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The continuous dynamic berth allocation problem at a marine container terminal with tidal constraints in the access channel

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Abstract

We consider the problem of continuous dynamic berth allocation to containerships in a tidal seaport. In some container ports, low water depth in coastal area causes many restrictions on providing vessel's services. Therefore, berth allocation planning for relatively large vessels with high draft is subject to tidal conditions when the vessels are in the access channel as from anchorage area to the quay. Tidal conditions sometimes have a significant effect on possibility of entrance and departure of these ships to or from ports. Shahid Rajaee Port Complex, Iran's largest container seaport and the case study of this research, located at northern coast of Persian Gulf and has low water depth in its area. Historical data of seaside operations in this port is applied to the proposed model. This model also takes into account the variations of water depth in different berths. Simultaneous programming for two or more container terminals and exertion of priority and precedency coefficients based on vessel size and voyage type altogether are other attributes of this model. Here, genetic algorithm in combination with pattern search algorithm was used for solving the problem. Computational experiments have indicated that the proposed heuristic is relatively effective just for small size instances.

Keywords: *Berth allocation, Container terminal, Seaport management, Tidal constraints, Mathematical programming, Genetic algorithm.*

1. Introduction

One of the consequences of economic globalization and increasing world trade is the growing volumes of discharge and loading operations at marine container terminals. Iran as a developing economy has a strategic plan for the development of its maritime transportation capacity. Due to the development plan of Shahid Rajaee Port, Iran's largest container seaport, total throughput increases from 3 million up to 6 million TEU per year. Therefore, due to development of new generations of container ships, further increase in the traffic and size of container vessels calling the port is predictable. Because of low water depth in the northern coast of Persian Gulf, tidal influence on the berth allocation planning at this port is so significant.

This paper deals with the formulation and solve of the berth allocation problem considering tidal constraints.

The model proposed here, will discuss optimization of berth allocation for container vessels, in a short term planning horizon (operational planning). For designing this model, furnishing a new formulation for the purpose of conforming with real needs and limitations been in sight and formulation of the model completed have been proceeded to solve the problem by genetic algorithm. Distinctions, innovations and attributes of this model will be introduced later on:

- Dynamic berth allocation

This qualification will promote service rendering from the viewpoint of those who involved in and / or benefit from port operation (ship owners) and also more conformation to the reality will possible. In this way, some of waiting times will be saved and increase of vessel speed which concludes to bunker consumption is not necessary anymore.

- Continuous berth allocation

This specific attribute is effective to increase utilization rate of the quay and avoids idle times of the resources. Therefore, the model has enhancing eligibility, from the viewpoint of service providers (i.e. Port authorities and operators).

- Considering the variations of water depth in different berths

Considering non-uniform water depth in existing berths

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of a container terminal, therefore inclusion of this point for formulating the problem have impact on practicability of the model outcomes. In this paper, the term Berth implies to a continuous length of the quay that has the uniform water depth along itself. Hence, the model conformation with external actuality will improve.

- Simultaneous programming for two or more container terminals

On the basis of this attribute, the berth allocation problem in case of separate quays is solved concurrently and optimum position of allocation for each vessel is searchable amid all available spaces (some being separated). It is obvious that efficacy of this case is subject to alike container terminal owners.

- Determination and exertion of priority coefficients for vessels per capacity

By this arrangement, burden of waiting times on container ships present at anchorage area is weighted and modified with observing importance and value of the vessels. This matter increase results eligibility from the viewpoint of port users and service providers. In this method, larger vessels (based on ship capacity in TEU) will burden less waiting times, which may have a significant effect on port marketing as well.

- Possibility for precedency of vessels based on voyage type

With these means, imposing waiting times on container vessels at anchorage with observation of voyage type of each vessel and with discern of the port authorities is weighted and improved. In another words, port authority could apply more importance in service priority for liner ships (that are valuable and habitual port users) than to feeder ships.

- Continuous programming in consecutive time horizons

As a result, possibility for conveyance of remaining vessels from former planning horizon to later (next) planning horizon is provided. Therefore, unified programming in time length is being possible and practically, no time will be elapsed without being programmed.

- Considering the fluctuations of water level in the access channel due to tidal effects

In some container ports, low water depth in coastal area causes many restrictions on providing vessel's services. Therefore, berth allocation planning for relatively large vessels (with high draft) is subject to tidal conditions when the vessels are in the access channel as from anchorage area to the quay. Considering the fluctuations of water level in the access channel due to tidal effects implies to the checking of entrance and departure times of vessels to / from the port in compliance with the tidal conditions. In this method, instead of estimating the average handling time of the vessels, estimated time required is minimal handling time of the vessels. Thus, negative effects of documentary processes and interruptions in the pilotage and towage operations are ignored. In spite of results being obtained from the model, apparently, have less qualification and increases waiting times, but in quid pro quo conformation of the model with reality and execution of the solutions is practically possible.

2. Literature Review

Berth allocation problems could be formulated as different combinatorial optimization problems according to the specific attributes, objectives and constraints that have to be considered.

The continuous static BAP has been introduced by Li et al., (1998) [1]. “Multiple-job-on-one-processor” scheduling problem is the motivation of this model formulation. This allows adapting the First-Fit-Decreasing heuristic, well-known from Bin Packing, for minimizing the maximum port time among the vessels. Then, the suggestion of minimizing total weighted port time of vessels for this type of problem and furnish a priority rule based heuristic has been presented by Guan et al., (2002) [2].

Berth allocation problem has been shown to be an *N P*-hard problem by relating it to the set partitioning problem (Lim, 1998, [3]), the single machine scheduling problem with release dates (Hansen and Oguz, 2003 [4]), and the two dimensional cutting stock problem (Imai et al., 2005 [5]).

BAP as a restricted form of the two-dimensional packing problem is formulated and a graph theoretical representation is explored (Lim, 1998, [3]). NP-completeness of this specific berth allocation problem is shown for this reformulation. An effective heuristic algorithm for solving the problem is proposed and applied to historical test data.

Nishimura et al., (2001), [6] focus on the dynamic berth allocation problem for ships in the public berth system (not especially container ports). A heuristic procedure, based on a genetic algorithm (GA) is developed.

Similar to Nishimura et al., (2001), [6], Imai et al., (2001), [7] study berth allocation problem using a heuristic procedure, which is based on a mixed-integer programming (MIP) formulation of static and dynamic versions of the problem and its Lagrangian relaxation. The same authors develop a GA-based heuristic procedure for solving the nonlinear berth allocation problem for vessels with different service priorities (Imai et al., 2003, [8]). Imai et al., (1997), [9] relate berth allocation to machine scheduling problems and discuss a bi-objective nonlinear optimization problem with consideration of ship waiting times and terminal utilization.

The continuous berth allocation problem with handling times depending on berthing positions is studied by Imai et al., (2005), [5]. The authors propose a heuristic solution method which solves a discrete BAP first and then improves the obtained solution by shifting vessels along the quay as allowed in the continuous BAP.

Barros et al., (2011), [10] develop and analyze a berth allocation model with introducing tidal time windows (i.e., time periods with high tide), where ships can be served by the quay only during those time windows. This model focuses on tidal bulk ports and marine container terminal (MCT) management is not matter of the paper.

Xu et al., (2012), [11] propose a discrete berth allocation model for container terminals in which the assignment of vessels to berths is limited by water depth and tidal condition. In this model, the time horizon is divided into two periods for low-water and high-water conditions and the processing sets in these two periods are different.

As the literature shows, consideration of tidal effects on the berth allocation planning in MCTs has little history. While some of the papers mentioned above have focused on continuous berth allocation and some of new papers considered tidal effects in their planning, none of them have contemplated both of the continuousness and tidal conditions in a mathematical model. In this paper, continuous BAP in conjunction with the exertion of detailed and accurate tidal data and without categorization of tidal conditions into two or more classes has been considered.

3. Mathematical Model

In this section, mathematical programming of the berth allocation problem in its continuous and dynamic formation will be presented. First, proposed notation and the model's input data are introduced. Then, the suggested formulation and its necessary explanations are provided.

3.1. Notation and input data

In this part, for smooth treatment leading to an accurate understanding of complex nature of the problem, have proceeded with edit of icons set. In continuation, we have provided explanations in regard to the concept and necessity of these icons.

Table 1 Different sets used in the model

Icon	Explanations
SAVIC	Set of All Vessels in the Initial Conditions {M}
SAVAF	Set of All Vessels Arriving in the Future {N}
SAVPH	Set of All Vessels in the Planning Horizon {M+N}
SABQB	Set of All Berths in the Quay Boundaries {K}

Table 1 displays the icons of different sets used in the model. The first set consists of M members, second one consists of N members and third set consists of M+N members. Also, Set of All Berths in the Quay Boundaries includes K members and encompasses descriptions of existing berth places.

Table 2 Key times

Icon	Unit	Explanations
T_i^E	(Date & Time)	Estimated Time of Arrival for Ship S_i {for $\forall S_i \in$ SAVAF}
T_i^B	(Date & Time)	Berthing Time of Ship S_i {for $\forall S_i \in$ SAVPH}
T_i^U	(Date & Time)	Unberthing Time of Ship S_i {for $\forall S_i \in$ SAVPH}

Table 2 displays the icons of key times used in the model. Albeit, ultimately in giving data to the model these times are fig used as per their difference with onset moment of planning horizon, but have to notice that in this case a particular moment of planning is mentioned and not to a period of time. At the T_i^B, vessel i occupies the berth and relevant quay space and at the T_i^U, the vessel i will leave and vacate the space of the relevant berth. In another words, time of vacating the berth is the same as unberthing for the purpose of departure from port. Here, have to bear in mind that clearance times for all vessels (even those that at the outset of planning horizon are berthed) have to be determined.

Table 3 Times length

Icon	Unit	Explanations
H_i	(Hour)	Handling Time of Ship S_i {for $\forall S_i \in$ SAVAF}
R_i	(Hour)	Remain Time of Ship S_i {for $\forall S_i \in$ SAVIC}

Table 3 displays the icons of times length. This table includes vessels data of time nature and per hour. H_i is each *SAVAF* vessel's handling time which is per estimated time for discharge and loading of the particular vessel plus time of crane deployment on the vessel and the time evacuating and unberthing of the vessel from berth will be predicted. Length of handling time means time operation length plus times consumed pre and post of that, which the case relates to time length for allocation and deployment of quay cranes (QCs) on the vessel and beginning of the operation. The second case turns out from vessel's waiting for preparation and assigning sufficient number of tugs to start departure pilotage toward out of the port boundary. Time length of discharge and loading is a respective function of "discharge and loading operation workload" and "average of working QCs deployed on the vessel".

As mentioned earlier in this paper, rather than based on a historical data estimates of handling time per vessel, obtained low estimates of handling time is used. This approach is complementary to the idea of checking the tidal conditions in the access channel and, in addition, the effects of disturbances in documentary processes and fluctuations in the QCs set up times and pilotage and towage operations are ignored. Such disturbances in the historical data of Shahid Rajaee Port are abundant and could be destructive to the planning quality. According to **Fig. 1**, the handling time of each vessel includes times needed for inward clearance, outward clearance and discharge and loading operations.

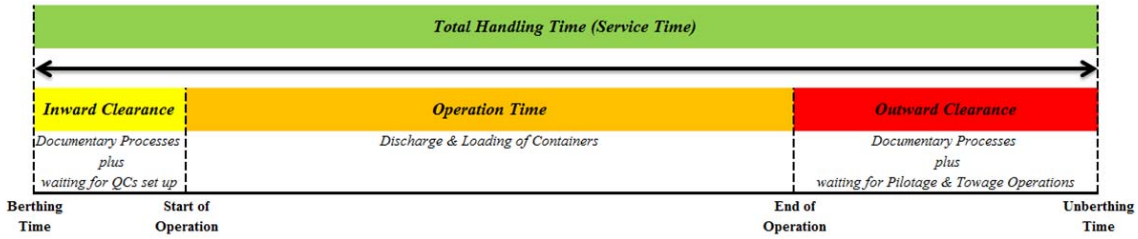

Fig. 1 Total handling time of a containership consists of 3 items

According to the estimations of Shaihd Rajaee Port's executives, times needed for inward and outward clearances in the normal conditions of port and ships are 30 and 60 minutes, respectively. In addition, with considering the assignment of more QCs to larger ships at this port, the following formula is used for estimation of discharge and loading operation time:

$$Operation\ Time\ (Hour) = \frac{3.54 * Total\ Operation\ (Box)}{Vessel\ Length\ (Meter)} \quad (1)$$

Therefore, handling time was assumed 1.5 hours more than operation time.

Fig. 1. Total handling time of a containership consists of 3 items

R_i also is the remained time of each *SAVIC* vessel that in fact is the handling time remaining of the vessel from former planning horizon. In order to update the model and its conformity with reality, it is assumed that the outset moment of each horizon (whatever the time is) been part of port operation and efficiency of the model and utilization rate of the quay is subject to non-stop programming. Therefore, always some of vessels of former horizon are at the berth and have to include them in later planning horizon. It is assumed that handling time of this group of vessels being already computed and determined, where indicating how long of there is remained to complete their operation.

Table 4 Auxiliary variables

Icon	Unit	Explanations
T	(Hour)	$t \geq 0$
P	(Meter)	$p \in [0, L_E^Q]$ {for $\forall S_i \in$ SAVPH}
δ_i^K		$\delta_i^K \in \{0,1\}$ {for $\forall S_i \in$ SAVAF}
η_i^t		$\eta_i^t \in \{0,1\}$ {for $\forall S_i \in$ SAVAF}
ν_i^t		$\nu_i^t \in \{0,1\}$ {for $\forall S_i \in$ SAVIC}

Table 4 displays icons of auxiliary variables. These icons include variables relating to model's endogenous computations. Parameter "*t*" indicates appropriated time of any decision making which is per hour with time length being more than or equal to zero. Parameter "*p*" is the location fixed for a vessel. δ_i^K is an auxiliary variable of zero-one type which indicates status of berth *K* whether being (completely or partially) occupied by the vessel *i* as a member of *SAVAF*, or not. η_i^t is also an auxiliary variable of zero-one type which indicates whether arrival or departure time of the vessel *i* as a member of *SAVAF* will be on time *t*, or not. ν_i^t is similar to η_i^t and represents the same features for vessel *i* as a member of *SAVIC* set.

Table 5 Input variables for SAVIC

Icon	Unit	Explanations
S_i	(Ship)	$\forall S_i \in$ SAVIC {M}
L_i	(Meter)	Length of Ship S_i
D_i	(Meter)	Draft of Ship S_i
P_i	(Meter)	Position of Ship S_i in the Quay
R_i	(Hour)	Remain Time of Ship S_i

Table 5 displays icons of input variables for *SAVIC*. S_i refers to each vessel as a decision making unit. L_i is vessel's length per meter. D_i is needed draft depth for the vessel per meter. P_i is allocated position of each vessel at quay per meter and is measured from one of the quay's boundaries. R_i is minimal remaining time for vessel's staying per hour. When this time passed, the vessel will be piloted to outer port limit if all situations allow sailing out through access channel.

Table 6 Input variables for SAVAF

Icon	Unit	Explanations
S_i	(Ship)	$\forall S_i \in$ SAVAF {N}
L_i	(Meter)	Length of Ship S_i
D_i	(Meter)	Draft of Ship S_i
H_i	(Hour)	Handling Time of Ship S_i
T_i^E	(Date & Time)	Estimated Time of Arrival for Ship S_i
W_i	(Coefficient)	Weighted Precedency of Ship S_i
V_i	(Coefficient)	Voyage Type of Ship S_i

Table 6 displays icons of input variables for *SAVAF*. S_i and L_i are representing the same features discussed before in the previous table. D_i is needed draft depth for the vessel per meter, and H_i is the vessel's handling time per hour. T_i^E is the estimated time of arrival for vessel *i*. This variable is of “date and time” type and normally is used in dynamic BAP models as the base for vessel’s planning in port operations. W_i is for prioritizing vessel *i*. This coefficient states importance degree of each vessel per her size (capacity in TEU), which is computable given vessels time charter (T/C) hire rate ($/Day). In this case, importance of each vessel is prioritized with appropriate monetary value that equals to one day vessel’s idle waiting time.

Table 7. Estimation of W_i coefficients

Size (capacity in TEU)		Relative Weight
From	**To**	**based on TC Rate ($/Day)**
200	399	1
400	649	1.12
650	899	1.38
900	1299	1.81
1300	1999	2.16
2000	2999	2.61
3000	3949	3.05
3950	5199	3.95

Table 7 shows estimation of W_i coefficients computed based on Maersk Broker Container Market-Weekly Report, (2012), [12]. Average container T/C rates from January 2011 to August 2012 were considered in this estimation. V_i is the coefficient for voyage type of vessel *i* which here for feeders is posited as 1 and determination of the same for liner vessels will be left for container terminal operator. In this way, container terminal operators in ports, by applying changes in these coefficients will be functional to demonstrate the importance value of liner vessels above feeder vessels. In the inputs given to the model, rate of this coefficient for liner vessels is assumed as 1.2, but their final determination is definitely ascribed to the port management.

Table 8 Input variables of resource characteristics

Icon	Unit	Explanations
P_k^B	(Meter)	Final Position of Berth k in the Quay {K+1}
L_S^Q	(Meter)	Separation Length of the Quay
L_E^Q	(Meter)	End Length of the Quay
DE_k^Q	(Meter)	Depth of Quay in the Berth k {K}
DE_{AC}	(Meter)	Depth of the Access Channel
ΔD_t	(Meter)	Variations in the Tidal Levels at Time t

Table 8 displays icons of input variables related to existing resources and facilities. P_k^B indicates the cut-off position of berth *K* in the quay per meter (*K* is the number of *SABQB* members). P_k^B have to be entered respectively for consecutive berths and for berth 0 (dummy), 0 is considered. L_S^Q states separation boundary of each quay per meter. If the entire of supplied quay consists of several separated and apart quays of each other, should enter this parameter. L_E^Q indicates cut-off position of the quay per meter. DE_k^Q presents information about quay depth in different locations (*K* input items). Due to the segmentation accomplished by Shahid Rajaee Port authorities, quay no. 1 and quay no. 2 are composed of 4 and 3 berths, respectively which length and data of each of these 7 berths are available. But with assumption illustrated in this paper for the term Berth, may state that Quay no. 1 of 3 berths and quay no. 2 of 1 berth are consisted. DE_{AC} states minimum depth of access channel as from anchorage area to the quay. This access channel is used in arrival and departure of vessels. ΔD_t states fluctuations and changes in level and depth of water ensued by tidal effects and it is assumed as a variable related to time. Data relevant to tidal effects at any time and fluctuations of water level at geographical position under study (Shahid Rajaee Port) per date and time (with accuracy of every 5 minutes) from an exterior Data Bank enters to the model. Department of Hydrography of The National Cartographic Center of Iran, (2012), [13] provides this data on its website. Table 9 shows input data of the existing resources and facilities.

Table 9 Input data of the existing resources and facilities

MCT Name	Berth No.	Length (Meter)	Draught (Meter)
1	1	240	12
1	2	480	12.5
1	3	220	11.7
2	4	850	16

Outputs of the optimization model are different from *SAVIC* to *SAVAF*. For *M SAVIC* vessels, only unberthing times are treated ($T_i^U\{for\ \forall S_i \in SAVIC\}$). But for *N SAVAF* vessels, berthing times ($T_i^B\{for\ \forall S_i \in SAVAF\}$), unberthing times ($T_i^U\{for\ \forall S_i \in SAVAF\}$) and berthing positions ($P_i\{for\ \forall S_i \in SAVAF\}$) will be figured in the solution.

3.2. Problem formulation

In this part, descriptions of the proposed BAP formulation with tidal constraints are presented.

Table 10 Proposed BAP formulation with tidal constraints

No.	Equation	Extent
(2)	$\text{Minimize } Z = \sum_{i=1}^{N} W_i V_i (T_i^U - T_i^E) + \sum_{j=1}^{M} (T_j^U - R_j)$	$\{\text{for } \forall S_i \in SAVAF \;\&\; \forall S_j \in SAVIC\}$
	Subject to:	
(3)	$T_i^E \leq T_i^B$	$\{\text{for } \forall\ S_i \in SAVAF\}$

(4)	$H_i \le T_i^U - T_i^B$	$\{\text{for } \forall\ S_i \in SAVAF\}$
(5)	$R_i \le T_i^U - T_i^B$	$\{\text{for } \forall\ S_i \in SAVIC\}$
(6)	$P_i + L_i \le L_E^Q$	$\{\text{for } \forall\ S_i \in SAVAF\}$
(7)	$\text{if } P_i < L_S^Q \rightarrow P_i + L_i \le L_S^Q$	$\{\text{for } \forall\ S_i \in SAVAF\}$
(8)	$\text{if } T_i^B \le T_j^B < T_i^U \rightarrow P_j - P_i \ge L_i \text{ or } P_i - P_j \ge L_j$	$\{\text{for } \forall\ S_i, S_j (i \ne j) \in SAVPH\}$
(9)	$\text{if } P_{K-1}^B \le \left(P_i \text{ or } \left(\frac{P_i + L_i}{2}\right) \text{ or } (P_i + L_i)\right) < P_K^B \rightarrow \delta_i^K = 1;\ \text{Otherwise } \delta_i^K = 0$	$\{\text{for } \forall\ S_i \in SAVAF\ \&\ K \in SABQB\}$
(10)	$D_i \le DE_K^Q$	$\{\text{for } \forall S_i \in SAVAF\ \&\ \forall \delta_i^K = 1\}$
(11)	$\text{if } t = T_i^B \text{ or } T_i^U \rightarrow \eta_i^t = 1;\ \text{Otherwise } \eta_i^t = 0$	$\{\text{for } \forall\ S_i \in SAVAF\}$
(12)	$D_i \le DE_{AC} + \Delta D_t$	$\{\text{for } \forall S_i \in SAVAF\ \&\ \forall \eta_i^t = 1\}$
(13)	$\text{if } t = T_i^U \rightarrow \nu_i^t = 1;\ \text{Otherwise } \nu_i^t = 0$	$\{\text{for } \forall\ S_i \in SAVIC\}$
(14)	$D_i \le DE_{AC} + \Delta D_t$	$\{\text{for } \forall S_i \in SAVIC\ \&\ \forall \nu_i^t = 1\}$
(15)	$T_i^B = 0$	$\{\text{for } \forall\ S_i \in SAVIC\}$
(16)	$P_0^B = 0$	
(17)	$T_i^E,\ T_i^B,\ T_i^U,\ W_i,\ V_i,\ H_i,\ R_i,\ t,\ P_i,\ L_i,\ D_i,\ \Delta D_t,\ DE_{AC},\ DE_K^Q,\ P_K^B,\ L_E^Q,\ L_S^Q \ge 0$	
(18)	$\delta_i^K, \eta_i^t, \nu_i^t \in \{0,1\}$	

Table 10 shows proposed BAP formulation. Equation (2) is the problem's objective function of minimizing type. First term of this objective function is computing sum of the weighted times between "vessel's estimated time of arrival" and "unberthing from the quay" for all members of the *SAVAF* set. In this term, application of prioritizing coefficients and voyage type coefficients are included for weighting of vessels waiting times. But in the second term of objective function, sum of total times between "least remaining time for vessel's stay" and "unberthing from the quay" for all members of the *SAVIC* set is calculated. This means that the *SAVIC* vessels have to leave the quay at the first viable opportunity.

Equations (3) to (5) are limitations relating to berthing time and restraints of unberthing from the quay. Equation (3) states that berthing time should be following to accomplishing estimation of vessel's arrival time as a member of *SAVAF* set. Pursuant to Equation (4), the least necessary time for vessel to stay at quay (difference between berthing and unberthing times) is equal to each vessel handling time as a member of *SAVAF* set. And though, according to Equation (5), each vessel being a member of *SAVIC* have to have least spare time, as much as "least remaining of allowed time to stay at quay" up to the moment of evacuating the quay.

Equations (6) and (7) are relating to not to contravention boundaries of quay separation, and also non-infringement of the quay cut-off. Equation (6) indicates that sum of length and position of each vessel as a member of *SAVAF* should be less than the cut-off boundary of the quay. Also, by equation (7) if the position of vessel as a member of *SAVAF* set is ahead of boundary of separation, then sum of length and position of that vessel should not exceeds the separation boundary. In this way, the possibility for simultaneous berth allocation programming for MCTs (Marine Container Terminals) 1 and 2 will be viable. Therefore, can to search for most appropriate position of berth allocation for each vessel, concurrently in both MCTs.

Equation (8) illustrates limitation of vessels overlapping in the Time-Space chart. According to this equation, if two vessels of *SAVPH* set faces overlapping with each other, have to obstruct their positional overlapping.

Equations (9) and (10) describe limitations relating with draught of berths. According to these equations if initial, median or ending positions of a vessel of *SAVAF* set stands within boundaries of a particular berth, then have to control for that depth of draft of the vessel to be less than draught of that particular berth. Reason for checking 3 initial, median and ending positions of each vessel is because length of some of largest vessels can be more than length of shortest berths, but mentioned vessel's length is not more than length of two adjacent berths.

Equations (11) to (14) examine limitations relating to tidal effects on depth of access channel. According to Equations (11) and (12), at the berthing time and unberthing time of a *SAVAF* vessel have to control that draft of the vessel have to be less than draught of access channel at that particular moment. Also based on equations (13) and (14), at the unberthing time of a *SAVIC* vessel have to make sure that draft of the vessel to be less than depth of water in access channel.

Equation (15) states that for all *SAVIC* vessels which from the outset of planning horizon are staying at the quay, 0 is inserted as berthing time. Also, in equation (16) cut-off position of the dummy berth (no. 0) puts 0, so the equation (9) will be always correct. Equations (17) and (18) state that all decision variables presented in this formulation been either more than or equal to zero and three decision variables of zero-one type are also applied in formulating the problem.

4. Computational Experiments

For the sake of smoother impelling of the problem towards problem solving, in continuation details of presupposition in the model and in the method of problem solving are presented. In the developed model, vessel's estimated time of arrival is the basis of programming and handling time of each vessel been obtained in accordance with explanations presented in **Section 3.1.** Based on historical data of seaside operations in the Shahid Rajaee Port, different time slices have been selected. Also, accurate and detailed tidal data for any date and time in this case study is provided from the website of Department of Hydrography of The National Cartographic Center of Iran.

The problem is employed designation of 9 *SAVAF* vessels berthing and been assumed that in the preliminary state 7 *SAVIC* vessels are during operations of loading, unloading and service proving. Arrival time of the first ship is the base and others are stated per comparative delay hours. Input length of each vessel is assumed to be 5 % more than its real measure for the reason of providing clearance between ships allocated in the quay.

Since nearing approach of vessels on time axis means delays reduction, obviously the optimized answer of the problem is on frontiers of overlapped binding rectangular. Therefore, for having faster convergence of the solutions tried to start with least penalties and when generations becoming more elite, penalties will be increased. General approach on determination of penalty coefficients in the objective function is so that after production of certain number of the generations, this coefficient will be increased. For designation of these figures, trial and error is applied to gain the final answer in least time.

The main stopping criteria applied in genetic algorithm is when improvement of the objective function is being discontinued and stall generations occurred. Although, for the sake of avoiding from high runtime, the maximum number of generations is restricted too, but usually first criterion is dominant one.

General problem solving process accomplished in the following 7 successive phases, these phases composed of:

1) Determining appropriate conditions of giving inputs to the model;
2) Explaining the characteristics of genetic algorithm;
3) Performing search by the genetic algorithm;
4) Switching to the pattern search algorithm;
5) Discovering the minimized objective function and optimized berth allocation to the ships;
6) Final checking on satisfaction of restrictions which are applied by imposing penalty; and
7) Graphic illustration of the obtained optimal solution.

After accomplishing optimization by Genetic Algorithm (GA), another optimization method will be run that in this case Pattern Search has been selected. Pattern search uses numerical but non-differential methods for finding final solution. This method is very adequate and smooth to reach to a solution close to the local minimum solution and in the meantime have complete coincidence with restrictions of the problem. Stopping criterion in pattern search is size of the meshing.

It is necessary to explain that solving the problem of two quays (one with 940 meter length and the other with length of 850 meter) is considered. Here must be mentioned that according to one of model's constraints, no vessel can berth in the space between two quays, because two quays are practically apart.

As already mentioned, a function titled as “genetic algorithm objective function” is defined. This objective function includes “calculating of main problem's objective function” and additionally “calculation of applied penalty values for some restrictions”.

Length and handling time of each vessel is modeled as a rectangular in the time-space diagram. As been explained before, here for calculation of vessel’s overlapping penalty function at first have to determine overlapping area. Then total of these areas are computed and of course overlapping of each vessel with itself finally will be deleted.

The same method that has been used for interference between the vessels will be used for computation of draught constraint of the berths too. The only difference is that in this time, length and width of rectangular of the problem are those length and depth needed by vessel or quay.

For each rectangular coordinates of one of its points and also the length and width are known. Therefore, calculation of every corner's coordinates will be possible. Then have to express these points in a matrix formation. Consequently for calculation of vessel’s overlapping penalty function, just computing one to one overlap of all matrixes is needed.

For vessels which have limitation with respect to water depth of the access channel, needed draft for the vessel at entering time will be compared with draft of access channel been impacted by tidal effects and in case of any discrepancy, another penalty function will be applied. Also the same survey will be carried on designated outward moment, with this difference that in this state if discrepancy exists will compute vessel’s waiting time until level of water reaches to needed level and duration of said time will be added to the vessels stay time.

Fig. 2 represents the flowchart of successive application of Genetic Algorithm (GA) and Pattern Search Algorithm for solving the model. In completion of this chart, the flowchart of “evaluation of cost for all individuals in the population” is presented in the Fig. 3.

In continuation of this paper, an instance of model's results will be presented. Input data of this specific instance based on historical data of seaside operations at Shahid Rajaee Port Complex as the case study of this research is provided in Table 11 Minimum water depth in the access channel of this port is equal to 12.5 meters. This measure implies to the water depth in low water condition due to tidal effects.

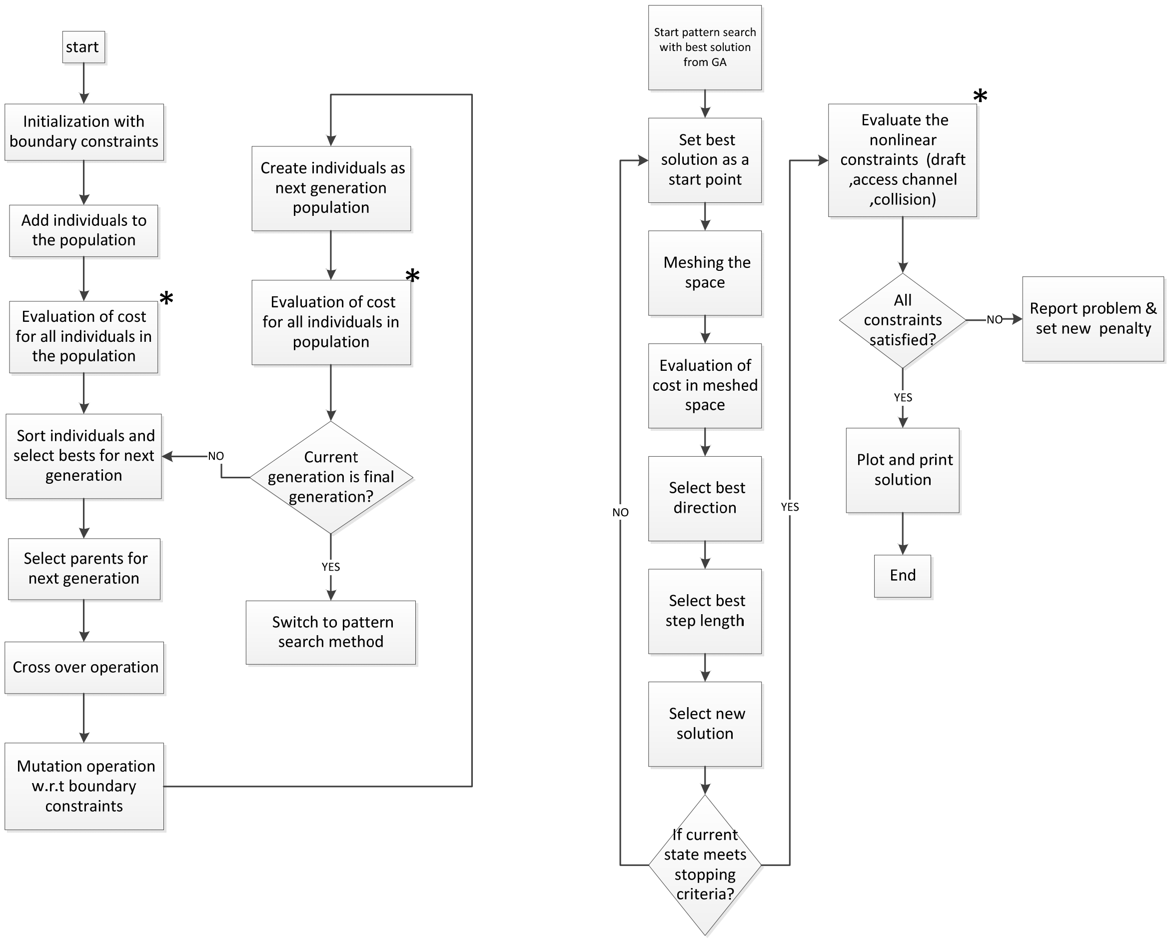

Fig. 2 Flowchart of successive application of Genetic Algorithm (GA) and Pattern Search Algorithm

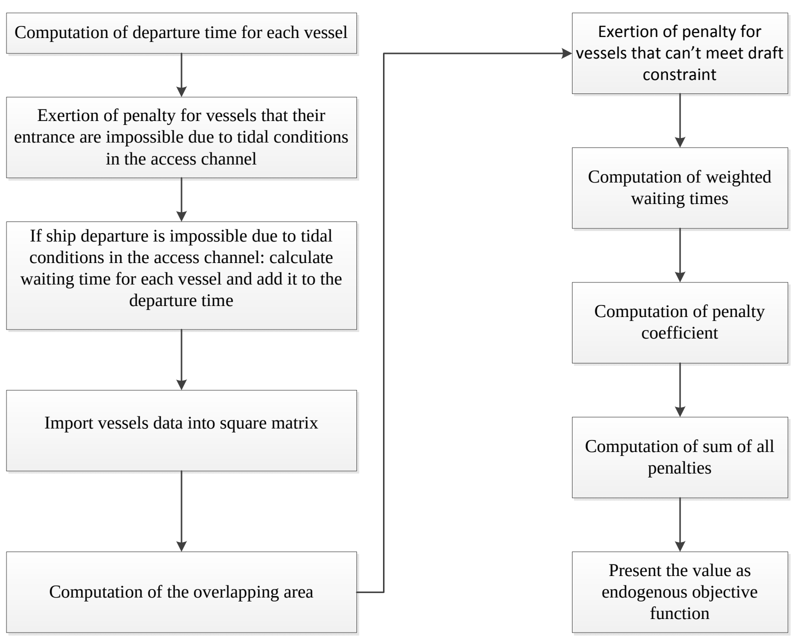

Fig. 3 Flowchart of evaluation of cost for all individuals in the population

Table 11 Input data of the model based on historical data of seaside operations at the case study

Length	Draft	Wi	Vi	Arrival Time	Handling Time	ETA
(Meter)	(Meter)			(Hour)	(Hour)	Date & Time
70	5.7	1	1.2	0	8.6	2010-01-10 08:30:00
186	8.8	2.61	1.2	1.75	18.1	2010-01-10 10:15:00
179	8.4	2.61	1	4.83	14.25	2010-01-10 13:20:00
282	13.3	3.95	1.2	15.4	32	2010-01-10 23:54:00
163	8.1	2.61	1	16.5	22.22	2010-01-11 01:00:00
181	8.6	2.61	1.2	17.75	4.48	2010-01-11 02:15:00
252	5.5	1	1.2	25	14.6	2010-01-11 09:30:00
273	12.8	3.95	1.2	27.43	29.5	2010-01-11 11:56:00
155	7.3	2.16	1.2	28.08	14.82	2010-01-11 12:35:00

Fig. 4 and Fig. 5 show convergence of endogenous objective function of the model in progress of new generations. In this charts, effect of penalty function's exertion can be viewed simply. Fig. 4 displays the value of objective function for best individuals found and Fig. 5 shows this value for average of all population at any stage.

Finally, Fig. 6. Displays the time-space diagram of best answer found for berth allocation problem. Horizontal and vertical axes represent time (per hour) and quay length (per kilometer). The assignment of ships S3, S5, S6 and S7 are located in quay no. 1. On the other hand, ships S1, S2, S4, S8 and S9 are allocated in quay no. 2. Time order of berth allocation to the vessels is S1, S3, S2, S5, S6, S4, S7, S9 and S8 respectively. In this diagram, S0 represents all *SAVIC* vessels in addition to the boundary between two quays.

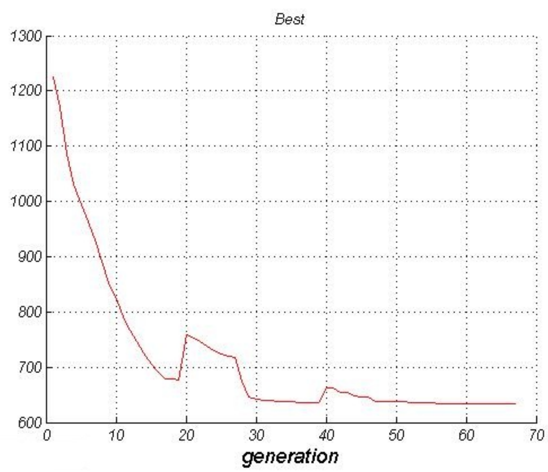

Fig. 4 Convergence of endogenous objective function for best individuals found

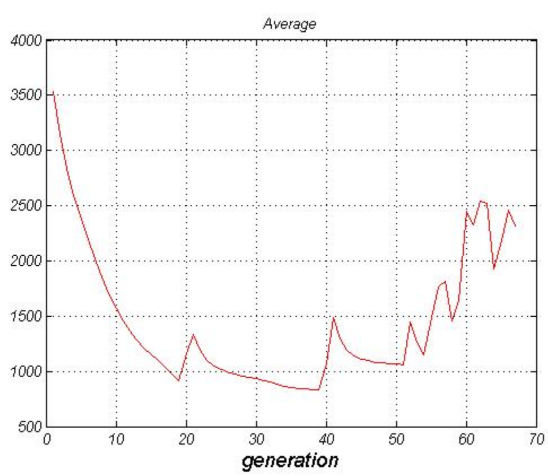

Fig. 5 Convergence of endogenous objective function for average of all population

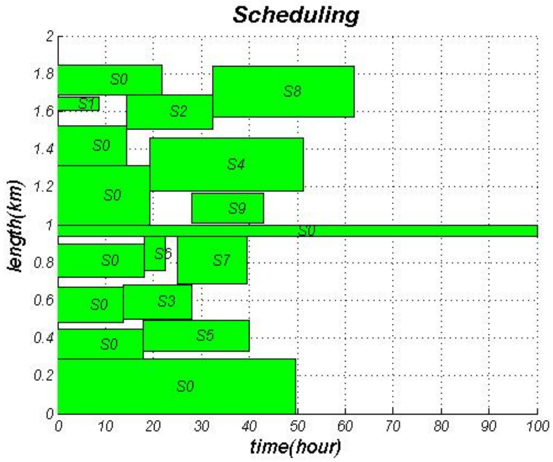

Fig. 6 Time-space diagram of best answer found for berth allocation problem

5. Conclusions

In this paper we have provided a continuous dynamic berth allocation model with consideration of tidal constraints in the access channel as from anchorage area to the quay. In some seaports like Shahid Rajaee Port, Iran's largest container seaport, restricted water depth in the access channel has serious effects on seaside operations. Relatively large vessels with high draft usually have various problems with this issue. Occurrence of long waiting times when ships are arrived or have to departure the port has significant effect on preplanning of port operations to the extent that practically this programming may become inefficient or useless. Taking into account that dredging operations impose costly and time-consuming options to ports, considering tidal influences on the BAP obviously will improve conformity of final solution of the model with external reality.

This model also takes into account the variations of water depth in different berths. Simultaneous programming for two or more container terminals is one of the other attributes of this proposed model. Exertion of priority and precedency coefficients based on vessel size and voyage type can also improve results from the viewpoint of port users and will help port marketing as well.

Nonetheless, our current model still has some limitations. Here, genetic algorithm (GA) as a customary method for the BAP in combination with pattern search algorithm was used for solving the formulated problem. Computational experiments have indicated that the proposed heuristic is relatively effective just for small size instances. Of course, in the future more efficient heuristics can be developed to solve this problem. Conducting computational studies to compare the efficiency of those proposed algorithms is guidance for future researches.

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