A New Mathematical Model for Container Stacking in Seaport Terminals: Case Study

Ines Rekik, Saber Benzina, and Diala Dhouib

Abstract—**Maritime transport is the operation of moving goods from one place to another by sea. It takes into account the loading and unloading of containers in ports. Once the vessels arrived at the quayside, they are unloaded by means of quay cranes and then transferred to the storage or transshipment areas. The Container Stacking Problem (CSP) is one of the major problems in seaport terminals, in particular in view of the considerable increase in the number of containers and the limitation of storage areas in the container ports. It has a considerable impact on the efficiency of port operations. In this paper, we propose a new mathematical model for determining the exact storage locations of incoming containers in the storage zone in order to minimize the total travelling distance from the quay to the storage location. The suggested model takes into account different types of containers. It has been validated based on the real case study of the Tunisian Sfax seaport. The obtained results are promising and the storage responsible is satisfied with the reached solutions.**

Index Terms—**Container stacking problem, seaport terminals, type of container, terminal capacity, mathematical modeling, Cplex.**

I. Introduction

A container terminal is a complex system made up of a set of interrelated logistics processes. It is a sequence of events from the arrival of a ship to the departure of containers and vice versa. Ships are now disembarked and embarked at large terminals. The loading and unloading process in a typical modern container terminal can be divided into sub-processes [1] (as shown in Fig.1).

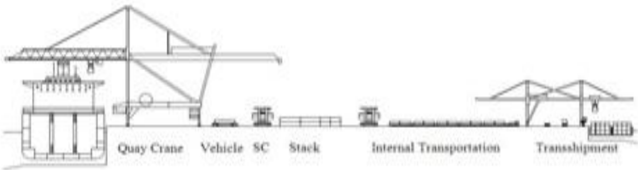

Fig. 1. Seaport terminal operations

When a ship arrives at port, import containers must be taken from the ship and placed on the platform using quay cranes. The containers are then transferred by vehicles to the stacks or storage areas (named also the storage yard) where they can be stored for a certain period of time.

The containers are moved using cranes or Straddle Carriers (SC). A straddle carrier can both transport and store a container in the stack yard. Other equipments are also used for container transport, such as automated guided vehicles (AGVs) and automatic stacker cranes.

The containers are picked up after a certain time by cranes and transported by vehicles to another mode of transport (trains, trucks, other ships). The loading and unloading process can also be done in reverse, to load the export containers onto a ship.

In a container terminal, we can find various problems including Yard Crane Scheduling [2]-[4], Container Stacking Problem [5], [6], Quay Crane Scheduling [7], [8].

This study is dedicated to Container Stacking Problem (CSP).iI consists on deciding almost in real time, upon the arrival of an import or export container, its exact location among the empty locations so as to make it efficient to load onto a ship, truck or train [9].

The container storage zone (the yard area) in a seaport terminal is characterized by a certain number of blocks composed by a number of bays, each bay contains a certain number of stacks characterized each one by a definite height named tier (see Fig. 2).

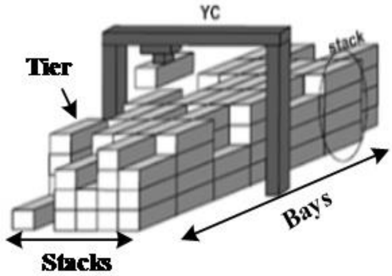

Fig. 2. A stacking block

In this paper, we propose a new mathematical model for the resolution of the CSP. The proposed model aims to minimize the total container travelled time between the quay side and the yard side. It takes into account different types of containers and respects the stacking rules related to each type. This constraint is not well treated in the literature. Most of existing studies consider only regular containers and neglect the other types. The proposed model is then validated by its application to the Tunisian Sfax seaport terminal.

The rest of this paper is organized as follows: Section II presents a literature review of the Container Stacking Problem. Section III introduces the Sfax Tunisian seaport terminal case study. Section IV details the proposed mathematical model based on a set of parameters, decision variables and constraints. Section V reports the

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implementation and computational results. Finally, section 6 presents the conclusion and future works.

II. Literature Review

In this paper, we focus on the Container Stacking Problem (CSP) which is one of the most important problems in seaport terminals. Different studies have been developed in the literature to solve this problem. Rekik *et al*. (2017) proposed a classification of CSPs into three main classes: Storage Space Allocation Problems (SSAPs), Container Allocation Problems (CAPs) and Container Relocation Problems (CRPs) [10].

The Storage Space Allocation Problems (SSAPs) consist on the reservation of a certain storage space of an incoming group of containers in the storage area [11]-[13]. For example, Chenhao et al. (2020) integrated the discrete event simulation with a proposed mixed integer programming model to solve the SSAP [11]. Lee *et al.* (2012) treated the Yard Allocation Problem (YAP) which is a variant of the SAP. It was defined as the storage yard space allocation for container transshipment movements between mother and feeder vessels within a terminal as well as between terminals. In this problem, each request of stacking a container is for a set of spaces within a yard required in a single time interval. The final objective is to minimize the area of yard space within this time interval [13]. Some studies treated the YAP dynamically as the work of (Jiang et al., 2012) the reservation of storage space is determined from a dynamic way for different vessels during different shifts [14].

The Container Allocation Problems (CAPs) are related to the search of the exact storage location in the yard of each arriving container [5], [6], [15]. Rekik and Elkosantini (2019) have proposed a multi agent system based on a Blieve Desire Intention (BDI) model for the resolution of the online container allocation [5]. In another study, Rekik et al. (2018) proposed a Case Based Reasoning heuristic for the resolution of the same problem [6].

The Container Relocation Problems (CRPs) concern the relocation of stacked containers in order to retrieve other containers or to facilitate their future retrieval [16]-[18]. CRPs are well treated in the literature. For example, Feng *et al.* (2020) have proposed a stochastic dynamic programming (SDP) model for the resolution of the stochastic container relocation problem in order to minimize the expected number of containers movements [16]. Hottung *et al.* (2020) have presented a deep learning tree search algorithm for the resolution of the Container Pre-Marshalling Problem (CPMP) [17]. Feillet *et al.* (2019) have presented a local search type improvement heuristic for the resolution of the unrestricted Block Relocation Problem [18].

The literature review conducted in this study reveal some limits related to the storage of different types of containers and the storage capacity of all over the terminal. In this paper, we propose a new mathematical formulation of the CAP. The proposed model integrates the combination of three constraints that have not been treated together in previous studies. The first constraint consists on the consideration of different types of containers (in this paper, we have considered three types of containers: regular, tank and open top containers). In other words, the type of the incoming containers intervenes in the allocation decision. The second contribution concerns the addition of the constraint of the capacity of the entire terminal. In a third aspect, containers of different sizes can be stored in the same stack and not in the same bay. In most existing studies, an entire bay is reserved for a specific size of containers, but this constraint generates a waste of space in the storage area as well as an increase in the traveled distance either to allocate or to retrieve containers.

III. Case Study

In this section, we present the Tuniasian Sfax seaport terminal case study in a first time, and we expose then our studied problem within this port.

A. Problematic and Objectives

Our research has been carried out using an application of a proposed approach for optimizing the movement of containers in the Port of Sfax which has a major problem related to the storage of containers. This problem id due to the evolution of containerized traffic at the Sfax port's gate. It is the state of container traffic over the planning horizon. The main problem at the port of Sfax then, is to optimize the storage space.

The objective in solving this problem is to find an optimal storage plan which specifies the ideal storage location for each incoming container and which takes into account the real storage constraints required by the Sfax port authorities. In this study, we deal with the problem of container storage in a port terminal, while respecting the constraints of the storage of different dimensions/sizes of containers and the storage capacity of the yard in order to preserve the security of all over the port; and taking into account the needs of the port of Sfax. it is then a question of determining how to store all the incoming containers by covering at minimum the overall distance between the quay and the storage areas, and while respecting the constraints required by the port.

The work of (Razouk et al., 2016) is limited to one type of container (regular container) [19]. There is also a lack of consideration of the different types of containers in the literature. In the same study, a bay must contain only one size of containers. But this constraint can cause a loss of space. Sometimes an entire bay is reserved for a fairly limited number of containers. In additiont, there is a risk of not finding space to store other containers of different sizes. As far as we know, the storage capacity constraint is also absent in the literature.

In this paper, we propose a new mathematical model in order to determine a container stacking plan in the storage yard of the Sfax seaport. In this model, we add the terminal storage capacity constraint and we take into account the storage of 3 types of containers: regular, open top and tank containers. We propose also the constraint of stacking containers of the same sizein the same stack and not in the same bay.

B. Sfax Seaport Case Study Presentation

Founded in 1894, the sea port of Sfax is one of major poles for the Tunisian economy thanks to its openness to international trade. This indicates the importance of this port and shows the position of the city of Sfax as a commercial and industrial pole. With its versatile berthing, the port has 13 stations and can actually accommodate 11 ships simultaneously depending on the ship size. The length of the Sfax port quays varies from 110 to 584 meters with drafts of 10.5 meters.

The port of Sfax is a multipurpose port; its dominant traffic consists of solid bulk (phosphate and derivatives, sulfur, sea salt, cereals, etc.) and containers. It is one of the main commercial ports in Tunisia, handling around 15% of the national maritime traffic (INS, 2016).

The Sfax seaport has an area of 28 hectares divided between two physically separate shores: the North shore containing various goods and the South shore responsible for the treatment and the storage of containers. The southern shore is composed of an import and an export area. The import area contains 30 non homogeneous blocks. Each block is constituted of 5 bays and each bay contains 4 stacks (the maximum stack height is 3). However, in export area, the containers are stacked in a same block. The departure date of these containers is known since the arrival date of the associated vessel is known in advance. In our study, we will be interested only in import containers.

The logistic currently used for the loading / unloading operations of import/export containers at the port of Sfax consists on assigning machinery (Reach stacker, forklift, Ro-Ro Trucks, Ro-Ro Trailers). The Ro-Ro Trucks with the Ro-Ro Trailers are used to transfer the containers to the storage areas. The reach stackers are then used to manipulate the containers (stacking or retrieval). In this context, the Sfax seaport features 17 forklift, 5 Reach stackers and 4 Ro-Ro Trucks.

In our study, we are interested in the container storage activity (loading / unloading) managed by the company STAM (SociétéTunisiennd'Acconageet de Manutention). This positioning is the obvious result of the notable increase in recent years in trade flows, particularly those of containers, by observing a clear doubling of maritime traffic in containerization, which reached 83,500 TEU units in 2016 against 40,000 TEU in 2010. Paradoxically, the port of Sfax has become incapable of absorbing the increasing flows of various goods, thus affecting its productivity by traffic congestion, the congestion of the docks leading to an increase in the waiting time of ships and the consequent increase in the costs of port passage of goods while penalizing in return the technical and the financial performance of the handling contractor.

The storage operation in this port depends on whether these containers are import or export. Certain requirements are also identified for handling some types of containers. For example, containers with dangerous goods are considered with higher priority and must then be transferred directly to their destination. Refrigerated containers must also be rapidly assigned to fridge outlets. Furthermore, the storage of empty containers should not exceed 48 hours.

IV. Proposed Mathematical Formulation

In this section, we propose a new mathematical model for the formulation of the Container Stacking Problem. In this model, we have integrated three types of containers (regular containers, open top containers and tank containers). We have also taken into account the size of containers as well as the stacking capacity in the yard in order to guarantee the safety of both containers and all over the seaport terminal.

A. Index and Parameters

This sub-section summarizes the different indexes and parameters used for the proposed mathematical model.

k : container index.

d : Index of type of container, as :

$$d = \begin{cases} 1, & \text{if it is a regular container} \\ 2, & \text{if it is an open top container} \\ 3, & \text{if it is a tank container} \end{cases}$$

b :Index of the bay in the yard.

r :Index of the row (stack) in the bay b.

e :Index of the tier (height level) in the row r of the bay b.

N :Total number of containers.

B :Total number of bays.

R :Total number of rows constituting a bay.

E : Maximum height level constituting a row.

w_k :The weight of the container k.

C_b :The free storage space in the bay b (free storage positions).

r_r :Size of the row r (we consider two sizes: 20, 40).

R_k :Size of container k.

D_k :Destination of container k.

D_b :Destination of the bay b.

t_k : Expected departure time of container k.

S :Resistance/capacityof the earth.

M : a great number

Y_k^b : The traveled distance of the container k between the quay and the bay b.

$N_c(d)$: Number of containers of type d.

B. Decision Variable

The decision variables are described in this sub-section by Equation (1).

$$X_{kd}^{bre} = \begin{cases} 1 & \text{if the container k of type d is assigned to the bay b,row r and tier e} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

C. Objective Function

The objective function aims to minimize the overall distance between the quay and the storage position of each container. The objective is selected in view of the importance of reducing container transport costs, which is one of the strengths of the port authorities (see Equation (2)).

$$\sum_{k=1}^{N}\sum_{d=1}^{3}\sum_{b=1}^{B}\sum_{r=1}^{R}\sum_{e=1}^{E} Y_k^b\, X_{kd}^{bre} \quad (2)$$

D. Constraints

$$\sum_{k=1}^{N}\sum_{d=1}^{3}\sum_{r=1}^{R}\sum_{e=1}^{E} X_{kd}^{bre} \le C_b \quad ; b \in \{1, \dots. B\} \quad (3)$$

In constraint (1), the total number of containers assigned to a certain bay must not exceed the number of free positions in this bay (this number is known at the start of the planning horizon) (as shown in Equation (3)).

$$\sum_{b=1}^{B}\sum_{r=1}^{R}\sum_{e=1}^{E} X_{kd}^{bre} = 1 \quad ; k \in \{1, \dots N\}\ , d \in \{1, \dots 3\} \tag{4}$$

Constraint (2) explained in Equation (4) ensures that each container is stored in a single bay during the planning horizon.

$$\sum_{k=1}^{N}\sum_{d=1}^{3}\sum_{e=1}^{E}(R_k - r_r)X_{kd}^{bre} = 0 \quad ; b \in \{1, \dots B\}\ , r \in \{1, \dots R\} \tag{5}$$

In constraint (3) detailed in Equation (5), a row must contain containers of the same size.

$$\sum_{k=1}^{N}\sum_{d=1}^{3}\sum_{r=1}^{R}\sum_{e=1}^{E} X_{kd}^{bre}(D_k - D_b) = 0 \quad ; b \in \{1, \dots B\} \tag{6}$$

The constraint (4) for the Equation (6) ensures that the destination of the bay and that of the stored container are the same in each planning horizon, the purpose of this constraint is to allow a grouping of the available containers to be defined according to their destination. Each free position in the storage space can only have one container stored at a time; this is what constraint (5) (Equation (7)) presents.

$$\sum_{k=1}^{N}\sum_{d=1}^{3} X_{kd}^{bre} = 1 \quad ; b \in \{1, \dots B\};\ r \in \{1, \dots R\}; e \in \{1, \dots E\} \tag{7}$$

$$w_k X_{kd}^{bre} \le w_{k'} X_{k'd'}^{br(e-1)} + M\left(1 - X_{k'd'}^{br(e-1)}\right);\ b \in \{1, \dots B\}, r \in \{1, \dots R\}, e\ \{1, \dots E\}, k \in \{1, \dots N\}, d \in \{1, \dots 3\}, k \ne k' \tag{8}$$

The weight constraint between the stored containers is set in constraint (6) (related to Equation (8)) so that the container at the top should have a lower weight than that stored in the previous level (below).

$$t_k X_{kd}^{bre} \le t_{k'} X_{k'd'}^{br(e-1)} + M\left(1 - X_{k'd'}^{br(e-1)}\right);\ b \in \{1, \dots B\}, r \in \{1, \dots R\}, e \in \{1, \dots E\}, k \in \{1, \dots N\}, d \in \{1, \dots 4\}, k \ne k' \tag{9}$$

Constraint (7), as shown in Equation (9), ensures that the containers should be stored in a row in a descending order of their departure dates (in other words, the containers that go out first will be placed in the highest positions).

$$\sum_{k=1}^{N}\sum_{d=1}^{3}\sum_{r=1}^{R}\sum_{e=1}^{E} X_{kd}^{bre} w_k \le S; \forall b \in \{1,\dots,B\}, r \in \{1,\dots,R\}, e \in \{1,\dots,E\}, k \in \{1,\dots,N\}, d \in \{1,\dots,3\} \tag{10}$$

In constraint (8) (Equation (10)), we define the storage capacity of the port terminal.

$$M(1 - X_{k2}^{bre}) + X_{k2}^{bre} > X_{k'd}^{br(e+1)}; \quad \forall b \in \{1, \dots B\}, r \in \{1, \dots R\},\ , k\ \{1, \dots N_c\},\ k' \in \{1, \dots N\}, d \in \{1, \dots 3\}, e \in \{1, \dots E\} \tag{11}$$

Constraint (9) explained in Equation (11) ensures that no containers can be stored above an open-top container.

$$M(1 - X_{k3}^{bre}) + X_{k3}^{bre} > X_{k'd}^{br(e+1)};\ \forall b \in \{1, \dots B\}, r \in \{1, \dots R\}, e \in \{1, \dots E\}, k \in \{1, \dots N_c(3)\}, k' \in \{1, \dots N_c(d)\} d \in \{1,2\} \tag{12}$$

Constraint (10) ensures that tank containers can only be stored above each other (see Equation (12)).

$$X_{kd}^{bre} \in \{0,1\} \tag{13}$$

V. Implementation and Computational Results

A. Implementation

In this paper, we consider the deterministic state of the container stacking problem, the input data are supposed to be known beforehand: State of the storage area as well as the number of the containers to be stored in a specific planning horizon. Information related to incoming containers includes container ID (Identification), arrival time, weight, size, type, EDT (Expected Departure Time).

- There are two types of containers (20 feet, 40 feet).
- We will consider a maximum number of 8 Quay Cranes (QCs).
- Each stack can contain at most four containers.
- The Expected Departure date of containers to be stored is randomly chosen between [2h, 96h].
- Destinations: 6

The proposed mathematical model is coded with the C programming language integrated with the Eclipse Standard Edition ILOG Cplex 12.4. The developed program is executed on a PC with an Intel(R), 2,00 GHz processor running and with 4-GB of memory.

The exact method (Branch & Cut) was tested and confirmed for the instances with small and medium parameters. In fact, this exact method can only used to verify the performance of our proposed method for this kind on instances. Usage is defined as the ratio between the total storage space used by all unloading containers and the total storage space in the storage yard.

B. Computational Results

For the validation of our proposal model, we have conducted a first numerical test based on a small instance taken from the Tunisian Sfax seaport terminal case study. We have considered the storage of only 5 containers and 3 bays. Input parameters are summarized in Table I and Table II.

The obtained total distance travelled from the quay side to the bays is equal to 289 m. The travelled distance obtained by the Sfax seaport in this case is equal to 314 m. in This first result has been encouraging and the storage manager in the Sfax seaport terminal has been satisfied by this initial test. But further tests should be done in small instances in a first way and in large instances in a second way to validate the proposed approach.

TABLE I: INPUT PARAMETERS

k	1	2	3	4	5
$N_c(d)$	1	2	2	3	1
R_k	20	40	40	20	20
C_b	2	1	2	3	1

W_k	8	4	9	4	5
t_k	10	11	12	14	15
D_k	2	4	6	7	8
D_b	4	3	5	6	9

TABLE II: MATRIX DISTANCE

d_k^b	k = 1	k = 2	k = 3	k = 4	k = 5
b = 1	54	53	62	64	65
b = 2	53	58	60	61	64
b = 3	59	56	61	65	65

VI. CONCLUSION

In this paper, we proposed a new mathematical model for the container stacking problem in seaport terminals. The suggested model considers different types of containers and integrates two novel constraints: a stack and not a bay is reserved to a single size of containers, the capacity of all over the terminal. The performance of the system has been tested based on the Tunisian Sfax seaport terminal and the obtained results of an initial test seem to be encouraging. As a future work, the system detailed in this study will be tested in other small and large instances.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The contribution of this manuscript consists in proposing a new mathematical model for the description and the resolution of the Container Stacking Problem in the Tunisian Sfax seaport terminal. The model takes into account the storage rules related to the different types of containers, the total storage capacity of the seaport and the reservation of each stack (and not each bay) for a certain size of container. As far as the authors' knowledge, these constraints are not considered in the existing literature.

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