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A Berth Allocation Policy by Considering Collaboration between Adjacent Container Terminals

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Abstract *–The volume of international maritime trade has increased significantly in recent years, and the growth is expected to be continued with similar rates. To meet the growing demand, it is necessary to improve productivity with minimal investment in container terminals infrastructures. Iranian Rajaee port is the main gateway of Iran import and export and is chosen as the case study of this research. Rajaee port has two container terminals with different depths. Currently, these two container terminals are working separately by two different operators. To meet the growing demand for maritime trade, these two container terminals could share their resources based on a policy presented in this study. This research has developed a berth allocation policy where demand could be driven from a container terminal to an adjacent container terminal with an additional cost. The goal of the Original Container Terminal is to minimize the total cost of vessel services. Several numerical examples are presented to evaluate the effectiveness of the new berth allocation policy. The results show that the proposed berth allocation policy offers significant cost savings over high demand periods.*

Keywords– Container Terminals, Berth Allocation Problem, Collaborative Agreement, Iranian Rajaee Port.

I. INTRODUCTION

Sea transport is critical as one of the factors influencing international trade. It is estimated that over 80% of the global trade mass is shipped by vessels. Due to increased living standards, rapid industrialization, population growth, and competitive markets, international maritime trade increased by more than 120% of the volume from 1980 to 2008. The overall volume of international maritime trade over the past few years has dramatically increased. In the last five years, the volume of exchange has increased by 4%, reflecting the global business improvement process and the world's economic recovery (Trade & Development, 2018). The total volume of international maritime trade in 2017 reached 10.7 billion tonnes. From 1980 to 2017, tanker vessels' trade has grown by an average of 1.4% annually, while dry bulk cargo has increased by 4.6%. The container trade is the fastest-growing segment with an annual growth rate of 8.1 percent. This rate is expected to continue with the same trend.

To respond to the growing demand, with limitations on capacity expansion, it needs to have a proportionate approach to guarantee shipping liners and container terminals' interests. One approach that could be used is developing collaborative agreements between container terminals. Integration and cooperation, especially to overcome resource capacity constraints, is one of the approaches that has received much attention recently. Building new infrastructure or

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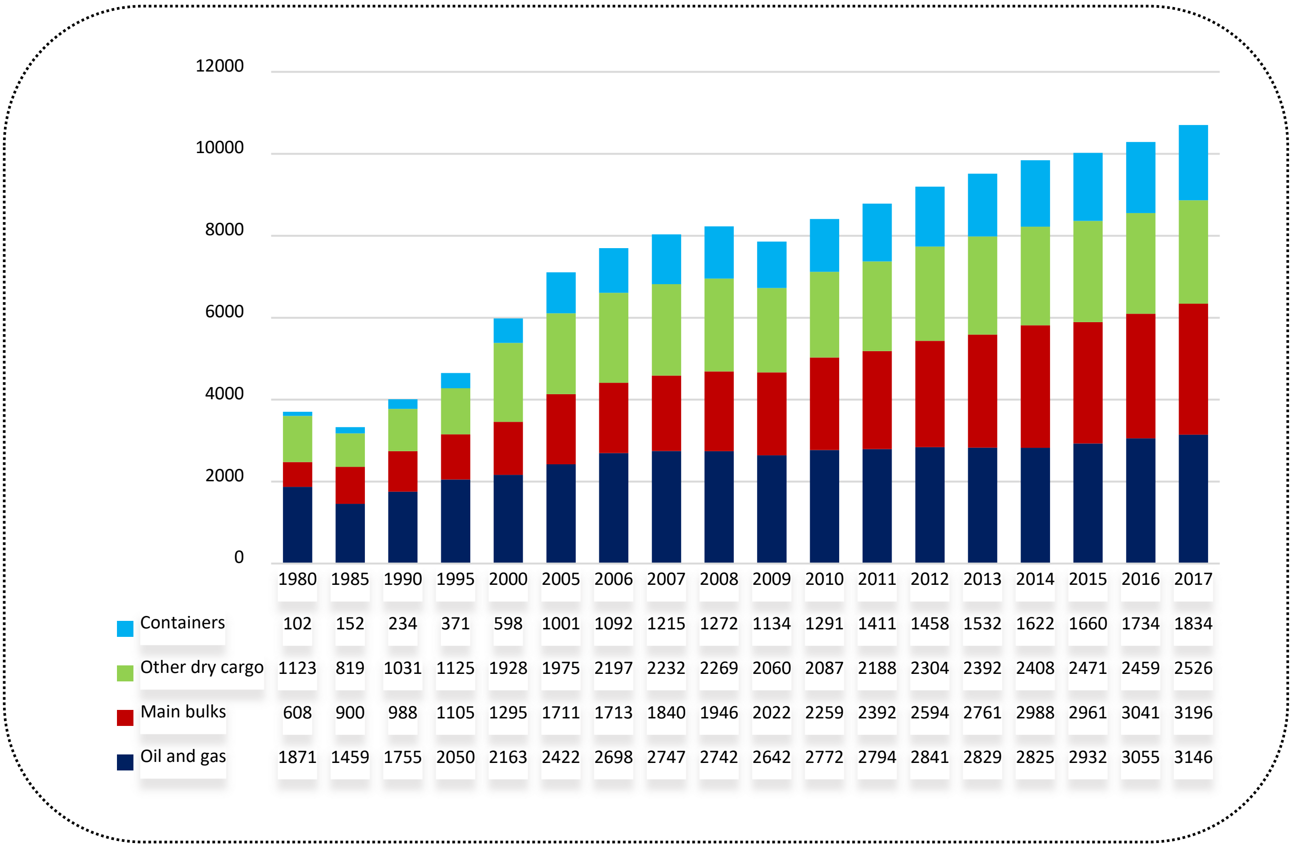

	1980	1985	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Containers	102	152	234	371	598	1001	1092	1215	1272	1134	1291	1411	1458	1532	1622	1660	1734	1834
Other dry cargo	1123	819	1031	1125	1928	1975	2197	2232	2269	2060	2087	2188	2304	2392	2408	2471	2459	2526
Main bulks	608	900	988	1105	1295	1711	1713	1840	1946	2022	2259	2392	2594	2761	2988	2961	3041	3196
Oil and gas	1871	1459	1755	2050	2163	2422	2698	2747	2742	2642	2772	2794	2841	2829	2825	2932	3055	3146

Fig. 1. International Seaborne Trade Trends (Hoffmann & Sirimanne, 2017)

upgrading existing ports can increase the port capacity, but this requires a substantial investment. (Cordeau et al., 2015). There is no possibility of expanding space for all container terminals, and container terminals are looking to improve their operational efficiency with minimum investment. Improving container terminals for optimal use of existing resources is another approach in this regard. Better use of the existing port capacity with collaboration between container terminals is one of the approaches that could increase container terminals' productivity without significant investment in infrastructures.

To fill the gap in the present study proposes a mixed-integer nonlinear mathematical model, which involves the simultaneous allotment of vessels at container terminals. Moreover, a collaborative agreement concerning vessel service time window (TW) negotiated between adjacent container terminals at a port is suggested and evaluated.

The remainder of the paper is structured so: Section II presents a literature review that gives attention to the seaside operations at container terminals. Section III is devoted to introducing the developed berths allocation policy at container terminals by considering collaborative agreements. Section IV presents the proposed model related to the berths allocation policy between adjacent terminals. Section V analyzed the data and demonstrated the results obtained. The last section provides the general conclusions of this study and ends with suggestions for future research.

II. LITERATUR REVIEW

The operations of the maritime container terminals and the decisions that must be made have drawn a significant amount of research over the last two decades. Many research papers have been published to date about seaside operations in container terminals. (Carlo et al., 2013) and (Bierwirth & Meisel, 2015) provide a detailed review of the operation of the container terminal and outline the significant decision problems that a container terminal manager deals with them, such as Berth Allocation Problem (BAP), Quay Crane Assignment Problem (QCAP). BAP is one of the operational decisions required to ascertain the sequence of vessel loading and unloading operations in a container terminal (Theofanis, Boile, & Golias, 2009). The berth allocating problem has been modeled in different ways because most of the proposed models are developed based on case studies, and each case study has its characteristics. The difference between the proposed models is the differences in the hypotheses considered on the problem's parameters and constraints. (Bierwirth & Meisel, 2010) propounded a framework for classifying the BAP based on three attributes, which are as follows:

- The spatial attribute: the berth space can be categories into discrete (disc), continuous (cont), hybrid (hybr) groups. In the discrete case, the quay is split-off into a certain number of births, and only one ship could be assigned to each berth. The vessels can berth at any available position in the quay space in continuous mode. In the hybrid case, the berthing area during a quay could be (cont) or (disc). Another case about the spatial attribute is the draft of the berth. If the depth of the berth is low, vessels with greater depth cannot be moored.
- The temporal attribute is related to the arrival time, the mooring, and the vessel's departure from the berth, and it can be divided into static arrivals (stat) and dynamic arrivals (dyn) categories. The static case indicates that all vessels have already arrived at the harbor and does not consider the vessels that will enter the harbor later. In the dynamic case expected arrival time of vessels is contemplated for a specified period.
- The Handling time attribute refers to the assumptions intended for the time of the discharge operation and loading of vessels.

Cooperation between container terminals is one of the emerging areas in maritime transport. Given the challenges and limitations of capacity expansion, this area of research has become more critical. So far, Several studies have focused on collaborative agreements between shipping line and container terminals, but there have been few studies have been devoted to modeling different types of collaborative agreements only between container terminals.

(Imai et al., 2008) proposed BAP in a discrete dynamic model at container terminals. In this research, vessels with excessive waiting times are consigned to an external container terminal. The aim is the minimization of the total service time of ships in the external terminal. An Evolutionary Algorithm (EA) was expanded to solve the problem. The developed model results showed that it performs well in reducing external container usage and could help busy ports, especially within extreme peaking conditions.

(Karafa et al., 2011) propounded a mathematical model, where a dedicated terminal can divert vessels to a public terminal. The objective is to minimize total handling and delayed departure costs for all the ships belonging to the dedicated terminal; an EA has been used to solve it. Several computational experiments were employed to examine the algorithm's efficiency, which indicates that the proposed heuristics are efficient.

(Dulebenets et al. 2015) proposes a new heuristic approach for the green ship scheduling, which minimizes the total route service cost, including greenhouse gas emissions produced by ships. The results indicate the efficiency of the suggested heuristic in terms of solution quality and computational time. (Alharbi et al., 2015) modeled a cooperation mechanism betwixt the company of liner shipping and a container terminal. The objective aimed to minimization the sum of ship cost and fuel cost. The results show that the port time windows, which are conferred between the container terminal and the liner shipping company, affect the optimal number of ships to deploy, ship sailing velocity, and the total cost of route service. (Liu et al., 2016) presented Cooperation mechanism between shipping lines and container terminals. The agreement provides different handling rates to the port operators. The objective aimed to minimization the total fuel consumption of vessels and port operation costs. An optimization algorithm has been developed to solve the problem. (Venturini et al., 2017) proposed a new formula with the integrating BAP by optimizing the ship's velocity for various ports in a sequence, under environmental observances, especially vessel air emissions. The proposed model's objective is to minimize the fuel consumption of long distances traveled between several ports, taking into account the optimization of vessel speed and considerations related to the emission of pollutants from the vessel. The results show that implementing a more skilled method of mooring and adjusting the speed of vessels can have a considerable impact on reducing the total operation time and fuel consumption, and emissions and increase the share of cooperation.

(Dulebenets et al., 2018) formulated BAP for public container terminals, where demand can be diverted from a public terminal with additional cost to another container terminal. The aim is to minimization the total ship service cost in the public terminal. The results demonstrated that the proposed policy has more significant savings within the high demand periods. (Prayogo and Hidayatno, 2019) proposed the integrated planning model for seaside operations in terminal containers considering the ship's uncertain arrival time and the number of containers to be discharged and loaded into the arrived ships. The goal is to balance the benefits of the terminal managers and the shipping liner owners, including minimizing the total seaside operations costs and maximizing service levels for shipping liners. The proposed model has been solved by using Preemptive Multi-Objective Programming in a small-scale problem. (Kavirathna et al., 2020) proposed a mixed-integer programming model to increment port competitiveness by minimizing ship traffic aggregation and mooring delays in terminals. This paper discusses the effects of cooperation among terminal operators in a single port as a part of their cooperation strategy. Table I has presented an outline of BAP formulations.

Table I. Overview Of The BAP Formulations

Authors (year)	***Spatial***	***Vessel Arrivals***	***Handling Time***	***Objective(s)***
(Kim & Moon, 2003)	Cont	*Dyn*	Fix	Σ[w_1(Pos)+w_2(Tard)]
(Gkolias, 2007)	*Disc &* Cont	*Dyn*	Variable	Σ[w_1(Wait) + w_2(Hand) + w_3(Tard)] +w_4(Misc)]
(Imai et al., 2008)	*Disc*	*Stat & Dyn*	Variable	Σ(Wait + Hand)
(Golias et al., 2009)	*Disc*	*Dyn*	Variable	Σ[w (Wait) + Tard]
(Golias et al., 2010)	*Disc*	*Dyn*	Variable	Σ[w_1(Wait) + w_2 (Hand) + w_3(Tard) + w_4(Misc)]
(Golias et al., 2011)	*Disc*	*Dyn*	Variable	Σ[w_1(Wait) + w_2(Tard) + w_3(Misc)]
(Xu et al., 2012)	*Disc & draft*	*Stat & Dyn*	Fix	*Σw(Wait + Hand)*
(Karafa et al., 2013)	*Disc*	*Dyn*	Variable	*Σ(Wait + Hand)* + Misc
(Golias et al., 2014)	*Disc*	*Dyn*	Variable	*Σ(Wait + Hand)* + Misc
(Sheikholeslami, Ilati, & Kobari, 2014)	Cont *& draft*	*Dyn*	Variable	Σw(Wait + Hand)
(Liu et al., 2016)	*Disc*	*Dyn*	Fix	Σ(Fuel + Hand)
(Dulebenets, 2017)	*Disc*	*Dyn*	Variable	Σ(Hand + Wait + Tard) + Misc
(Dadashi et al., 2017)	Cont	*Dyn*	Variable	Σw (Tard)
(Xu, Du et al., 2018)	Cont	*Dyn*	Variable	Σ(Compl + Misc)
(Dulebenets et al., 2018)	*Disc*	*Dyn*	Fix	Σ(Hand + Tard)
(Xu et al., 2018)	Cont	*Dyn*	Variable	Σ(Tard)
Current paper	Disc & draft	Dyn	Fix	Σ(Hand + Wait + Tard)

The congestion in terminals and the ship's size increasing force container terminal operators to find new container handling methods. The majority of studies focused on alliance or the collaborative agreement betwixt companies of liner shipping and container terminals. However, there have been few attempts to modeling different types of collaborative agreements only betwixt container terminals. This study expands the collaborative agreements betwixt marine container terminals, which have been used in the literature (Dulebenets et al., 2018). A more general kind of collaborative agreement is assessed betwixt the container terminal operators, where the container terminals negotiations of the TW duration. This study presents a new mathematical model for the BAP at container terminals in a port which considers the waiting time, the depth, and the length.

Competition in today's world has made the need for more cooperation more visible, leading to an increase in research on collaboration day by day. In this study, the mathematical model of berth allocation decisions at the container terminal is modeled with consideration of cooperation. The goal is to minimize the ship's service's total cost to meet existing constraints and conditions.

III. ASSUMPTIONS AND PROBLEM DESCRIPTION

A. Problem definition

In this study, two container terminals with different operators in a single port are considered. The terminals have a discrete berthing layout, so, at any time, a berth should serve only one vessel. In this study, the berth allocation problem is considered with cooperation between container terminals. There are contractual agreements between container terminals that a container terminal could divert some of its vessels to the adjacent container terminal based on the contractual agreement. Accordingly, since the auxiliary terminal first services its ships, diverted vessels can only be allocated during the predetermined time windows. The auxiliary terminal's priority is its berth schedule, and it will not change its berthing plan to serve the original terminal vessels. Other assumptions are as follows:

- There is no uncertainty at the arrival times, loading and unloading of the vessels;
- The arrival time of the vessel in this study follows a dynamic mode;
- The arrival time of vessels has been already announced to the container terminal management;
- Since the berthing until completion of a vessel's operations, it is not possible to departure from the berth;
- The departure time of a vessel has been announced;
- The length of each vessel, including the vessel's actual length, is considered with a safe distance.

The proposed berth allocation model determines which vessels would be diverted to the external terminal. Considering vessel delay times, vessel service time (waiting times + handling times), and external container terminal available time windows, this paper determines its scheduling plans. The proposed model also considers the depth and length of the berths. The time windows restrictions are imposed to depict better a real-world problem, which it is improbable that a terminal would take a ship from another container terminal at any time, as it may disrupt its customer's service times. Therefore, it is more likely that the external container terminal will have availability time windows to service the adjacent container terminals. The next section is described the contractual agreement between container terminals.

B. Contractual agreement

The cooperation agreement between the original container terminal and the adjacent container terminal could divert vessels to the adjacent container terminal during specific time windows. The adjacent container terminal does not change its berthing plan to meet guided demand. An example of the ship schedules for the original terminal and adjacent terminal shown in Fig. 2. The vessels servicing at the original container terminal (OCT) are blue, and the vessels servicing at the adjacent container terminal (ACT) are shown green. The ACT has an available time window, after "vessel 1", departure time (ST_t), and before "vessel 2" berthing (FT_t). At OCT, some vessel's departure times will increase, and the OCT cannot meet the vessels' announced departure times. This event leads to customers' dissatisfaction, (especially vessels, "3", "4", "5", "6" and "7"). So, the OCT could agree with ACT to service one of its customers during the time window that ACT is idle.

The ACT suggests several time windows based on weekly planning and provides a different discount rate for each one. Each vessel's handling time could be estimated based on available berth at ACT, available quay cranes, and the number of assigned quay cranes to a vessel. OCT could ask for service at the ACT idle time windows.

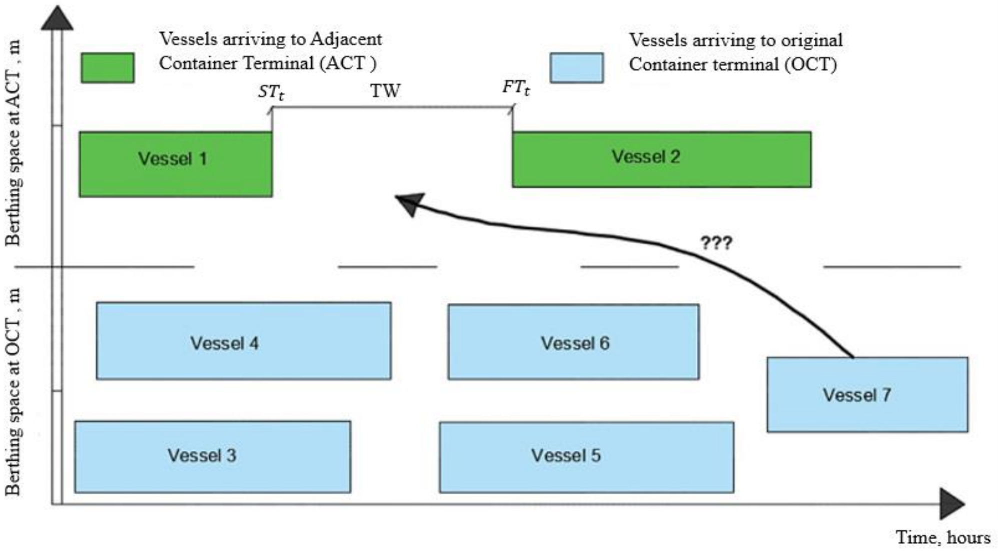

Fig. 2. Suggested Berth Allocation Policy. (Dulebenets et al., 2018)

C. Service of vessels at the adjacent container terminal

The service completion time has two possible scenarios if a guided ship to be able served in the range of a time window at the adjacent container terminal:

1. The vessel operations complete before the requested departure time (RD), and the complete services cost is equivalent to the cost of loading and unloading containers.

2. The vessel service completes after RD, and the entire cost of service is equivalent to the handling cost of the vessel, and a penalty cost due to pass over from the vessel's requested departure time.

If a ship's service is completed, no cost will be imposed on the original container terminal. It is supposed that a vessel will not have deviated to the adjacent container terminal if its service cannot be completed within a time window with assigning all of the available quay cranes to the vessel

Figure 3 depicts the pre-mentioned scenarios at the adjacent container terminal, with a simple case of a one-time window. Fig. 3 shows the three different berthing cases. In the first case, the original container terminal diverts vessel "V" to be operated at the external container terminal during the time window. The vessel will be handled before the end time of the time window and before RD the vessel "V". Therefore, the total cost is equivalent to the first scenario. In the second case, the vessel "V" servicing is finished before the finish time of the time window and after its RD. Therefore, the total cost of service in the second case for the vessel "V" is equivalent to the second scenario. In the third case, the original terminal operator cannot divert the vessel "V" to the external container terminal because it cannot be serviced before the time window's finish time.

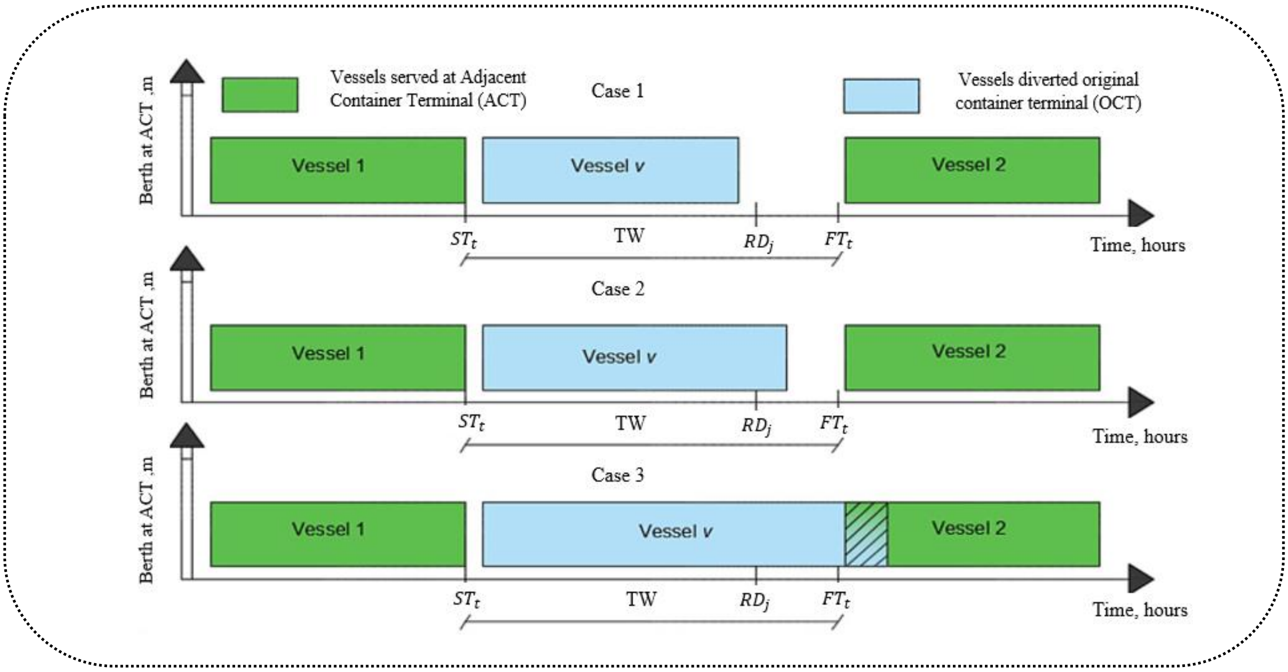

Fig. 3. Different Scenarios for Adjacent container Terminal Time Window Note: ST_t **_ start time of Time Window t,** FT_t **_ end of Time Window t,** RD_j **_ Requested Departure Time of Vessel j. (Dulebenets et al., 2018)**

IV. PROPOSED MODELS

A. Problem Formulation

This paper used the following BAP mathematical model to obtain the adjacent container terminal's available time windows. After finding the idle times, new constraints are added to the BAP. The developed mathematical model is called Collaborative Berth Allocation Problem (CBAP), where ships can be diverted to the adjacent container terminal to serve according to the negotiated time windows.

Mathematical representations for the CBAP, including indices and parameters, constraints, and decision variables, are given as follow:

Sets:

$(i = 1, 2, ..., m)$	set of berths
$(j = 1, 2, ..., n)$	set of vessels
$(t = 1, 2, ..., t)$	set of available Time Windows at Adjacent Container Terminal (ACT)

Parameres:

a_j	the arrival time of vessel j
$p_j = (NC_j / hd_{ij})$	the handling time of vessel j
h_{jt}	the handling time of vessel j within TW t at ACT
NC_j	the number of Containers loaded/unloaded to/from vessel j
hd_{ij}	vessel j handling productivity at berth i
hp_{jt}	vessel j handling productivity at TW t at ACT
ch_{ij}	handling cost for vessel j at berth i
che_{jt}	handling cost of vessel j for TW t at ACT
cwt_j	waiting time cost of vessel j
cld_j	penalty for delay in departure for vessel j
RD_j	requested departure time of vessel j
RD_{jt}	requested departure time of vessel j for TW t at ACT
st_t	the start time of TW t
ft_t	the end time of TW t
TW	the number of time window(s)
ps_{jt}	1 if ACT could service vessel j during TW t (=0 otherwise)
D_i	*depth of* berth i
D_j	*draft of vessel* j
D_t	*wharf depth at ACT for TW* t
L_i	*the length of berth* i
l_j	*the length of vessel* j *, including a safety distance between adjacent vessels*
L_t	*the length of the berth at ACT for TW* t
M	*large positive number*

Decision Variables

x_{ij}	1 if vessel j is planned to be moored at the berth i of original container terminal (=0 otherwise)
d_{jt}	1 if vessel j is diverted to ACT during TW t (=0 otherwise)
$I_{ijj'}$	1 if vessel j' is processed after ship j and both ships are allocated to the berth i (=0 otherwise)
s_j	Denotes the time that j ship operations is started
wt_j	waiting time of vessel j
LD_j	delay in departure of vessel j

For the collaboration between adjacent container terminals at Iranian Rajaee port, the following mathematical modeling is developed:

BAP:

$$\min \sum_{j=1}^{n}\sum_{i=1}^{m} ch_{ij} NC_j x_{ij} + \sum_{j=1}^{n} wt_j cwt_j + \sum_{j=1}^{n} LD_j cld_j \qquad (1)$$

Subject to:

$$\sum_{i=1}^{m} x_{ij} = 1 \qquad (j = 1, 2, ..., n) \qquad (2)$$

$$s_j \geq a_j \qquad (j = 1, 2, ..., n) \qquad (3)$$

$$s_{j'} \geq s_j + p_j - M(1 - I_{ijj'}) \qquad (j, j' = 1, 2, ..., n; s.t. j \neq j'; i = 1, 2, ..., m) \qquad (4)$$

$$I_{ijj'} + I_{ij'j} \leq 0.5(x_{ij} + x_{ij'}) \qquad (j, j' = 1, 2, ..., n; s.t. j \prec j'; i = 1, 2, ..., m) \qquad (5)$$

$$I_{ijj'} + I_{ij'j} \geq (x_{ij} + x_{ij'}) - 1 \qquad (j, j' = 1, 2, ..., n; s.t. j \prec j'; i = 1, 2, ..., m) \qquad (6)$$

$$wt_j \geq s_j - a_j \qquad (j = 1, 2, ..., n) \qquad (7)$$

$$LD_j \geq s_j + \sum_{i=1}^{m} p_j x_{ij} - RD_j \qquad (j = 1, 2, ..., n) \qquad (8)$$

$$(D_i - D_j) x_{ij} \geq 0 \qquad (j = 1, 2, ..., n; i = 1, 2, ..., m) \qquad (9)$$

$$(L_i - l_j) x_{ij} \geq 0 \qquad (j = 1, 2, ..., n; i = 1, 2, ..., m) \qquad (10)$$

The purpose of model BAP is to minimization the entire cost of the service of all the ships. The first part of the objective function calculates vessel handling costs. The second component determines the waiting time cost of all vessels, and the last component determines the cost of delay in departure for all vessels.

According to equation (2), a vessel must be served once. Based on equation (3), a ship must enter the harbor then moored. If vessels j and j' are assigned to berth i, and vessel j is processed before vessel j', then the start time of vessel j' must be no earlier than the start time of vessel j plus vessel j handling time. This constraint is formulated via equation (4). Equations (5) and (6) guarantee that $I_{ijj'}=1$ or $I_{ij'j}=1$ if both vessels are allocated to the berth i. These constraints also ensure that $I_{ijj'}=I_{ij'j}=0$ if one of the vessels j and j' is not assigned to berth i. Equations (7) and (8) are embedded to calculate the waiting times and delays in departure times of vessels, respectively. Equations (9) and (10) ensure that mooring is not allowed for ships with longer lengths of the berth or less depth than at the assigned terminal.

Using Rajaee port data and the proposed BAP model, vessel service sequence for the adjacent container terminal will be obtained, and based on that, the container terminal idle time and the time window(s) will be achieved. By specifying the time window(s) and the start time and end time of each time window in the adjacent container terminal concerning the contractual agreement, CBAP formulation would be as follow:

CBAP:

$$\min \sum_{i=1}^{m}\sum_{j=1}^{n} NC_j ch_{ij} x_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n} cwt_j wt_j x_{ij} + \sum_{j=1}^{n} LD_j cld_j + \sum_{j=1}^{n}\sum_{t=1}^{t} NC_j che_{jt} d_{jt} \tag{11}$$

Subject to:

$$\sum_{i=1}^{m} x_{ij} + \sum_{t=1}^{t} d_{jt} = 1 \qquad (j=1,2,...,n) \tag{12}$$

$$s_j \geq a_j \qquad (j=1,2,...,n) \tag{13}$$

$$s_{j'} \geq s_j + p_j - M(1-I_{ijj'}) \qquad (j,j'=1,2,...,n; s.t. j \neq j'; i=1,2,...,m) \tag{14}$$

$$I_{ijj'} + I_{ij'j} \leq 0.5(x_{ij} + x_{ij'}) \qquad (j,j'=1,2,...,n; s.t. j \prec j'; i=1,2,...,m) \tag{15}$$

$$I_{ijj'} + I_{ij'j} \geq (x_{ij} + x_{ij'}) - 1 \qquad (j,j'=1,2,...,n; s.t. j \prec j'; i=1,2,...,m) \tag{16}$$

$$wt_j \geq s_j - a_j \qquad (j=1,2,...,n) \tag{17}$$

$$LD_j \geq s_j + \sum_{i=1}^{m} p_j x_{ij} - RD_j - M\left(1-\sum_{i=1}^{m} x_{ij}\right) \qquad (j=1,2,...,n) \tag{18}$$

$$LD_j \geq s_j + \sum_{t=1}^{t} h_{jt} d_{jt} - \sum_{t=1}^{t} RD_{jt} - M(1 - \sum_{t=1}^{t} d_{jt}) \quad (j = 1, 2, ..., n) \tag{19}$$

$$s_j \geq \sum_{t=1}^{t} st_t d_{jt} \qquad (j = 1, 2, ..., n) \tag{20}$$

$$ft_t \geq st_t + h_{jt} - M(1 - d_{jt}) \qquad (j = 1, 2, ..., n; t = 1, 2, ..., t) \tag{21}$$

$$\sum_{t=1}^{t} \sum_{j=1}^{n} d_{jt} \leq TW \tag{22}$$

$$d_{jt} \leq ps_{jt} \qquad (j = 1, 2, ..., n; t = 1, 2, ..., t) \tag{23}$$

$$\sum_{j=1}^{n} d_{jt} \leq 1 \qquad (t = 1, 2, ..., t) \tag{24}$$

$$(D_i - D_j) x_{ij} + (D_t - D_j) d_{jt} \geq 0 \qquad (j = 1, 2, ..., n; i = 1, 2, ..., m; t = 1, 2, ..., t) \tag{25}$$

$$(L_i - L_j) x_{ij} + (L_t - L_j) d_{jt} \geq 0 \qquad (j = 1, 2, ..., n; i = 1, 2, ..., m; t = 1, 2, ..., t) \tag{26}$$

The proposed CBAP of this paper has equations that differ from the BAP formulation. There is a fourth component that estimates the cost of delay in departure for the vessel(s) that are diverted to the adjacent container terminal Equation (2) ensures that each vessel will be operated once (either at the original container terminal or transferred to an external container terminal). Equation (19) calculates the delay in departure time for vessels diverted to the adjacent container terminal. Equation (20) ensures that the operation should be started after time window start time if a ship is assigned to a time window. Equation (21) ensures that a vessel will be assigned to a time window at the adjacent container terminal only if it can be operated before the end time of the time window. Equation (22) guarantees that the number of ships guided is no longer than the available TW numbers in the adjacent container terminal. Equation (23) is embedded to guarantee that if the time window's duration is not enough to service a ship, the ship will not be diverted to that time window. Equations (24) and (25) ensure that mooring is not allowed for ships with longer lengths of the berth or less depth than at the assigned terminal.

B. Linearization of the proposed model

In the proposed CBAP model, the second component is the product of two nonlinear decision variables.

Suppose that the $z = xy$ is the product of a binary variable x in a continuous variable y. When the variable x takes a value one, the variable z (non - negative) will be equal to the continuous variable's value and otherwise takes zero. Three constraints are used as follows to linearize this term:

$$z \le y \tag{26}$$

$$z \le Mx \tag{27}$$

$$z \ge y - M(1-x) \tag{28}$$

The objective function of the proposed model is nonlinear. For clarity, the objective function is rewritten in Equations (29) and (30). Based on the linearization, the continuous variable f_{ij} and the –equations (31), (32), and (33) are added to the CBAP model.

$$\min \sum_{i=1}^{m}\sum_{j=1}^{n} NC_j ch_{ij} x_{ij} + \sum_{j=1}^{n}\sum_{t=1}^{t} NC_j che_{jt} d_{jt} + \sum_{i=1}^{m}\sum_{j=1}^{n} cwt_j wt_j x_{ij} + \sum_{j=1}^{n} LD_j cld_j \tag{29}$$

$$\min \sum_{i=1}^{m}\sum_{j=1}^{n} NC_j ch_{ij} x_{ij} + \sum_{j=1}^{n}\sum_{t=1}^{t} NC_j che_{jt} d_{jt} + \sum_{i=1}^{m}\sum_{j=1}^{n} cwt_j f_{ij} + \sum_{j=1}^{n} LD_j cld_j \tag{30}$$

$$f_{ij} \le wt_j \qquad (j = 1, 2, ..., n; i = 1, 2, ..., m) \tag{31}$$

$$f_{ij} \le Mx_{ij} \qquad (j = 1, 2, ..., n; i = 1, 2, ..., m) \tag{32}$$

$$f_{ij} \ge wt_j - M(1 - x_{ij}) \qquad (j = 1, 2, ..., n; i = 1, 2, ..., m) \tag{33}$$

After adding the linearization constraints, the proposed nonlinear model is converted to a linear mixed-integer model, GAMS software.

V. COMPUTATIONAL RESULTS AND DISCUSSION

In this study, the case of Iranian Rajaee Port modeled that has two container terminals. Two adjacent container terminals in this port provide the possibility of proposing a cooperation agreement between them to decrease vessel service times. Real data of the Iranian Rajaee port is provided to verify the validity of the proposed model. After linearization, the model was coded by the GAMS software and implemented by the CPLEX solve.

A. RAJAEE PORT

The container sector in Iran has a rapidly growing market. Such growth in the Rajaee Port may face limitations on physical constraints. The Rajaee Port enjoys a specific geographical position is located 23 km west of Bandar Abbas, north of the Strait of Hormuz. With maritime relations and exchanging goods with 80 famous international ports, this port accounts for nearly half of Iran's trade. Due to the short distance from the main traffic route of intercontinental vessels, it is the most crucial gateway to the Iranian world trade. The Rajaee Port has two container terminals with different depths and the overall view of the berth presented in Fig. 4. The two terminals are presently operating autonomously, where each has its berth, quay crane and

RTG, internal transporter, and container yard. Table II presents the information for container terminals of Rajaee Port. The operational data were available for the period between 2009 through 2012.

Terminal No. 1 is located in the east of basin No. 1 in the range of berths 4 to 7. This terminal has berth lengths of 850 m and depths of 12.5 m with 70 hectares of the yard (including full containers yard, empty containers yard, glacial containers yard, and containers yard with particular dimensions). The reception capacity of the port is exceeded 3.3 million TEUs per year. This capacity cannot satisfy all incoming requests due to significant growth in container operations. To tackle this problem, we can use the existing docks' sharing capacity between two container terminals to meet the growing demand and improve customer service.

Table II: The information of Rajaee Port

Terminal no.	*Berth no.*	*Length meter*	*Draft meter*	*The number of available quay cranes*
1	4	340	12	10
	5	300	12.5	
	6	270	12.4	
	7	250	11.7	
2	25	365	15.8	9
	26	370	16	
	27	375	16.2	

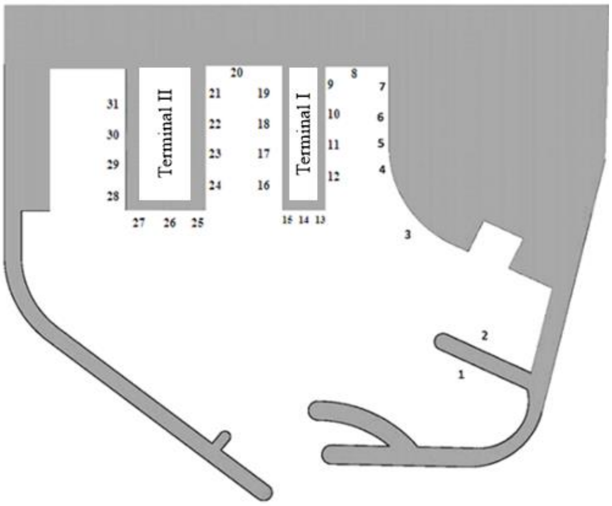

Fig. 4. A schematic view of Rajaee Port

B. Proposed model evaluation

The results of the proposed model (a collaboration between container terminals) are compared with the results obtained from the loading and unloading operations of the Rajaee port (no cooperation between two terminals) to evaluate the proposed change model in minimizing the service cost of vessels in this section. The samples were extracted from the existing operational data set to perform numerical experiments. These sample problems were divided into two groups of medium demand (with a sample size of 20 vessels) and high demand (with a sample size of 30 vessels). In both container terminals, discharge and loading productivity are different depending on the number of quay cranes per berth. It is supposed that the handling charges in the adjacent terminal are more significant than the handling charges at the original terminal.

Two performance measures, total cost savings for the adjacent container terminal (ACT) on the planning horizon, and the use of time windows were selected to evaluate the proposed CBAP model. The total cost savings as a discrepancy in the objective function quantity for the situation that all ships are service in the OCT (no-cooperation between two terminals) and the case that a part of the demands are diverted to ACT (a collaboration between the two terminals) are presented at Table III. The results for each combination of the demand, OCT berth capacity, and the Time Window(s) availability at the adjacent container terminal is presented in Table III.

As expected, the highest savings were observed for the highest demand and lowest mooring capacity at the original container terminal. For example, when there are two available time windows and the high demand period and the original terminal has three berths, the original terminal's profits from directing vessels to the adjacent container terminal are 802200. The total cost savings increases with an increase in time windows in high demand. There are no cost savings for the capacity of 4 berths and medium demand.

Table III: Total Cost Savings For The Recipient Terminal In Planning

	Time window	*Two berth*	*Three berth*	*Four berth*
High Demand	1	-	-	-
	2	1809400	802200	0
	3	1809400	802200	0
	4	3621900	2614700	1812500
Medium Demand	1	-	-	-
	2	1284500	685100	-
	3	1284500	685100	-
	4	1300000	685100	-

Fig. 5 shows the analysis results, in which the x-axis contains the maximum number of TWs in the ACT and the number of berths at OCT.

More savings are observed in this chart at a capacity of 2 berths and the high demand at the original container terminal. For example, at the berth's high capacity, the terminal can be servicing more ships in its terminal, and the maximum number of time windows available in the ACT is recorded as 6.811 percent of cost savings for the high demand period in the original terminal. In contrast, no savings are observed for the period with medium demand. An adjacent container terminal will benefit from this collaboration's benefits with servicing to the main terminal ships.

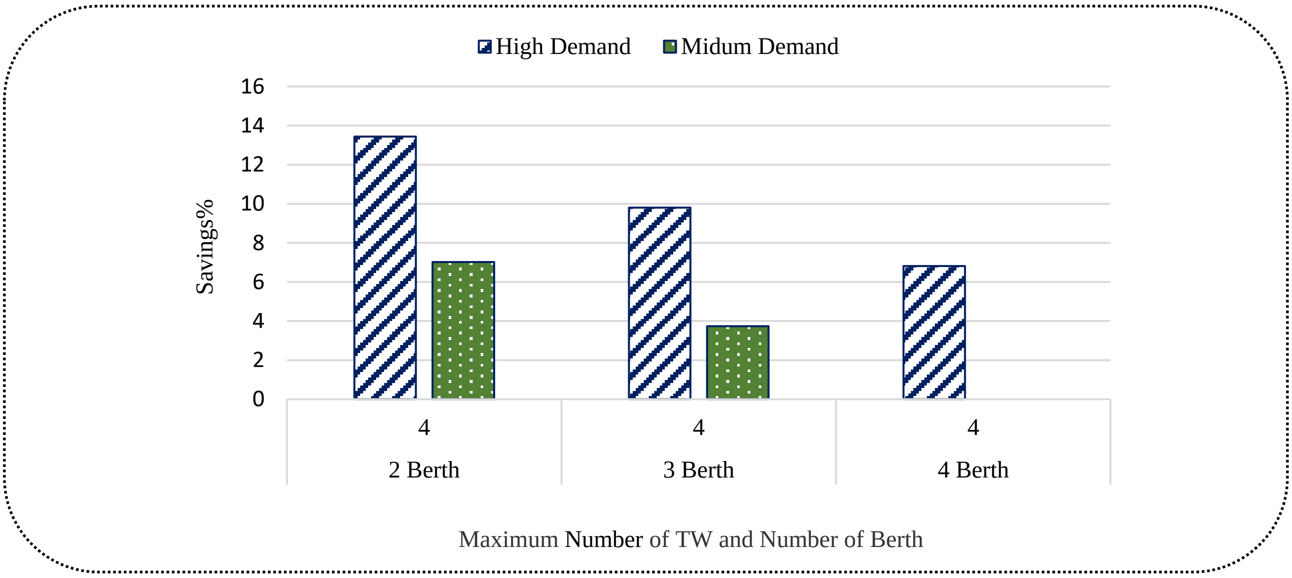

Fig. 5. Total Cost Savings

The second criterion for evaluation of CBAP is to compare the number of ships directed from the original terminal to the number of time windows available in the adjacent container terminal (time windows utilization in collaboration between the two container terminals). The time windows utilization is obtained for each instance for every composition of demand, OCT berth capacity, and time windows availability at the ACT results are presented in Table IV. It is observed that the time windows utilization is increased in high demand and two berths of OCT. The number of directed ships reduced during the Medium demand and high berthing capacity of ACT.

Table IV: Using Time Windows In Planning

	Time window	*Two berth*	*Three berth*	*Four berth*
High Demand	1	0	0	0
	2	1	1	0
	3	1	1	0
	4	2	2	1
Medium Demand	1	0	0	0
	2	1	1	0
	3	1	1	0
	4	2	1	0

Time Windows utilization is shown in Figure 6, in which the x-axis contains the maximum number of TWs in the ACT and the number of berths at OCT. It is observed that fewer vessels have been diverted to the adjacent container terminal by increasing the berth's capacity in either period.

For further analysis, the results are given in Fig. 7. As observed in the figure, by increasing the berth capacity, fewer vessels are diverted to the adjacent terminal, indicating that cooperation could be more effective in the original terminal's congested situations.

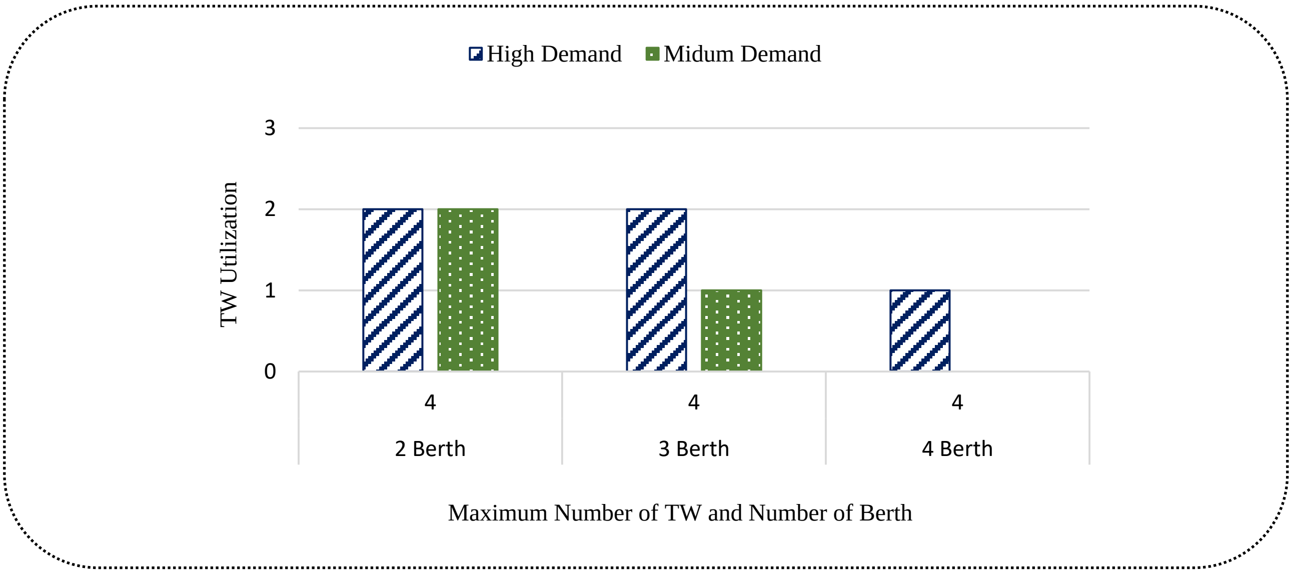

Fig. 6. TW Utilization by Number of TWs and Number of Berth

It can also be seen that in high demand, more vessels in all three berth capacities have been diverted to the adjacent terminal, and as expected, more savings are observing for the high demand period. The results demonstrate that the berth allocation policy obtained under the suggested mechanism can considerably decrease the cost of servicing the ship in the main terminal and provide economic interests for both terminals.

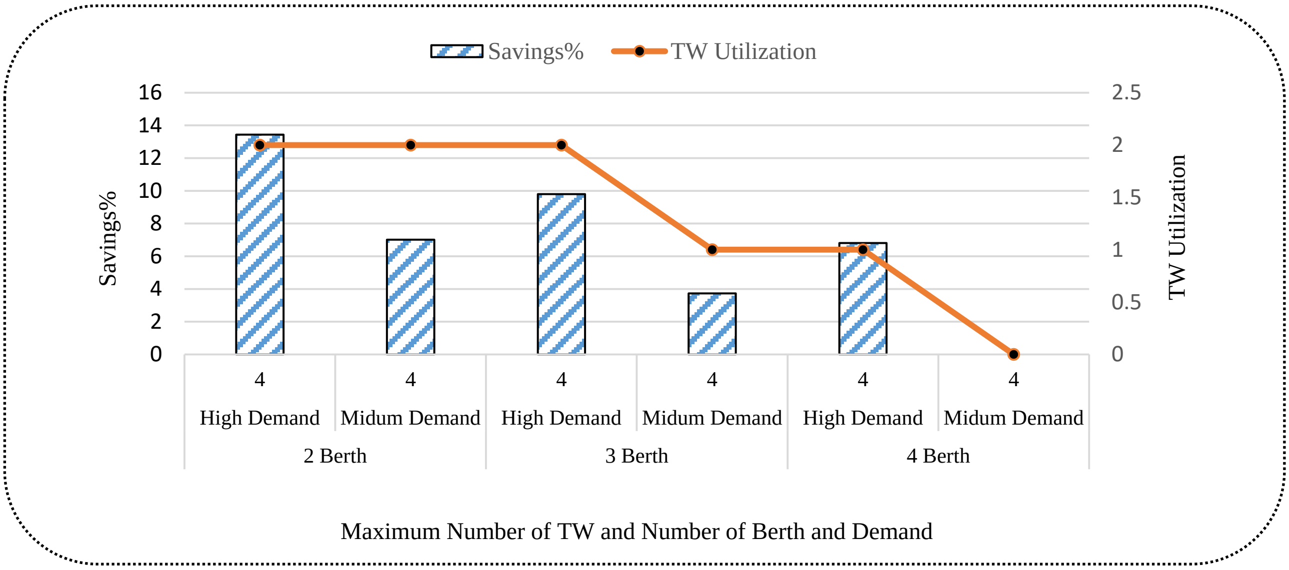

Fig. 7. Further analysis by Number of TWs and Number of Berth and Demand

VI. CONCLUSION

This study aimed to present a berth allocation policy to minimize the vessel's total service cost by considering cooperation between container terminals located in the Iranian Rajaee port, where the adjacent terminal can serve the ships directed from the original terminal. A dynamic BAP formulation was proposed for the simultaneous allocation of container terminals at the Rajaee Port. Two performance measures, cost savings, and time windows, are proposed to determine the proposed berth allocation policy's benefits. Appraisal berth allocation policy was conducted to compare the states of non-cooperation and collaboration between container terminals. The policy shows more savings for higher demand and when the mooring capacity of the original container terminal is low. The proposed model improved the performance of the berth by reducing the total cost of the container terminals, especially in higher demands. Also, the maximum TW utilization is similar to the cases with the highest cost savings. The total cost savings increased (more than %52) with an increase in the number of time windows in high demand situations, and there were no significant savings for periods with average demand and high mooring capacity. This shows the superiority of the proposed model in increasing customer satisfaction by reducing the waiting time for ships as well as the greater profitability of container terminals due to the sharing of resources. In the proposed model, not only the original container terminal gets to benefit from lower operating cost advantages and more efficient operations, but also the adjacent terminal benefits from the cooperation. Therefore, the proposed model could be used as an efficient scheduling tool in high demand periods. The design of sustainable systems has received particular attention in recent studies due to the growing need to move towards a more sustainable future. In this regard, extending the proposed model formulation to reduce pollution in ports and consider the assessment of the alternative container handling equipment types and their effects on the environmental sustainability of the terminal operations is highly recommended. Besides, applying a continuous approach for berthing vessels along berths is suggested to improve the efficiency of the proposed cooperation agreement policy.

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