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BERTH ALLOCATION PROBLEM: FORMULATION AND A TUNISIAN CASE STUDY

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Abstract:

This paper examines one of the most important operational problems in seaport terminals, namely the Berth Allocation Problem (BAP) which finds an optimal assignment of ships to the berths that minimize the total waiting time of all ships and reduce congestion in ports. Our problem is to affect and schedule n ships on m berths to minimize the processing time and the waiting time for all the ships in the port. Therefore, ships stay time in the port known by the flow time, while respecting the physical constraints existing at the port (such as the depth of the water berth and the draft of the ship's water), knowing that each ship can only accommodate one ship at a time. It is as if it was a case of n tasks and m machines in parallel, and we wanted to schedule the passage of different tasks on different machines, knowing that each task can only pass on one machine and that the interruption of the task is not allowed. For example, if a job started on a machine, it will remain on this machine up to its completion. In our case, tasks are ships and machines are berths that are opting to minimize the total flow time and, therefore, to decrease the residence time of all the ships in the port. In a first step, a Mixed Integer Linear Program model is designed to address the BAP with the aim of minimizing the flow time of the ships in the port, our sample can be used for both static and dynamic berth allocation cases.

In a second step, this model is illustrated with a real case study in the Tunisian port of Rades and solved by a commercial solver CPLEX. Calculation results are presented and compared with those obtained by port authorities in Radès.

Keywords: *containers terminal, Berth Allocation, flow time, scheduling*

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1. Introduction

Increases in trade by sea, have contributed to substantial increase in traffic on sea lanes and progress in technology has made it possible to build ships having big displacement. More than 80% of the world trade makes use of maritime transport, which has become one of the pillars of international trade, Mironiuk (2015).

Considered as an inter-modal interface in maritime Supply Chain, seaport container terminals play a primary role in maritime transportation. The process begins with a port allocation ship entering the dock where containers will be unloaded by shore cranes and transported by a Straddle Carrier (SC) or Reach Stacker (RS) to the storage area. Thus, this mode of transport changes from maritime to inland. Allocating berths for arriving containers is a key factor in promoting the efficiency of container handling as well as reducing the turnaround time and the congestion of a ship in the port. A practical way of enhancing the efficiency and competitiveness of the container terminals depends on the identification and resolution of several operational problems that usually occur in the port. These optimization problems include

Stowage Planning (Imai et al., 2006, Quay Crane Scheduling Lee, Wang, and Miao, 2008), Yard Truck Scheduling, Yard Crane Scheduling Lee, Cao, and (Meng, 2007), Storage Allocation (Lee et al., 2006) and Berth Allocation (Imai, Nishimura, and Papadimitriou, 2001).

In practice, most ships are unproductive while they are stuck in a port. Accelerating the handling operation and improving the assignment of ships to berths are equally important to reduce the waste of time. Therefore, an efficient berth allocation at the seaport terminal is highly crucial for reducing the time spent by ships in the port and enhancing the competitiveness of ports. Further minimizing ships' stay time and reducing congestion in ports, has become a vital priority for seaport terminals.

It should be noted, that each berth can handle one ship at the same time and that the handling time of a ship depends on the distance between the berth and the storage area. Thus, we must consider the availability of berths and cranes responsible for unloading of the ship.

Due to the importance of choosing the berths, in order to minimize the time spent of the ships in the port and therefore the total flow ; and reduce the congestion of a ship in the port, we have dedicated this paper, to deal with the Berth Allocation Problem (BAP) and this based on a real case in a Tunisian port. (Imai, Nishimura, and Papadimitriou, 2001, Zoubeir and Benabdelhafid, 2014 and Zeinebou and Abdellatif, 2013), which serve as a background for our paper.

This paper examines the BAP with the aim of minimizing ships' stay time in the port. To address these problem, we present a mathematical models solved using CPLEX. The outline of the paper including a review of the literature provided in section 2. In section 3 a description of the BAP and its mathematical model are presented. In section 4, a real-life example from the port of Radès in Tunisia is presented. Finally, concluding remarks and directions for future research are suggested in Section 5.

2. Literature review

The transports between the main centers of the modern world economy, ie Western Europe, North America and Southeast Asia, systematically increase, favors the development of global logistics. The volume of trading increases with all load groups, especially with containerized loads. The large potential of the container market and the changing requirements of shippers cause the consolidation of market entities, including in the sector of shipping companies (Salmonowicz, 2014).

The substantial increase of international trade dependent on maritime transport, and more particularly containerization, has placed the maritime container shipping industry at the centre of the global economy. Consequently, competition between ports has become fiercer with a view to improving the customer service. Chief among the performance measures of customer service, is the berthing time of container carrying ships that accounts for a considerable proportion of its journey (Preston and Kozan, 2001).Shipping lines are mainly concerned with the waiting time and berthing time of the ships at the port. Nevertheless, the docking time for all the ports must be as small as possible to service all the ships efficiently. This will consequently satisfy customer requirements and reduce the costs and congestion in the port as well (Lee et al., 2009).

In order to reduce the overall time spent in the port, it is essential to reduce the time in which the ships stay in the port (known in the Scheduling Theory by

the flow time). This problem is conceptualized in the literature as the Berth Allocation Problem BAP. Thus, the aim is to reach an optimal assignment of ships to the berths.
However, in practice, the BAP consists in assigning all the ships to berths along the dock, but when we assign these ships we must take into consideration some constraints such as the depth of water for ships berthing, the preferred docking area, etc. (Zeinebou and Abdellatif, 2014). Worth mentioning is that the BAP exists in a static version, in which the arrival times of ships are known in advance, and a dynamic version, where ships do not follow a schedule.
The BAP has been thoroughly studied in the literature. Some researchers for example: Imai, Nishimura, and Papadimitriou (2001), Hansen and Oguz (2003), Zeinebou and Abdellatif (2014), Xu, Li, and Leung (2012), Imai, Nishimura, and Papadimitriou (2003), Monaco and Sammarra (2007), Hansen, Oguz, and Mladenovic (2008) and Golias, Boile, and Theofanis (2009) presented the discrete BAP as a platform of a definite set of places. Others Kim and Moon (2003), Guan and Cheung (2004), Imai et al. (2005), Moorthy and Teo (2006) and Lee, Chen, and Cao (2010) argued that ships can dock anywhere on the quay in the continuous BAP.
These researchers, have investigated several techniques in an attempt to find a better solution to the BAP. Many approximate methods have been used, namely Heuristics, Meta-Heuristics and hybridization procedures. For example, Zeinebou and Abdellatif (2014) proposed a mathematical model, to minimize the time spent by the ships in the port and the distance travelled by containers of berth to the storage area. Different meta-heuristics have been used to solve this problem, such as Genetic Algorithm, Simulated Annealing and their Hybridization. Barros et al. (2011) presented a mathematical model addressed to the BAP, and using a Heuristic based on simulated annealing; in their model they take into consideration only the static case of ship in the port (all the ships are present in the port before the scheduling plan). Arango et al. (2011), proposed a mathematical model to resolve the BAP in port of Seville, and developed a Heuristic procedure based on a genetic algorithm to solve a non-linear problem, this model can be applied only on the static case in the port, and they don’t take in their model, the physical constraints of ships and berths. while Zhen et al. (2011), designed a Meta-Heuristic approach to solve a model that decides on uncertainties for the BAP and taking into account the arrival time of ship, but they don’t take into consideration the delay of ships and the availability of berths.
Lai and Shih (1992) proposed heuristic algorithms for a BAP on the assumption of the FCFS (First Come First Served) allocation strategy, but in their model they does not take into account the physical constraints in the port and the residence time of ship is high, according to the principle FIFO (First In First Out).
Vacca et al. (2013), dealt with the simultaneous optimization of berth allocation and quay crane assignment in seaport container terminals. They presented a mathematical model based on an exponential number of variables that is solved using Column generation and an exact branch-and-price algorithm in order to produce optimal integer solutions to the problem, but they not consider in their model the availability time of berth and the waiting time of ships.
Based in work of Zeinebou and Abdellatif (2014), who present a mathematical model for minimizing the time spent by the ship in sea port terminal , we can conclude that their formulation of this problem can only be solved by using a simple known rule called SPT (Shortest Processing Time) method to obtain a solution to BAP, then they use this SPT method for scheduling the sequence and determining the set of service ships orders according to the processing or handling time of the ship on the berth, and they consider that all ships are available for assignment at time zero. While this model allows the reduction of the flow time or the time stay of all ships in port, it is still so limited that it can only be solved by using the SPT method and the Hungarian method. Moreover, they use two mathematical models to reduce the length of ships stay in the port: the first for the static BAP (the arrival times of all vessels are known in advance) and the second for the dynamic BAP (all the ships may come after the start of the scheduled plan).
In practice and in most ports, we can notice that all the ships are serviced using the method on a First Come First Served basis, but this method does not necessarily minimize the total stay time of ships. Our work seeks to minimize the flow time of all the ships in the port. In light of the seminal work of Zeinebou and Abdellatif (2014), we propose in this paper a new formulation for this problem and which

has been applied to a real case in the port of Rades in Tunisia. The BAP model aims to decrease the flow time of all the ships in the port and can be used for both the static and dynamic berth allocation cases where ships' ready time and berths' availability are different from zero, and tacking in consideration same physical constraints such as, the depth of the water in the berth and the length of the ship and the berth.

Compared with that adopted by Zeinebou and Abdellatif (2014), our model has distinct additional characteristics. In fact, our model finds an independent optimal solution for both the BAP static and dynamic in the same time and can be solved without using the SPT or the Hungarian methods. A new formulation of the BAP where the flow time is modelled as a variable is presented, and may be limited by the upper bound (the flow time of each ship must not exceed an upper bound that is defined, if not the ship with the highest processing time will always be assigned the last one on the berth). Also, our model takes into account all the possible cases of the time of availability for the treatment of ship and the time of availability of the berth.

3. Optimal assignment for a Berth Allocation Problem

In this section, we present a mathematical model that is designed to minimize the total flow time of all the ships in the port, and to reduce the waiting time and overall length of stay for all ships in the port. We notice that the BAP is similar to the problem of scheduling *n* tasks on *m* parallel machines. In this case, tasks are ships and machines are berths; thus, it is similar to the problem of scheduling *n* ships on *m* berth.

Lenstra et al. (1977) have shown that the scheduling problem on one machine and *n* tasks with $r_j \neq 0$, (***rj*** is the 'ready time' which corresponds to the date of availability for treatment of ship *j*), considering the objective of minimizing the total flow time is an NP Hard problem in the strong sense. Therefore our problem of scheduling *n* ships on *m* berths is also NP-hard in the strong sense.

Inspired by the work of Zeinebou and Abdellatif (2014) and Imai et al. (2006), we develop a new formulation, that seek to minimize the flow time for the static and the dynamic BAP; respectively. In the mathematical model presented in this section, we consider that both the ready time and availability of ships are different from zero. We notice that this model can solve the static and dynamic versions of BAP at the same time. Zeinebou and Abdellatif (2014) and Imai et al. (2006) provided an efficient formulation of the BAP problem, but they don't put the upper bound on the flow time.

The periodical execution of the BAP model, that minimize the total flow time, may have the consequence that the ships with large processing times remain in the port for a long time. The FCFS policy, which is frequently used rule may have a poor flow time, however it is commonly conceived as a fair used method. Therefore, we propose in this paper a mathematical model that reduces the flow time, while including an upper bound on the ship stay time in the port (flow time). So, by including a guarantee of upper bound on the waiting time and the flow time, we provide a fair solution that represents a compromise between the two extreme approaches.

This mathematical model takes into account the following hypotheses:

- The planning process is considered at the same time as static (SBAP) (the arrival times of all the ships are known in advance) or dynamic (DBAP) (all the ships may come after the start of the scheduled plan).
- Each berth can accommodate only one ship at the same time.
- Each ship can be assigned to only one berth.
- The processing time of the ship remains unchangeable for all berths.
- Physical restrictions on the docks considered here are water depth and berth length.
- When a ship is assigned to a dock post, it will remain there until the end of its stay in the port.

3.1. Notation and model formulation

3.1.1. Parameters

– *The indices used in this model are*:

i : The index of available berths, *i* (= 1…….I) ∈ B

j : The index of entering ships, *j* (=1…..T) ∈ V

k : The index of the service order; in each berth, the number of the service order is equal to the number of Ships, *k* (=1…. T) ∈ O.

– *Sets and parameters used in this model are as follows:*

B: The set of available berths.

V: The set of entering ships.

O: The set of the service order.

P_j: Processing time of ship *j*.

$\boldsymbol{r_j}$**:** Ready time which corresponds to the date of availability for the treatment of ship *j*.

$\boldsymbol{S_i}$: '*Set up /availability'*, which corresponds to the date of availability of the berth *i*.

$\boldsymbol{W_i}$: Depth of the water berth *i*.

$\boldsymbol{E_j}$: Draft of the ship's *j* water.

$\boldsymbol{Q_i}$: Length of berth *i*.

$\boldsymbol{L_j}$: Length of ship *j*.

$\boldsymbol{F_{j\,max}}$**:** Maximum flow time. The flow time of each ship shall not exceed this upper limit.

3.1.2. Decision Variables

$\boldsymbol{F_{ijk}}$: Flow time of ship *j* assigned in berth *i* in order *k*.

$\boldsymbol{X_{ijk}} = 1$ if the ship *j* is assigned to berth *i* in order *k*, 0 otherwise.

$\boldsymbol{C_{ijk}}$: '*Completion time'*, which corresponds to the end date of the execution of the ship *j* on the berth *i* in the order *k*. according to formula:

$$\boldsymbol{C_{ijk}=F_{ijk}+(r_j*X_{ijk})}$$

Then, the mathematical model **G** is outlined as follows:

$$\boldsymbol{G = Min \sum_{i\in B}\sum_{j\in V}\sum_{K\in O} F_{ijk}} \quad (1)$$

$$\sum_{i\in B}\sum_{K\in O} X_{ijk} = 1 \quad ; \forall j \in V \qquad (2)$$

$$\sum_{j\in V} X_{ijk} \le 1 \quad ; \forall i \in B, k \in O \qquad (3)$$

$$F_{ijk} \ge C_{it(k-1)} - (r_j * X_{ijk}) + (P_j * X_{ijk}) \quad ; \forall i \in B, j \in V, k \in O, t \in V \; et \; t \neq j \qquad (4)$$

$$F_{ijk} \ge (P_j * X_{ijk}) \quad ; \forall i \in B, j \in V, k \in O \qquad (5)$$

$$F_{ijk} = C_{ijk} - (r_j * X_{ijk}) \quad ; \forall i \in B, j \in V, k \in O \qquad (6)$$

$$F_{ijk} \le F_{j\,max} \quad ; \forall i \in B, j \in V, k \in O \qquad (7)$$

$$(W_i - E_j)\, X_{ijk} \ge 0 \quad ; \forall i \in B, j \in V, k \in O \qquad (8)$$

$$(Q_i - L_j)\, X_{ijk} \ge 0 \quad ; \forall i \in B, j \in V, k \in O \qquad (9)$$

$$C_{it0} = S_i \quad ; \forall i \in B, t \in V \qquad (10)$$

$$X_{ijk} \in \{0,1\} \quad ; \forall i \in B, j \in V, k \in O \qquad (11)$$

$$F_{ijk} \in \mathbb{R} \quad ; \forall i \in B, j \in V, k \in O \qquad (12)$$

3.2. Objective function and constraints description

- The objective function (1) aims to minimize the processing time and the waiting time for all the ships in the port and, therefore, ships 'stay time in the port.
- Constraint (2) ensures that all ships are served on a berth in a given service order.
- Constraint (3) ensures that each berth can only accommodate one ship at a time (i.e. a dock cannot accommodate two ships or more at the same time. It can only accommodate one single ship).
- Constraint (4) gives the value of the flow time of the ship *j* on the berth *i* according to the order *k*, where $\boldsymbol{C_{it(k-1)}}$ is greater than $\boldsymbol{r_j}$ that is to say the end date of the execution of the ship *t* exceeds the availability date of the ship *j*.
- Constraint (5) gives the value of the flow time of the ship *j* on the berth *i* according to the order *k*, when $\boldsymbol{r_j}$ is greater than $\boldsymbol{C_{it(k-1)}}$ that is to say the beginning date of the execution of the ship *j* exceeds the completion time of the ship *t* ordered in the position *(k-1)*.
- Constraint (6) stands for the relation between the flow time and completion time.
- Constraint (7) gives the upper bound on the flow time.
- Constraint (8) ensures compatibility between the depth of the water and the berth requested by the ship.

– Constraint (9) ensures compatibility between the length of the ship and the berth length.
– Constraint (10) gives the initial value of the completion time $\boldsymbol{C_{it0}}$ and is equal to $\boldsymbol{S_i}$.
– Constraint (11) and (12) defines the decision variables.

4. Case study: Port of Rades in Tunisia

In this section, we propose a solution to the BAP using the mathematical model presented in Section 3.

4.1. Experimental data from the port of Rades

During the data collection period at the port of Rades, we noted that ships were assigned and allocated to berths on the basis of the 'first come, first served' (FCFS) principle. Besides, we managed to collect data during the period between May and December 2016.The number of container ships during this period is provided by the Office of the Merchant Marine and Ports (OMMP) and presented in Table 1.

Table 1. Monthly number of container ships at theport of Rades in 2016 (OMMP)

	Number of ships containers
May	12
June	13
July	10
August	13
September	11
October	12
November	10
December	14

To validate our mathematical model for the assignment and allocation ships to berths on the basis of real data, we selected data from the month of December marked by the largest number of incoming container ships.
The container ships incoming to the port of Rades during the month of December, their characteristics, and arrival dates to the harbor as well as the number of containers and their treatment times at the dockare presented in Table A1 (Appendix A).

The characteristics of the berths reserved for the allocation of container ships, namely water depth and berth length, are presented in Table 2.

Table 2. The Depth of water and the length of berth

Berths	**Water Depth W_i (meters)**	**Berth Length Q_i (meters)**
Berth 1	9.5	150
Berth 2	9.5	150
Berth 3	11	180

It should be noted that 7 berths are reserved in the Port of Rades for incoming ships and only 3 berths for container ships.
In the next section, we will present the results of ships assignments to berths by comparing them to the policy of assigning incoming ships to berths carried out by the OMMP.

4.2. Results and benchmarking

4.2.1. Results of assignment and allocation ships to berths

We start assigning ships to berths on the 01/12/2016. This principle is applied every 10 days taking into account the ships completion time presented by $C_{it0} = S_i$ and the unloading operations of the ships assigned to the docks which have not beencompleted yet. In other words, if some ships can arrive and be served as planned, the problem of allocating berths for a dynamic case would arise.

a) First planning of ship allocation to berths (during the period from 01/12/2016 until 10/12/2016)
The available data on the allocation of the last ships to berths for the month of November are provided by the OMMP and presented in Table 3. Noteworthy is that no ships entered the harbor of the port of Rades on the date 01/12/2016.
Therefore, we will calculate the availability of each berth on the date of 01/12/2016 presented by S_i in Table 4.

Table 3. State of assignment of the last ships on berth in November 2016 (OMMP)

Stopover Number	Consignee	Name of Entering Ship	The Draft Of The Ship E_j (Meters)	The Length Of Ship L_j (Meters)	Arrival Date Of the Ship on the Berth	Processing Time P_j (Hours)	Departure Date Of the Ship On the Berth	Allocation Result On Berths
5907	MAERSK	KMAX MARS	7.1	132.7	28/11/2016 10 :52	77	01/12/2016 15 :10	2
6516	MSC	GRAND	9.5	236	29/11/2016 00 :40	93	02/12/2016 21:00	3
6208	ASA	HENS-AL-LEGRO	8.7	125	30/11/2016 04 :45	2	30/11/2016 06 :45	1

Table 4. Availability of the berth of the date of 01/12/2016

Berths	S_i (hours)
Berth 1	0
Berth 2	15
Berth 3	45

Subsequently, we calculate the availability of each ship to be treated. It is equal to r_j and is calculated starting from the date of 01/12/2016, taking into account the arrival date of the ship in the harbor already presented in Table A1 (Appendix A).
Table 5 introduces the data required for the first planning of allocating ships to berths.

The experimental tests were conducted using a personal computer with 2.2 GHz, core 2 Duo processor and 3 GB of RAM. The Integer Linear Programming solver used is CPLEX 12.2. The following assignment results are obtained in 31.344 seconds:
$X_{131} = 1, X_{162} = 1, X_{221} = 1, X_{272} = 1, X_{311} = 1, X_{352} = 1$ and $X_{343} = 1$.
$F_{131} = 140, F_{162} = 171, F_{221} = 184, F_{272} = 251, F_{311} = 53, F_{352} = 45$ and $F_{343} = 356$.
$C_{131} = 203, C_{162} = 337, C_{221} = 233, C_{272} = 426, C_{311} = 95, C_{352} = 196$ and $C_{343} = 459$.
The objective function is equal to 1200 hours.
The table 6 below summarizes the arrival and departure dates of ships at berths.

Table 5 : Experimental data for the first ship allocation planning to berths on 01/12/2016

Stopover number	Ship number	Consignee	Name of The Entering Ship	Arrival Date of Ships in The Harbor	The draft of the ship's E_j (meters)	The length of the ship's L_j (meters)	Processing time P_j (hours)	Availability for the treatment of ship r_j (hours)
6558	1	CMA	KARINA	02/12/2016 17:30	8.7	122	50	42
6542	2	MSC	REECON EMRE	03/12/2016 00:40	8.9	141	184	49
6537	3	MAERSK	PASSAT	03/12/2016 15:00	8.7	125	140	63
6561	4	MAERSK	AVERA	05/12/2016 07:00	8.7	125	263	103
6552	5	GENMAR	HEINZ SCHEPPERS	07/12/2016 07:00	6.46	96	45	151
6569	6	CMA	NICOLA	07/12/2016 22:00	7.7	122	134	166
6553	7	ASA	ALLEGRO	08/12/2016 07:00	8.7	125	193	175

Table 6. Results of assigning ships to berths for the first planning

Berth Number	Ship Number	Arrival Date Of the Ship at The Harbor	Assignment Date of Ship to the Berth	*Processing Time P_j* (Hours)	Departure Date of Ship From The Berth
1	Ship 3	03/12/2016 15 :00	03/12/2016 15 :00	140	09/12/2016 11 :00
	Ship 6	07/12/2016 22 :00	09/12/216 11 :00	134	15/12/2016 01 :00
2	Ship 2	03/12/2016 00 :40	03/12/2016 00 :40	184	10/12/2016 16 :40
	Ship 7	08/12/2016 07 :00	10/12/2016 16 :40	193	18/12/2016 17 :40
3	Ship 1	02/12/2016 17 :30	02/12/2016 21 :00	50	04/12/2016 23 :00
	Ship 5	07/12/2016 07 :00	07/12/2016 07 :00	45	09/12/2016 04 :00
	Ship 4	05/12/2016 07 :00	09/12/2016 04 :00	263	20/12/2016 03 :00

The last ships assigned to the berths for this planning are ship number 6 on berth 1, ship number 7 on berth 2 and ship number 4 on berth 3. These assignment results will be used to calculate the availability of berths for the second planning.

b) Second planning of ships allocation to berths (during the period from 11/12/2016 until 20/12/2016)

Our second planning covers the period from the 11th to the 20th of December 2016. The calculation of the availability of each berth S_i for this period is based on the allocation of the last ships to the berths in the first allocation plan. The availability times S_i of the berths 1.2 and 3 are presented in Table 7.

Table 7. Availability of the berths $\mathbf{S_i}$ on the 11/12/2016

Berths	S_i (hours)
Berth 1	97
Berth 2	186
Berth 3	219

Then, for each ship, the date of availability for treatment, which is equal to r_j, is calculated starting from the date of 11/12/2016,.The arrival date of the ship in the harbor, which is already presented in Table A1 (Appendix A), is taken into account.

The data required for the second ships allocation planning to berths are provided in Table 8.

Table 8. Experimental data for the second ships allocation planning to berths on 11/12/2016

Stopover Number	Ship Number	Consignee	Name Of Entering Ship	Arrival Date of the Ship on the Harbor	The Draft Of The Ship's E_j (Meters)	The Length Of The Ship's L_j (Meters)	Processing Time P_j (Hours)	Availability For The Treatment Of The Ship r_j (Hours)
6545	1	GREEN T	MAX CAVALIER	13/12/2016 15:40	8.5	141	140	64
6595	2	MSC	GRAND	14/12/2016 00:40	9.6	126	211	73
6575	3	SEAWAVE	JSR CAPILA	15/12/2016 13 :00	7.2	130	32	109
6597	4	MAERSK	JSP SLIDUR	20/12/2016 16:00	8.7	125	129	232

The assignment results obtained in 0.203 seconds are as follows:
$X_{121} = 1$, $X_{211} = 1$, $X_{331} = 1$ and $X_{342} = 1$.
$F_{121} = 235$, $F_{211} = 262$, $F_{331} = 142$ and $F_{342} = 148$.
$C_{121} = 308$, $C_{211} = 326$, $C_{331} = 251$ and $C_{342} = 380$
The objective function is equal to 787 hours.
Below is a table 9 summarizing the arrival and departure dates of the ships to/from berths. These assignment results will be used to calculate the availability of berths for the third planning.

c) Third planning of Ships allocation to berths (during the period from 21/12/2016 until 31/12/2016)

Our third planning covers a time period from 21/12/2016 until 31/12/2016. The calculation of the availability of each berth S_i for this period is based on the allocation of the last ships to the berths in the second allocation plan. The availability times S_i of the berths 1.2 and 3 are given in Table 10.

Table 10. Availability of the berths at the date Of 21/12/2016

Berths	**S_i (hours)**
Berth 1	0
Berth 2	157
Berth 3	140

Thereafter, the date of availability for the treatment of each ship, which is equal to r_j, is calculated starting from the date of 21/12/2016.The arrival date of the ship in the harbor is taken into consideration. These data are already presented in Table 2 (Appendix). Table 11 presents the data required for the third ships allocation planning to berths.

Table 9. Results of assigning ships to berths for the second planning

Berth Number	**Ship Number**	**Arrival Date of the Ship in the Harbor**	**Assignment Date of the Ship to the Berth**	**Processing Time P_j (Hours)**	**Arrival Date Of the Ship to the Berth**
1	Ship 2	14/12/2016 00:40	15/12/2016 01 :00	140	20/12/2016 21 :00
2	Ship 1	13/12/2016 15:40	18/12/2016 17 :40	211	27/12/2016 12 :40
3	Ship 3	15/12/2016 13 :00	20/12/2016 03 :00	32	21/12/2016 11 :00
	Ship 4	20/12/2016 16:00	21/12/2016 11 :00	129	26/12/2016 20 :00

Table 11 *:* Experimental data for the third ships allocation planning to berths on 21/12/2016

Stopover number	**Ship number**	**Consignee**	**Name of Entering Ship**	**Arrival Date of the Ship in the Harbor**	**The draft of the ship's E_j (meters)**	**The length of the ship's L_j (meters)**	**Processing time P_j (hours)**	**Availability for the Treatment of the Ship r_j (Hours)**
6615	1	MAERSK	PASSAT	21/12/2016 08:00	8.7	125	258	8
6610	2	GENMAR	HEINZ SCHEPPERS	21/12/2016 11:06	6.46	96	44	11
6638	3	MSC	MANDO	23/12/2016 00:40	10.1	142	92	49

The assignment results obtained in 0.063 seconds are as follows:
$X_{111} = 1$, $X_{221} = 1$ and $X_{331} = 1$.
$F_{111} = 258$, $F_{221} = 190$ and $F_{331} = 183$.
$C_{111} = 266$, $C_{221} = 201$ and $C_{331} = 232$.
The objective function is equal to 631 hours.
Table 12 shows the arrival and departure dates of ships on berths
The last ships assigned to berths for this planning are ships number 1 on berth 1, ship number 2 on berth 2and ship number 3 on berth 3.
Further more, all the ships are assigned to the berth, and this mathematical model reduces the total flow time of the ships in the port. But given this real case where we find the optimal solution in a reasonable time, we noticed for high instances, the resolution time results increases, when the number of ships and berths are very high, so this problem can be considered to bein class NP-Hard, and that will be presented in an another research work.
In the following section we will compare our results of berths assignment and allocation obtained at the port of Rades to those achieved by the OMMP.

4.2.2. Benchmarking

After presenting the results of our assignment and allocation ships to berths during December, we will compare them to the results of ship allocation obtained by OMMP.
The results summarizing the assignment and allocation of ships at the berths according to the planning carried out by the OMMP are introduced in Table A2 (Appendix A).Noteworthy is that the « *first come first served* » (FCFS) principle is adopted as a basis of the planning.
Table 13 allows us to compare our results with those obtained by the authorities of the port of Rades in terms of the number of days spent in the harbor for each ship starting from their date of entry in the harbor to the date of their assignment to berths.
As can be seen in table 13, the total waiting time of ships in the harbor has been reduced from 1842 hours to 703 hours; hence, we reach a gain of 1139 hours or 62%. In addition, we have successfully reduced the waiting time in the harbor for12out of 14 ships. Better still, the waiting time for ships 2, 3, 5 and 12 is equal to zero. The reduction of ships waiting time represents a major gain for the Rades port authorities in terms of competitiveness as it will allow customers to be served in a timely manner and to feel satisfied.
A comparison of our findings with those carried out by Rades port authorities concerning the date of completion of the unloading operations of each ship on the berth (which corresponds to the date of departure of the ship from the berth) as well as the total stay time spent by the ship at the port (both in the harbor and the berth) is presented in Table 14.
As can be seen in table 13, the total waiting time of ships in the harbor has been reduced from 1842 hours to 703 hours; hence, we reach a gain of 1139 hours or 62%. In addition, we have successfully reduced the waiting time in the harbor for12out of 14 ships. Better still, the waiting time for ships 2, 3, 5 and 12 is equal to zero. The reduction of ships waiting time represents a major gain for the Rades port authorities in terms of competitiveness as it will allow customers to be served in a timely manner and to feel satisfied.
A comparison of our findings with those carried out by Rades port authorities concerning the date of completion of the unloading operations of each ship on the berth (which corresponds to the date of departure of the ship from the berth) as well as the total stay time spent by the ship at the port (both in the harbor and the berth) is presented in Table 14.

Table 12. Result of assigning ships to berths for the third planning

Berth Number	**Ship Number**	**Arrival Date of the Ship in the Harbor**	**Assignment Date of the Ship to the Berth**	**Processing Time P_j (Hours)**	**Departure Date of the Ship to the Berth**
1	Ship1	21/12/2016 08 :00	21/12/2016 08 :00	258	01/01/2017 02 :00
2	Ship 2	21/12/2016 11:06	27/12/2016 12 :50	44	29/12/2016 08 :50
3	Ship 3	23/12/2016 00:40	26/12/2016 20 :00	92	30/12/2016 16 :00

Table 13. Comparative table of ships stay time in the harbor

Stopover number	Ship number	Consignee	Name Of the Entering Ship	Arrival Date of the Ship in The Harbor	Results Of the Allocation of Ships To Berths (According To OMMP)		Results Of the Assignment Of Ships To Berths (According To Model G)	
					Assignment Date On Berth	Stay In The Harbor (Hours)	Assignment Date On Berth	Stay In The Harbor (Hours)
6558	1	CMA	KARINA	02/12/2016 17:30	03/12/2016 16 :40	23 :10	02/12/2016 21 :00	03 :30
6542	2	MSC	REECON EMRE	03/12/2016 00:40	09/12/2016 15 :50	159 :10	03/12/2016 00 :40	00 :00
6537	3	MAERSK	PASSAT	03/12/2016 15:00	06/12/2016 06 :30	63 :30	03/12/2016 15 :00	00 :00
6561	4	MAERSK	AVERA	05/12/2016 07:00	13/12/2016 14 :30	199 :30	09/12/2016 04 :00	93 :00
6552	5	GENMAR	HEINZ SCHEPPERS	07/12/2016 07:00	12/12/2016 06 :30	119 :30	07/12/2016 07 :00	00 :00
6569	6	CMA	NICOLA	07/12/2016 22:00	07/12/2016 23 :00	01 :00	09/12/216 11 :00	37 :00
6553	7	ASA	ALLEGRO	08/12/2016 07:00	14/12/2016 06 :45	143 :45	10/12/2016 16 :40	57 :40
6545	8	GREENT	MAX CAVALIER	13/12/2016 15:40	17/12/2016 09 :30	89 :50	18/12/2016 17 :40	122 :00
6595	9	MSC	GRAND	14/12/2016 00:40	22/12/2016 09 :15	200 :35	15/12/2016 01 :00	24 :20
6575	10	SEAWAVE	JSR CAPILA	15/12/2016 13:00	24/12/2016 14 :40	217 :40	20/12/2016 03 :00	110 :00
6597	11	MAERSK	JSP SLIDUR	20/12/2016 16:00	23/12/2016 10 :55	66 :55	21/12/2016 11 :00	19 :00
6615	12	MAERSK	PASSAT	21/12/2016 08:00	25/12/2016 23 :45	111 :45	21/12/2016 08 :00	00 :00
6610	13	GENMAR	HEINZ SCHEPPERS	21/12/2016 11:06	31/12/2016 07 :30	236 :24	27/12/2016 12 :50	145 :44
6638	14	MSC	MANDO	23/12/2016 00:40	31/12/2016 18 :20	209 :40	26/12/2016 20 :00	91 :20
					Total	**1842 :24**	**Total**	**703 :34**

Table 14. Comparative table of the total stay time of ships in the port

Stopover Number	Ship Number	Consignee	Name of Entering Ship	Entry Date of the Ship in the Harbor	Results of Ship Allocation to Berths (according to OMMP)		Results of Ships Assignment to Berths (according to model G)	
					Departure Date of the Ship from the Berth	Stay Time of the Ship in the Port (hours)	Departure Date of the Ship from the Berth	Stay Time of the Ship in the Port (hours)
6558	1	CMA	KARINA	02/12/2016 17:30	05/12/2016 18 :45	73 :15	04/12/2016 23 :00	53 :30
6542	2	MSC	REECON EMRE	03/12/2016 00:40	17/12/2016 08 :00	343 :20	10/12/2016 16 :40	184
6537	3	MAERSK	PASSAT	03/12/2016 15:00	12/12/2016 02 :45	203 :45	09/12/2016 11 :00	140
6561	4	MAERSK	AVERA	05/12/2016 07:00	24/12/2016 13 :20	462 :20	20/12/2016 03 :00	356

Stopover Number	Ship Number	Consignee	Name of Entering Ship	Entry Date of the Ship in the Harbor	Results of Ship Allocation to Berths (according to OMMP)		Results of Ships Assignment to Berths (according to model G)	
					Departure Date of the Ship from the Berth	Stay Time of the Ship in the Port (hours)	Departure Date of the Ship from the Berth	Stay Time of the Ship in the Port (hours)
6552	5	GENMAR	HEINZ SCHEPPERS	07/12/2016 07:00	14/12/2016 03 :50	164 :50	09/12/2016 04 :00	45
6569	6	CMA	NICOLA	07/12/2016 22:00	13/12/2016 12 :50	134 :50	15/12/2016 01 :00	171
6553	7	ASA	ALLEGRO	08/12/2016 07:00	22/12/2016 07 :30	336 :30	18/12/2016 17 :40	250 :40
6545	8	GREEN T	MAX CAVALIER	13/12/2016 15:40	23/12/2016 04 :50	229 :10	27/12/2016 12 :40	333
6595	9	MSC	GRAND	14/12/2016 00:40	31/12/2016 04 :30	411 :50	20/12/2016 21 :00	164 :20
6575	10	SEAWAVE	JSR CAPILA	15/12/2016 13:00	25/12/2016 22 :00	249	21/12/2016 11 :00	142
6597	11	MAERSK	JSP SLIDUR	20/12/2016 16:00	28/12/2016 20 :00	196	26/12/2016 20 :00	148
6615	12	MAERSK	PASSAT	21/12/2016 08:00	05/12/2016 17 :25	369 :25	01/01/2017 02 :00	258
6610	13	GENMAR	HEINZ SCHEPPERS	21/12/2016 11:06	05/01/2017 07 :30	356 :24	29/12/2016 08 :50	189 :44
6638	14	MSC	MANDO	23/12/2016 00:40	04/01/2017 13 :45	301 :05	30/12/2016 16 :00	183 :20
					Total	**3831 :44**	**Total**	**2618 :34**

As the table 14 shows the total flow time of ships in the port has been significantly reduced from 3831 hours to 2618 hours which corresponds to 1213 hours representing 31.6% of the usual time. Besides, the total stay time of 12 out of 14 ships has been reduced, which represents a major gain for Rades port authorities. Consequently, the port's competitiveness is raised and customer services are improved.

Based on the data presented in Table 14, we can compare the variation in the number of days spent by each ship in the port according to our model and that adopted by OMMP.

Table 15 demonstrates a considerable decrease in total stay time spent by ships at the port of Rades. For example, the period spent at the port by ship 9 has decreased from 17 to 7 days and from 15 to 8 days by ship 2. It is also shown that on 12 out of 14 ships managed to reduce the total stay in the port. We also note that using model G the upper bound of the flow time has been respected and we have succeeded in reducing the total stay time of ships 4, 9 and 12 so they respect the upper bound of 15 days.

In light of the afore-mentioned results, we conclude that the mathematical model G does well to reduce the congestion of ships and their total time spent in the port for both the static and dynamic cases. Indeed, it makes it possible to successfully minimize and optimize ships flow time and waiting time in the port which, in return, has a significant impact on the length of ships stay time in the port. The flow time of all ships has been minimized, providing a competitive advantage for Rades port authorities as well for their customers and their consignees. It is noteworthy that the OMMP received our findings positively because they can address their major problem which is the minimization of ships waiting time in the harbor and the total ships stay time in the port.

Table 15. Variation of the total ship stay time at the port in rades

Ship Number	Name of Entering Ship	Total Stay Time of the Ship at the Port *(according to OMMP) (days)*	Total Stay Time of the Ship at the Port ***(according the model G) (days)***	Total Stay Time variation ***(days)***
1	KARINA	3	2	(-) 1
2	REECON EMRE	15	8	(-) 7
3	PASSAT	9	6	(-) 3
4	AVERA	20	15	(-) 5
5	HEINZ SCHEPPERS	7	2	(-) 5
6	NICOLA	6	7	(+) 1
7	ALLEGRO	14	11	(-) 3
8	MAX CAVALIER	10	14	(+) 4
9	GRAND	17	7	(-) 10
10	JSR CAPILA	11	6	(-) 5
11	JSP SLIDUR	8	6	(-) 2
12	PASSAT	16	11	(-) 5
13	HEINZ SCHEPPERS	15	8	(-) 7
14	MANDO	13	8	(-) 5

5. Conclusion and perspectives

In this paper, we have investigated the Ships to Berths Assignment Problem. A mathematical model is developed with the aim of minimizing the time during which ships stay in the port (known by the Flow Time) as well as decreasing the waiting time of all the ships in the port, while matching characteristics of the ships with those of berths such as depth, length, etc. This model is illustrated with a real case study in the Tunisian port of Rades and solved by a commercial solver CPLEX. Its results are compared with those obtained from the port authorities of Rades. Our approach have shown a significant improvement over the current Ships to Berths assignment solution used in the port of Rades.

New research directions can be identified in light of the following remarks:

– This model is limited because when the problem size increases it becomes difficult to optimally solve the associated assignment problem; either approximate methods Heuristics or Meta-Heuristics can be used.
– The model proposed could be completed by adding the travelling time between the berth and the storage area.
– Applying the BAP in a continuous dock space.
– Considering the environmental and social constraints during the assignment of ships to berths.
– Developing a new model, for reducing the flow time and guarantee for ships that they don’t stay in the port for a long time.

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APPENDIX

Table A.1 – Incoming Containers Ships During The Month Of Decembre At The Port Of Rades

Stopover Number	**Consignee**	**Name Of Entering Ship**	**Arrival Date of the Ship on the Harbor**	**Number of containers for each ship C_j**									**The Draft Of The Ship's E_j**	**The Length Of The Ship's L_j**	**Processing Time P_j**
				IMPORT				**EXPORT**				**TOTAL**			
				20'P	**20'V**	**40'P**	**40'V**	**20'P**	**20'V**	**40'P**	**40'V**				
6558	CMA	KARINA	02/12/2016 17:30	0	0	0	0	0	485	0	0	485	8.7	122	50
6542	MSC	REECON EMRE	03/12/2016 00:40	200	0	225	0	50	0	92	300	867	8.9	141	184
6537	MAERSK	PASSAT	03/12/2016 15:00	85	10	215	0	50	112	167	55	694	8.7	125	140
6561	MAERSK	AVERA	05/12/2016 07:00	88	10	281	0	75	20	68	236	778	8.7	125	263
6552	GENMAR	HEINZ SCHEPPERS	07/12/2016 07:00	82	0	43	0	4	59	13	136	337	6.46	96	45
6569	CMA	NICOLA	07/12/2016 22:00	79	0	88	0	12	7	25	292	503	7.7	122	134
6553	ASA	ALLEGRO	08/12/2016 07:00	106	0	263	0	42	1	65	55	532	8.7	125	193
6545	GREEN T	MAX CAVALIER	13/12/2016 15:40	108	0	139	0	107	85	43	32	514	8.5	141	140
6595	MSC	GRAND	14/12/2016 00:40	223	0	216	0	212	160	165	0	976	9.6	126	211
6575	SEAWAVE	JSR CAPILA	15/12/2016 13:00	34	0	19	0	51	0	49	23	176	7.2	130	32
6597	MAERSK	JSP SLIDUR	20/12/2016 16:00	110	0	274	0	65	4	146	148	747	8.7	125	129
6615	MAERSK	PASSAT	21/12/2016 08:00	104	0	252	0	59	4	172	55	646	8.7	125	258
6610	GENMAR	HEINZ SCHEPPERS	21/12/2016 11:06	55	0	41	0	38	100	31	113	378	6.46	96	44
6638	MSC	MANDO	23/12/2016 00:40	199	0	248	0	58	144	37	148	834	10.1	142	92
		TOTAL	-	1473	20	2304	0	823	1181	1073	1593	8467	-	-	1915

Table A.2- Assignment Ships To Berths Realized By OMMP

Stopover Number	Ship Number	Consi-gnee	Name Of Entering Ship	Arrival Date of the Ship on the Harbor	Number of containers for each ship C_j									The Draft Of The Ship's E_j	The Length Of The Ship's L_j	Processing Time P_j (hours)	Arrival Date of the Ship on The Berth	Date Of Departure From The Berth	Allocation To The Berth
					IMPORT				EXPORT				TOTAL						
					20' P	20' V	40' P	40' V	20' P	20' V	40' P	40' V							
6558	1	CMA	KARINA	02/12/2016 17:30	0	0	0	0	0	485	0	0	485	8.7	122	50	03/12/2016	05/12/2016	1
6542	2	MSC	REECON EMRE	03/12/2016 00:40	200	0	225	0	50	0	92	300	867	8.9	141	184	09/12/2016	17/12/2016	3
6537	3	MA-ERSK	PASSAT	03/12/2016 15:00	85	10	215	0	50	112	167	55	694	8.7	125	140	06/12/2016	12/12/2016	1
6561	4	MA-ERSK	AVERA	05/12/2016 07:00	88	10	281	0	75	20	68	236	778	8.7	125	263	13/12/2016	24/12/2016	2
6552	5	GEN-MAR	HEINZ SCHEPPERS	07/12/2016 07:00	82	0	43	0	4	59	13	136	337	6.46	96	45	12/12/2016	14/12/2016	1
6569	6	CMA	NICOLA	07/12/2016 22:00	79	0	88	0	12	7	25	292	503	7.7	122	134	07/12/2016	13/12/2012	2
6553	7	ASA	ALLE-GRO	08/12/2016 07:00	106	0	263	0	42	1	65	55	532	8.7	125	193	14/12/2016	22/12/2016	1
6545	8	GREEN T	MAX CAVA-LIER	13/12/2016 15:40	108	0	139	0	107	85	43	32	514	8.5	141	140	17/12/2016	23/12/2016	3
6595	9	MSC	GRAND	14/12/2016 00:40	223	0	216	0	212	160	165	0	976	9.6	236	211	22/12/2016	31/12/2016	1
6575	10	SEA-WAVE	JSR CA-PILA	15/12/2016 13 :00	34	0	19	0	51	0	49	23	176	7.2	130	32	24/12/2016	25/12/2016	2
6597	11	MA-ERSK	JSP SLI-DUR	20/12/2016 16:00	110	0	274	0	65	4	146	148	747	8.7	125	129	23/12/2016	28/12/2016	3
6615	12	MA-ERSK	PASSAT	21/12/2016 08:00	104	0	252	0	59	4	172	55	646	8.7	125	258	25/12/2016	05/01/2017	2
6610	13	GEN-MAR	HEINZ SCHEPPERS	21/12/2016 11:06	55	0	41	0	38	100	31	113	378	6.46	96	44	31/12/2016	02/01/2017	1
6638	14	MSC	MANDO	23/12/2016 00:40	199	0	248	0	58	144	37	148	834	10.1	142	92	31/12/2016	04/01/2017	3