported in dry port, in order

to minimize the overall costs and the environmental impact due to containers' handling activities.

a)



b)



— Inbound container ---- Outbound container

Fig. 4. Framework in case of traditional containers' flow (a) and in case of dry port adoption (b).

The solution/s provided by mathematical model developed, that will depend on multiple factors (e.g. MHE adopted, intermodal facilities available, distance from port to dry port, etc.), will support the decision making, identifying the most cost-effective, and eco-friendly, containers' stocking configuration.

### Mathematical optimization model

The mathematical programming optimization model is based on function allowing to minimize cost and carbon footprint of containers' handling activity in port and in dry port, according to a strategy based on framework shown in Fig. 4. The jointly minimization of cost and carbon footprint allows to evaluate both economic that environmental aspects, consistently with a lean terminalization approaches.

As far as concern the economic evaluation, the model is based on minimization of equation in (1)

$$\begin{aligned}
 C_{tot} = \min & \left( CP + CDP + \frac{C_{MHE}}{60} \right. \\
 & \cdot \left( \left( \frac{2}{v_h} \sum_{i=1}^{(nx-1)} \sum_{j=1}^{(ny-1)} (id_x + jd_y) \right. \right. \\
 & \left. \left. + \frac{2}{v_v} \sum_{k=1}^{(nz-1)} id_z \right) + T_{reH} \right) + CP' + CDP' + CTR \Bigg). \quad (1)
 \end{aligned}$$

The overall cost ( $C_{tot}$ ) due to containers' handling activities are minimized by changing of number of containers to be stocked in port, according to number of containers to be allocated per bays, rows and tiers ( $n_x$ ,  $n_y$ , and  $n_z$ ). Equation (1) depends on to size of containers to be stocked ( $d_x$ ,  $d_y$ , and  $d_z$  in [m]) as well as to hourly average cost ( $C_{MHE}$ ) and to performance, i.e. travel and lift speed ( $v_h$  and  $v_v$  in [m/min]), of the MHE adopted for containers' handling [€/h]. The further parameters introduced in (1) represent: the rental cost of port and dry port area (2) and (3), the cost due to handling of containers in container yard considering also the re-handling movements (4), the cost for transfer the containers from quayside to container yard (7), as well as the cost for containers' handling in dry port (including the transshipment of the containers on the transport unit) (8) and the cost due to the transport of containers from port to dry port, in accordance with the transport unit adopted (by truck in(9) or train in (10)).

$$CP = A_p C_p T_w, \quad (2)$$

$$CDP = A_{dp} C_{dp} T_w, \quad (3)$$

where  $A_p$  and  $A_{dp}$  identify the available area for containers stocking in port and in dry port [m<sup>2</sup>], respectively. The parameters  $C_p$  and  $C_{dp}$  identify the hourly average cost per square meter for the rental of the container yard in port and in dry port [€/hm<sup>2</sup>], respectively (the value does not include the management costs). The average waiting time, i.e. the average time between stocking and picking of the same container from the area, is represented by  $T_w$  parameter [h]

$$T_{reH} = t_h N_{reH}, \quad (4)$$

where, according to [74]:

$$N_{reH} = (N_p - S N_p) S^{-1}, \quad (5)$$

$$S = \sum_{k=1}^{n_z} n_x n_y k^{-1}. \quad (6)$$

The average number of containers to be re-handled ( $N_{reH}$ ) depends on number of containers stocked in port ( $N_p$ ),  $S$  parameter (related to index of selectivity (IOS) assigned to each container in a stack), and from average time ( $t_h$ ) required for handling one container in a position characterized by IOS equal to one [min]

$$CP' = \frac{C_{MHE} N_p}{60} \left( t_h + \frac{d_{q-cy}}{v_h} \right), \quad (7)$$

$$CDP' = \frac{2C_{MHE} N_{dp}}{60} t_h. \quad (8)$$

Considering the model's assumption (detailed in next section), in both cases (7) and (8), the transfer of containers from quayside to container yard (in port), as well as the containers' handling in dry port, requires the same MHE, already adopted for stocking the containers in container yard. The distance from quayside to container yard ( $d_{q-cy}$  [m]) is identified for estimate the transfer time of the containers in port, in (8) the number of containers to be handled in dry port ( $N_{dp}$ ) is considered

$$CTR = 2C_{TRK} \frac{dN_{dp}}{v_{TRK} n_{\max TRK}}, \quad (9)$$

$$CTR = 2C_{TRN} \frac{dN_{dp}}{n_{\max TRN}}. \quad (10)$$

The economic and the environmental evaluation related to the transport of containers from port to dry port is strong related to transport unit adopted. In case of truck fleet adoption (9) the cost depends on hourly average cost of truck ( $C_{TRK}$  in [€/h]), distance between port to dry port ( $d$  in [km]), average speed of truck ( $v_{TRK}$  in [km/h]), and truck capacity load, in term of maximum number of containers that one truck allows to transport ( $n_{\max TRK}$ ). In case of train adoption, the equation shown in (10) is very similar to previous evaluation: the train cost is evaluated in term of distance to be travelled ( $C_{TRN}$  in [€/km]), and the maximum number of container transportable by one train is identified with  $n_{\max TRN}$ .

The model constraints are summarized in the follows:

$$N = N_p + N_{dp}, \quad (11)$$

$$N_p = n_x n_y n_z, \quad (12)$$

$$n_x n_y d_x d_y \partial^{-1} \leq A_p, \quad (13)$$

$$n_z \leq H_{MHE}^{\max}. \quad (14)$$

The overall number of containers to be stocked ( $N$ ) is identified in (11), the occupied surface by containers according to bays and rows of the blockstructure, shall be less than available area in container yard, considering the layout adopted (block or liner stacking, as shown in Fig. 3). Consistently with this constrain, in (13) is introduced the  $\partial$  parameter (included between 0 to 1). For  $\partial$  equal to 1 (ideal condition), in layout there are not unused space due to aisles, maneuvering area, or other operational areas. On the contrary,  $\partial$  decreases with decreasing of the surface utilization coefficient and with increasing of unused space. Equation (14) identified the maximum number of tiers in blockstructure, under no circumstances the maximum number of stackable containers ( $n_z$ ) shall be less than maximum lifting height allowed by MHE.



As far as concern the environmental evaluation due to containers handling activities, according to a lean terminalization approach. The model ensures the minimization of the carbon footprint ( $CF_{tot}$ ) on the basis of the equation (15):

$$CF_{tot} = \min \left( \frac{CF_{MHE}}{60} \left( \left( \frac{2}{v_h} \sum_{i=1}^{(nx-1)} \right. \right. \right. \\ \cdot \left. \left. \left. \sum_{j=1}^{(ny-1)} (id_x + jd_y) + \frac{2}{v_v} \sum_{k=1}^{(nz-1)} id_z \right) + T_{reH} \right) \right. \\ \left. + C_{FP}' + C_{FDP}' + C_{FTR} \right), \quad (15)$$

where ( $CF_{MHE}$ ) represents the equivalent carbon dioxide per hour emitted by MHE for containers' handling activities [kgCO<sub>2</sub>/h]. The estimation of the further parameters shown in (15) is based on the same equations, already introduced for the economic evaluation. In particular,  $C_{FP}'$  is evaluated by (7),  $C_{FDP}'$  by (8) and  $C_{FTR}$  by (9) or (10), in accordance with the transport unit adopted for containers' transport from port to the dry port. In every case the cost of the 'road' and 'non-road' MHE adopted (e.g. reach stacker, train or truck, etc.) applied in previously equations, is replaced by carbon footprint emitted per hour (or per km) by each MHE ( $CF_{MHE}$ ).

The model is based on two parallel computational routine for identifying the storage containers configuration, in order to minimizing the cost and the carbon footprint. Therefore, the identification of two different containers' configurations provided by the model, one under economic and one under environmental perspective, cannot be excluded.

### Model boundary conditions

The model allows to identify the containers' configuration able to minimize the economic and environmental impact due to handling activities, under the following boundary conditions:

- The containers are stored in stockpiles of the same height;
- All containers handled are characterized by same sizes;
- A stacking according to a ground strategy ( $n_z = 1$ ) is adopted in dry port;
- The speed of the MHE not depends on the weight of the container handled;
- The performances (e.g. travel speed, lifting speed, horizontal speed, etc.) of the available MHE and of

transport units are considered equal for the same handling means of the fleet;

- The emission of the MHE and of transport units adopted are not affected by weight of containers transported, traffic conditions, acceleration or deceleration, etc.
- The model assumes that the hourly cost area per square meter in dry-port ( $C_{dp}$ ) decreases with increasing of its distance from the port ( $d$ ). Over than 25 km the threshold minimum value, corresponding to 0.006 €/hm<sup>2</sup> (according to average Italian rental price (source: www.entetribunali.it)), is considered;
- The hourly cost of the 'road' and 'non-road' MHE include: staff cost, tax, maintenance and depreciation.

According to experts and insiders' opinion, the assumption above listed are considered acceptable under field conditions. Therefore, the results given by model can be taken into account for a real full case.

### Results

A numerical experimental case is introduced in order to evaluate the effectiveness of the model. The first step consists to query the computational algorithm, providing the input data requested by model. Three different cluster of information are needed:

1. Containers' features:  $N$ ,  $d_x$ ,  $d_y$ , and  $d_z$ ;
2. 'Road' and 'non-road' MHEs features:
  - (a) Reach Stacker:  $C_{MHE}$ ,  $CF_{MHE}$ ,  $v_h$ ,  $v_v$ ,  $t_h$ , and  $H_{MHE}^{max}$ ;
  - (b) Truck:  $C_{TRK}$ ,  $CF_{TRK}$ ,  $n_{maxTRK}$ , and  $v_{trk}$  or train:  $C_{TRN}$ ,  $CF_{TRN}$ , and  $n_{maxTRN}$ ;
3. Port and dry port features:  $A_p$ ,  $C_p$ ,  $A_{dp}$ ,  $C_{dp}$ ,  $T_w$ ,  $\partial$ ,  $d$ ,  $d_{q-cy}$ .

Consistently with the information above mentioned, the model will suggest the number of containers to be stocked in port, according to storage configuration based on number of containers for bays, rows, and tiers, as well as the number of containers to be stocked in dry port, in order to ensuring the minimal cost and carbon footprint (one solution for each aspect will be suggested).

In numerical case proposed, the number of TEU ( $d_x$ ,  $d_y$  and  $d_z$  are known) to be stocked is equal to 2500, an area of container yard of about 14000 m<sup>2</sup> with linear stacking layout, and a dry port (of unlimited capacity) placed at a distance of 25 km are considered. According to these information, the containers' configurations provided by model, in order to minimize  $C_{tot}$  and  $CF_{tot}$ , are shown in Table 2.

Table 2

Configuration of containers provided by model, according to economic (first line) and environmental (second line) perspective, in case of  $N = 2500$  TEU.

$N_p$	$n_x$	$n_y$	$n_z$	$N_{dp}$	
1875	25	25	3	625	$C_{tot} = 121$ k€
625	25	25	1	1875	$CF_{tot} = 8E3$ kgCO <sub>2</sub>

In both cases the train is adopted for containers' transport from port to dry port, and a reach stacker with  $H_{MHE}^{max} = 5$  containers, is used for stocking the containers in port. Two different configurations are suggested by model: in the first line is shown the configuration allowing to minimize the overall cost due to all containers' stocking, while in the second line the configuration allowing to minimize the carbon footprint, at same conditions, is identified. It is possible to evaluate the effectiveness of the configuration providing by the model, comparing the solution identified with the cost and the carbon footprint would be incurred in absence of the dry port, i.e. stocking all containers in port. In this case the cost and the carbon footprint would rise by 1% and 46%, respectively.

A further utilization of the model is focused on the identification of best containers' configuration in case of uncertainty of containers' number to be stocked. This is a recurring issue, in particular in case in which the evaluation of the potential use of the dry port over time, is faced (preliminary evaluation in case of dry port is not yet identified). Indeed, in these cases, the model can be repeatedly query, in order to evaluate the convenience due to possible adoption of the dry port for variable values of  $N$ . Considering the same conditions of the previously numerical simulation, the model is queried for identify, by changing of  $N$  parameter, the best container configuration under economic (Table 3) and environmental (Table 4) perspective.

Table 3

Containers configuration provided by model for minimizing the handling cost, in case of  $N$  is included in range [625–3125 TEU].  $C_{tot}$  identifies the comparison between cost, corresponding to best configuration, suggested by model, in case of dry port adoption versus to best configuration with lack of dry port.

$N$	$N_p$	$N_{dp}$	$\Delta C_{tot}$
625	625	0	+3.0%
1250	1250	0	+3.0%
1875	1875	0	+2.1%
2500	1875	625	-0.4%
3125	1875	1250	-10.7%

Table 4

Containers configuration provided by model for minimizing the handling carbon footprint, in case of  $N$  is included in range [625–3125 TEU].  $CF_{tot}$  identifies the comparison between carbon footprint, corresponding to best configuration, suggested by model, in case of dry port adoption versus to best configuration with lack of dry port.

$N$	$N_p$	$N_{dp}$	$\Delta CF_{tot}$
625	625	0	+13.8%
1250	625	625	-14.8%
1875	625	1250	-48.9%
2500	625	1875	-95.5%
3125	625	2500	-153.8%

It is possible to observe that as concern the environmental aspect, the adoption of the dry port is strong recommended for minimizing the carbon footprint due to containers' handling, indeed only in one case on five the containers are not stocked in dry port (Table 4). As far as concern the cost evaluation, the adoption of the dry port is suggested only in 40 percent of the cases. It is very interesting note that in these cases the cost saving due to adoption of dry port is particularly high if compared to other cases. In particular in case of 3125 TEU the adoption of the dry port ensuring a cost saving of around 11%, on the contrary for  $N$  included from 625 to 1875, the adoption of the dry port is not required, therefore in these cases an increasing of cost (around 3%) due to dry port rental cost is observed.

In case of  $N$ -value variable over time according to a gaussian distribution, it is possible to observe that the advantages due to dry port adoption are strong related to the average number ( $\bar{N}$ ) and standard deviation ( $\sigma_d$ ) of TEU to be stocked, as well as to available area of container yard. In particular, under economic perspective, the benefit due to stocking of the TEU only in port decrease with increasing of  $\bar{N}$ ,  $\sigma_d$  and  $A_p$ . Consistently with this evaluation, is shown that only for  $N \geq 410$  (and  $N \geq 815$ , respectively) is recommended the dry port adoption for  $\bar{N} = 300$  TEU and  $\bar{N} = 600$  TEU. Therefore, according to normal distribution, the probability of dry port adoption, in these cases, is around 3% (Figs 5a and 5b).

The benefit due to dry port adoption, increase in case of  $\bar{N} = 1875$  TEU (Fig. 5c), in this case indeed the dry port adoption is recommended for  $N \geq 2405$  (9% of probability of occurrence according to normal distribution) with a significantly increased of the overall cost saving. In all cases evaluated a linear stacking layout is considering, with a dry port (of unlimited capacity) placed at a distance of 25 km, and the train is adopted like a transport unit from port to dry port.

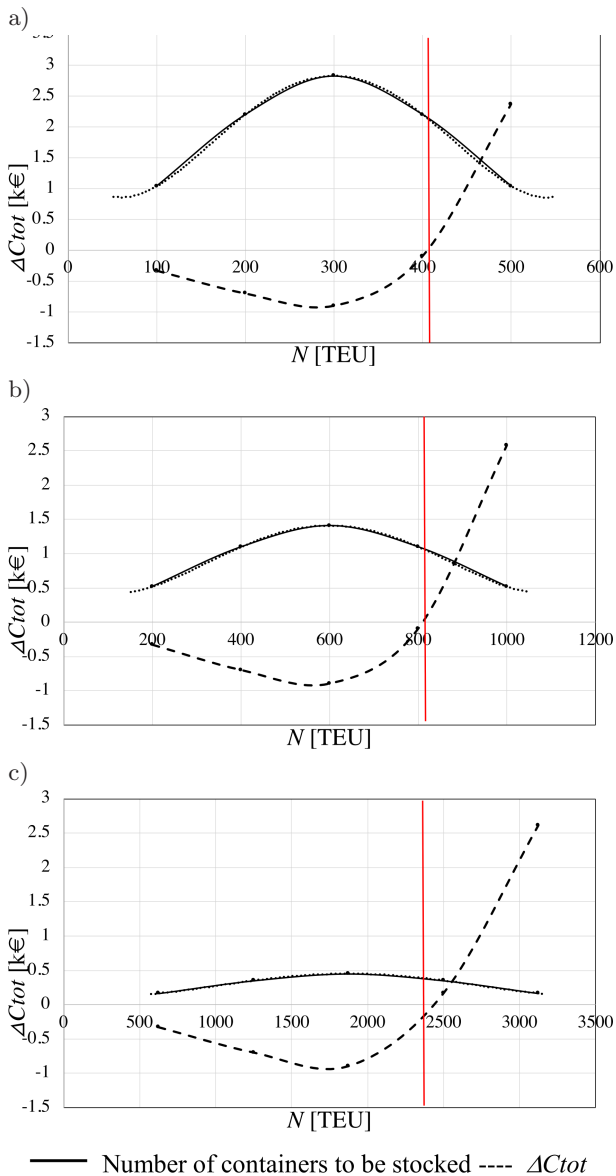


Fig. 5. Comparison between cost, corresponding to best configuration suggested by model for  $\bar{N} = 300$ ,  $\sigma_d = 158.11$ ,  $A_p = 2250 \text{ m}^2$  (a),  $\bar{N} = 600$ ,  $\sigma_d = 316.22$ ,  $A_p = 4500 \text{ m}^2$  (b), and  $\bar{N} = 1875$ ,  $\sigma_d = 988.21$ ,  $A_p = 11150 \text{ m}^2$  (c), in case of dry port adoption versus lack of dry port.

As far as concern the environmental aspect it is possible to observe that for  $d \leq 25 \text{ km}$ , the number of TEU stocked in port (linear stacking layout) shall be such as to ensure a number of tiers ( $n_z$ ) no more than one, since with increase of the number of tiers, significantly increasing the emission due to re-handling movements.

The share of different cost items due to containers' handling (Fig. 6) change for every configuration identified by model. In particular, given  $N$  and  $d$ , the rental costs of port and dry port are directly re-

lated to the number of containers stocked according to bays ( $n_x$ ) and rows ( $n_y$ ). The rental cost of port area is average higher than rental cost of the dry port area, since, according to Italian statistics (source: www.entietribunali.it), the average rental cost of areas close to sea is significantly higher than in-land areas. As consequence  $A_{dp} \ll A_p$ . As far as concern the containers' handling cost, in port depend on  $N_p$ , while the transport and handling cost of container in dry port are strictly related to  $N_{dp}$ .

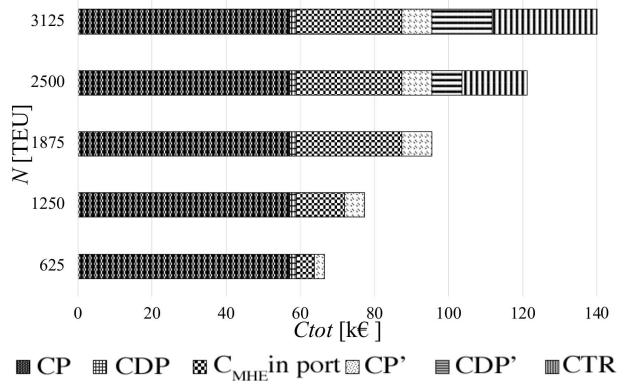


Fig. 6. Share of different cost items corresponding to best configurations of the containers provided by model, by changing  $N$ .

The convenience of dry port depends on  $d$ , according to assumption (see previously section) the model considers a gradual reduction of the rental cost of the hourly cost area per square meter in dry-port ( $C_{dp}$ ) with increasing of  $d$ . Therefore, if on one hand the cost of containers' transport from port to dry port ( $CTR$ ) increase with increasing of  $d$ , on the other hand the rental cost of dry port decreases. It is possible to observe that for stocking of 3125 TEU, the  $C_{tot}$  decrease with increasing of  $d$  (Fig. 7). The minimum overall cost is achieved for  $d = 25 \text{ km}$ , above this value the rental cost of dry port is not further reduced, therefore there is a change in trend of  $C_{tot}$  (due to  $CTR$ ).

It is very interesting note that over 36 km, the dry port is not recommended in any case, since the costs due to transport of containers are higher than costs due to handling of containers in port.

The model was tested considering the same numerical conditions, adopting a fleet of trucks (with  $n_{maxTRK} = 2 \text{ TEU}$ ) like transport unit. In this case the transport of containers in dry port, according to economic point of view, is recommended only for  $N \geq 4000 \text{ TEU}$  and  $d \approx 10 \text{ km}$ . Under no any conditions the model suggests the containers transfer in dry port by truck, in order to reducing the carbon footprint. Therefore, in both cases the containers'

transfer from port to dry port by truck, can be suggested only for other kind of issues (e.g. limit port capacity, goods distribution and sorting, inspection activities, etc.).

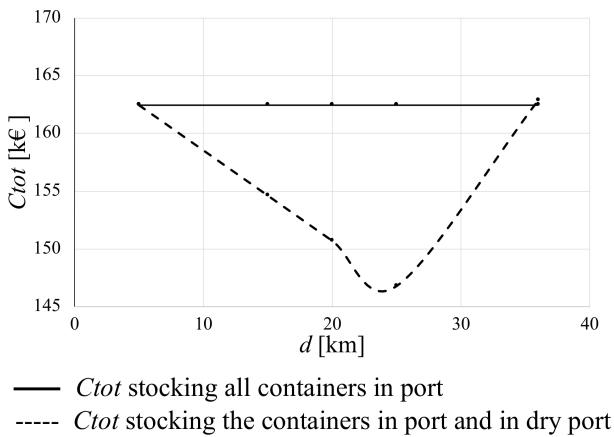


Fig. 7. Overall cost in case of containers' stocking in port and in dry port by changing  $d$  ( $N = 3125$  TEU).

## Conclusion

The model developed is an easy and effectiveness tool in order to evaluate the advantages, in terms of cost and carbon footprint, related to dry port adoption both 'pre' than 'post' scenarios. As far as concern the 'pre' scenario (when the dry port is not yet identified) the model allows to evaluate the convenience related to utilization of the potential dry port, on the basis of the average number and the variability of containers to be stocked, of the distance between port and potential dry port, as well as to the features of the available MHE (and transport units) to be adopted for handling activities. As far as concern the 'post' scenario (when the dry port is ready for the use), the model allows to identify the containers' configuration ( $N_p$  and  $N_{dp}$ ) and blockstructure layout ( $n_x$ ,  $n_y$  and  $n_z$ ) in order to minimize cost and/or carbon footprint due to inter-/intra terminal containers' activities.

In a more general perspective, is possible to claim that the adoption of the dry port in order to minimize the overall cost due to handling activities, in case of  $A_p \geq 10000$  m<sup>2</sup> and considering the model boundary conditions, is suggested in case of number of TEU to be stocked is exceed to 2000 TEU, assuming that the distance between port and dry port is no greater than around 30 km, by using the train ( $N_{\max TRN} \geq 10$  TEU) like transport units. Under environmental perspective and considering the same conditions, the adoption of dry port is suggested for  $N$  greater than 1000 TEU, by train and considering

a distance between port to dry port is not exceed to about 50 km.

Considering the RQs introduced by paper, the study shown that is possible a jointly evaluation of the economic and environmental aspects, for increase the productivity of container terminal hub (RQ1), but the model is not able to identifies one solution allows to fit both targets, in most of cases two solution, one for economic and one for environmental aspects, are identified. In order to overcome these limitations, the model should based on more complex analytical function (e.g. bi-objective optimization function, genetic algorithm, Pareto memetic algorithm etc.).

As far as concern the lean terminalization approach and the adoption of the dry port to reduce the congestion of the terminal hub and increase its productivity, in accordance with the lean perspective (RQ2 and RQ3), the numerical simulation shown that this is a possible goal and the model can support the stakeholders in order to more easily achieving this target.

In the next research, the model will be applied to a full-case study from a real ports, in order to evaluate the effectiveness of the model in identifying the best containers' handling strategy in a more complex scenarios, and in case of more than one dry-port available, each of them characterized by a different capacity and connected by different transport means to the seaport.

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