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Optimal Allocation of Ships to Quay Length in Container Ports

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ABSTRACT

Due to the continuously increasing container trade, many terminals are presently operating at or close to capacity. An efficient terminal is one that facilitates the quick transshipment of containers to and from ships. In this sake, this paper addresses the ship assignments problem at a maritime container terminal, where ships are normally assigned to specific quay cranes until the work is finished. The paper's target is to develop a new Continues Berth Allocation Problem (CBAP) in the form of a mixed integer nonlinear programming to achieve the best service time in a container terminal. For illustrating the accuracy of Proposed model (PM), Imai et. al. 's model (IM) (TRANSPORT RES B, 39 (2005) 199–221) was applied and a wide variety of computational test examples were conducted. The results of demonstrated that the presented BAPC reduces the number of nonlinear variables (constraints) and generates substantial savings in the CPU time.

***Keywords*:** Optimal transportation, Continues Berth allocation Problem (CBAP), mixed integer nonlinear programming

1. INTRODUCTION

Container terminals are essential inter-modal transportation network which work under multiple operational objectives. The main one is to minimize ships turnaround time (including serving time and waiting time) and subsequently maximize the terminal throughput. They can be achieved by efficient loading and discharging of ships. Therefore, accurate ship assignment is usually taken as the key performance measure for the operational efficiency of a terminal.

At a multi-user terminal, ships are usually berthed relatively close to their container storage in the yard for quicker container transshipment to and from the ships. However, in order to increase the usage of quay space in berthing ships, some ships may be assigned to a quay location far from their container storage. Optimum assignment of arrived ships to quay length is one of the most important factors to reduce the sum of ships turnaround time. So, this paper tries to consider the *Continues Berth Allocation Problem* (CBAP) to achieve higher productivity in ship berthing. The *Proposed model* (PM) is able to reflect the abilities of Imai et al. (2005)'s model (IM) in less solution time. To

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solve the model Branch and Bound (B & B) algorithm has been used. The rest of the paper is organized as follows:

The next section provides a literature review on the *Berth Allocation Problem* (BAP). Section 3, describes the model formulation. In section 4, a variety of computational experiments are conducted which demonstrate the efficiency of PM in decreasing computational time against IM. Section 6 provide the analysis of CBAP results and the final section concludes the paper.

2. LITERATURE REVIEW

Many researches have been conducted to increase the efficiency of container terminals operation. Different subjects of these researches include berth allocation problem (Brown et al. (1994), Brown et al. (1997), Guan et al. (2002), Imai et al. (1997), Imai et al. (2001), Imai et al. (2003), Imai et al. (2007), Imai et al. (2005), Kim and Moon (2003), Lai and Shih (1992), Li et al. (1998), Lim (1998), Nishimura et al. (2001), Park and Kim (2002), Park and Kim (2003), Ganji et al. (2009)); quay and yard cranes assignment (Javanshir and Ganji (2010), Tavakkoli-Moghaddam et al. (2009); yard storage management (Zhang et al. (2003)) Recently a unique classification of a paper is not possible according to the given information, the best fit of classifying attributes is taken in Vis and Koster (2003) and Bierwirth and Meisel (2010). Studies that have been focused on assignment of ships to berths are considered in detail.

Lai and Shih (1992) have used a First-Come- First-Served (FCFS) allocation rule in the form of a heuristic algorithm for analysis of the BAP. Brown et al. (1994, 1997) proposed the first mathematical models of BAP to maximize the sum of benefits for ships in naval port. Imai et al. (1997) address a *Discrete Berth Allocation Problem* (DBAP) in the static variant for commercial ports. In this problem, the assignment and sequencing of ships to berths is searched with respect to minimum waiting and handling times of the ships. A Lagrangean relaxation based heuristic is presented to solve the problem. Dynamic variant of the DBAP is considered by Imai et al. (2001) with regard to the port stay times of ships. They extended the static version of the DBAP presented into a dynamic treatment with only one objective named berth performance (Imai et al. 1997). A heuristic solution based on the sub gradient method with Lagrangian relaxation was developed to solve the model. Multi-water depth configuration of DBAP in Imai et al. (2001) is conducted by Nishimura et al. (2001). They proposed a genetic meta-heuristic solution method for solving that problem.

Another type of approach to the BAP is proposed in recent studies is the one with a continuous location called CBAP. Lim (1998) was the first to consider a berth as a continuous line and viewed the berth planning problem as a two-dimensional bin packing problem. He discussed how to locate berthing positions of ships so that the throughput of the berth is maximized, but did not consider the berthing time as a decision variable. The static CBAP with fixed ships handling time has been introduced by Li et al. (1998). The problem is formulated as a ‘‘multiple-job-on-one-processor” scheduling problem. This allows adapting the First-Fit-Decreasing heuristic, well-known from bin packing, for minimizing the maximum completion time among the ships. Guan et al. (2002) proposed an m-parallel machine scheduling formulation and developed a heuristic was developed for the CBAP to minimize the total weighted completion time of the ships. Park and Kim (2002) introduced the first model for the CBAP to determine simultaneously the berthing time and position for each ship with the objective of minimizing the costs resulting from delayed ships departures. The authors proposed a sub-gradient optimization technique. Kim and Moon (2003) solved the same CBAP as the one proposed by Park and Kim (2002) with the simulated annealing method. Park and Kim (2003) determine the optimal start times of ship service and associated mooring locations and at the same time they determine the optimal assignment of quay cranes to those ships. In their study, the handling time for a particular ship is a function of the number of quay cranes engaged in the ship, however, the handling time is independent from the mooring location of the ship. Imai et al. (2005) proposed an integer nonlinear mathematical model for CBAP. They assume that a ship's handling time depends on the quay location where the particular ship is handled. IM is presented in Appendix A. Recently, Imai et al. (2007) addressed the berth BAP at a multi-user container terminal with indented berths for fast handling of mega-containerships. They constructed a new integer linear programming formulation and then the formulation is extended to model the BAP at a terminal with indented berths, where both mega-containerships and feeder ships are to be served for higher berth productivity. The BAP at the indented berths is solved by genetic algorithm.

3. MATHEMATICAL FORMULATION

This section proposes a new mathematical formulation of CBAP. The assumptions in this model are as follow:

- There is no delay in ship arrival.
- Ships handling time increases linearly and with a slope of $\gamma_i \geq 0$. So, the handling time of a ship can be defined as follow (Imai et al. (2005)):

$$C_i = CM_i + |p_i - M_i|\gamma_i$$

Where CM_i is the handling time of the ship *i* in the best berthing location M_i and γ_i depends on quality port's internal equipments function.

- The required gap between adjacent ships for anchoring is considered in the length of ships.
- Elapsed time of ships berthing is considered in handling time of ships.

As illustrated in Figure 1, the problem is set in a 2-dimensional space, the berth length and the planning time defining the horizontal and vertical axes, respectively. We can represent a ship geometrically by a rectangle, such that the length of the rectangle is the length of the ship and the height of the rectangle is the duration of its stay (or handling time). The bottom edge of the rectangle represents the start time of handling the ship. The top edge represents the completion time of handling the ship (or the departure time of the ship). The quay space can be represented geometrically by an infinitely long rectangle where its length is the quay length and the height defines the time.

The following notations are used for a mathematical formulation.

Indices:

$i, j (=1,.....,T) \in v$ Number of ships to be allocated in the quay

Problem data:

Q: Quay length;

a_i : Arrival time of ship *i;*

l_i : The length of ship *i*.

M_i : Best berthing location of ship *i*. This location is represented by the center of ship *i* at the horizontal axis (Quay length axis);

γ_i : Additional travel cost of handling containers from or to ship *i* resulting from non-optimal berthing locations;

m : A sufficiently large constant;

Decision variables:

p_i : Berthing location of ship *i* (is integer);

t_i^B : Berthing time of ship *i;*

δ_{ij}^x : 1, if ship *i* is located to the left of ship *j* in the time-berth-length space; 0, otherwise;

δ_{ij}^y : 1, if ship *i* is located below ship *j* in the time-berth-length space; 0, otherwise;

Where p_i s and t_i^B s are variables and p_i s are integers.

The CBAP can be formulated as follows:

$$\textit{Minimize} \ \sum_{i=1}^{v} \left\{ t_i^B + CM_i + \gamma_i \times \left| p_i - M_i \right| - a_i \right\} \tag{1}$$

Subject to:

$$p_i + \frac{l_i + l_j}{2} \le \left(p_j + m\left(1 - \delta_{ij}^x\right)\right) \qquad j = 1,2,\ldots,v, \quad i \ne j \tag{2}$$

$$t_i^B + c_i \le \left(t_j^B + m\left(1 - \delta_{ij}^y\right)\right) \qquad i, j = 1,2,\ldots,v, \quad i \ne j \tag{3}$$

$$\delta_{ij}^x + \delta_{ji}^x + \delta_{ij}^y + \delta_{ji}^y \ge 1 \qquad i, j = 1,2,\ldots,v, \quad i < j \tag{4}$$

$$p_i + \frac{l_i}{2} \le Q \qquad i = 1,2,\ldots,v \tag{5}$$

$$p_i \ge \frac{l_i}{2} \qquad i = 1,2,\ldots,v \tag{6}$$

$$t_i^B \geq a_i \qquad i = 1,2,...,v \tag{7}$$

$$p_i \geq 0 \qquad i = 1,2,...,v \tag{8}$$

The objective function (1) is the sum of service times for all ships, where the service time is defined as the time spent from arrival to departure including the waiting time for a quay space to become available. Constraints (2)–(3) are the non-overlapping restriction. Note that as either quay-non-overlapping or time-non-overlapping should be satisfied, therefore $\delta_{ij}^x + \delta_{ji}^x + \delta_{ij}^y + \delta_{ji}^y - 1 \geq 0$ in constraint (4). Constraints (5) and (6) ensure that every ship must be berthed within the quay length. Constraint (7) assures that the ships are berthed after their arrival.

4. NUMERICAL EXPERIMENTS

The solution procedure is coded in ‘‘LINGO’’ software on a personal computer Pentium IV 2.8 GHz PC with 512MB RAM). We developed five basic problems with different quay lengths (from 600 to 2400) and numbers of ships 6, 7 and 8 in a day. For each basic problem, we set up different best handling times and one rate of increase in handling time as additional cost factor. The data sets are generated with average ship sizes of 200, 250, 300, 400 and 500 meters. The average best handling time per ship at the best quay location for the data sets is 7, 9, 10, 11and 13 hours, respectively. The ship arrival pattern follows the uniform distribution with average interval of 7, 10, 13, 15 and 18 hours. The best berthing location are in the distances of 0.25, 0.50, 0.75 length of quay repeated in order to arriving ships. In addition, every groups of an example is conducted with different additional cost factors 0.005, 0.05, 0.1, 0.08 and 0.2. Different data sets are given in Table 1.

Comparison between Imai's and PMs on the number of variables and the computational time are presented in Tables 2-7. As shown in Table 2, there are less non linear variables and constraints in the PM than their similar states in IM. The number of nonlinear terms ($|p_i - M_i|$) in the PM which is occurred in objective functions is equal 1. This amount is up to 120 constraints for IM. So, it is clear that less operation time is needed for PM rather than that one can be expected for Imai's model.

According to Tables 4-7, we can find the computational time of problem using the PM is much less than the similar one by opponent model. In many instances, the PM was able to solve more complex problem with less quay length or more amount of additional cost against other similar ones. This means that the sensitivity of IM against the increase of the problem's dimension is more than the sensitivity of PM. In the other word, there are lots of problems which might not be not solved by IM could be analyzed using the PM. Some of these unsolvable instances, of course, in acceptable running time (less than 1200 seconds), are referred in Tables 3-7. In Table 3, examples with 6 ships in a day and the quay length less than 1000 meters, 7 ships in a day and the quay length less than 1300 meters, and 8 ships in a day and the quay length less than 1600 meters are unsolvable using IM. In addition, among 93 instances in Tables 4-7 were solved by IM in acceptable solution time which is with 6 ships, quay length 1300 m and $\gamma_i = 0.1$. It is necessary to mention that these examples were solved in much more time than solving those ones by PM. From these tables we can easily understand that problems will become more complex to solve by increasing in the amount of additional cost.

5. RESULTS AND DISCUSSIONS

In this section we consider the output of five selected samples mentioned above in detail. These samples data are as follow:

1. 8 ships, quay length 1200 *m with* $\gamma_i = 0.005$ (Data set 1)

2. 6 ships, quay length 800 *m with* $\gamma_i = 0.05$ (Data set 2)

3. 7 ships, quay length 1000 *m with* $\gamma_i = 0.1$ (Data set 3)

4. 8 ships, quay length 1800 *m with* $\gamma_i = 0.08$ (Data set 4)

5. 8 ships, quay length 2200 *m with* $\gamma_i = 0.2$ (Data set 5)

The results of Samples 1, 2, 3, 4 and 5 can be observed in Table 8-12, respectively. The Outputs include the berthing time (t_i^B), the berthing location (p_i) of each ship. Moreover, the measure of every ship's delay is represented in these tables.

Results in Table 8 illustrates all ships except the second ship berthed in the best location exactly at the arriving time are located in the quayside with related delays. The delay amount of ships in this assumed port (5.125 hours) includes 9% of objective function. Whole ships except final ship are at arriving time. We can find similar results in Tables 9-12.

Figure 2 shows the changes of objective function against the quay length for the problem with 8 ships and $\gamma_i = 0.005$. Critical intervals in this diagram are between 940-950 and 1180-1200 meters. Reduction of objective function in these intervals is completely considerable. The important point is that the descending process of objective function's amount for the lengths more than 1500 meters, in above diagram, remains constant in its minimum amount, 58 hours.

Figure 3, illustrates the changes of objective function of 8 ships for the length of quay 1200 meters against different amount of γ_i. As observed in this figure, the amount of objective function for $\gamma_i = 0.04$ is about 78.00 hours that reduces by the linear reduction of γ_i with regression coefficient $r^2 = 0.97$. In this figure, the notable point is that with reduction of γ_i from 0.005 to 0.000, the amount of objective function with about 4 hours reduction reaches to about 55 hours. However, if $\gamma_i = 0.04$, the amounts of objective function with about 23 hours increase reaches to about 78 hours. It means we can decrease ship's turnaround time to maximum 23 hours only by adequate allocation of the container storages or the correct timing of handling tools. Similar results could be found for other samples that we disregard mentioning about them.

6. CONCLUSION

The Presented Model (PI) in this paper has been formulated based on the existing concepts in berth allocation problems continuously that have less integer and nonlinear variables rather than the presented model by Imai in 2005. Using PI can cause better analysis of the BAP in a more acceptable computational time. After presenting five various examples, two effective parameters in efficiency of container ports that is the length of quay and coefficient of handling time increasing (to the distance from the best berthing location) were reviewed as sensitivity analysis. According to these results, adequate allocation of container storages and also automation of handling process (simultaneous crane scheduling and trailers, use of multi-trailers systems, etc) can be proposed in the increasing of efficiency of containers port as the cheep alternatives, rather the construction and development alternatives.

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Appendix A. (IM)

The formulation is based on the following notations:

$i\,(=1,.....,T) \in V$: Set of ships,

A_i : Estimated arrival time of ship *i*,

L_i : Length of ship *i* (including the inter-ship clearance distance),

Q : Length of quay,

M_i : Berthing location with the minimum handling time of ship *i* ($L_i/2 \le M_i \le Q - L_i/2$),

C_{M_i} : Handling time of ship *i* in M_i ;

α_i : Additional travel cost

C_i : Handling time of ship *i*, $C_i = C_{M_i} + |p_i - M_i|\alpha_i$

p_i : Berthing location of ship *i*;

t_i^B : Start time of handling for ship *i*, and

$t_i^F = t_i^B + C_i$: Completion time of handling for ship *i*, Where p_i and t_i^B are variables and integer. The BAPC was formulated as follows:

$$[\mathrm{P}] \quad \mathrm{Min} \quad Z = \sum_{i \in V} \left(t_i^F - A_i \right) \tag{1}$$

Subject to

$$\left| p_i - p_j \right| \delta_{ij}^p \geq \frac{L_i + L_j}{2} \delta_{ij}^p \qquad \forall i, j (\neq i) \in V, \tag{2}$$

$$\left| \frac{t_i^B + t_i^F}{2} - \frac{t_j^B + t_j^F}{2} \right| \delta_{ij}^t \geq \frac{C_i + C_j}{2} \delta_{ij}^t \qquad \forall i, j (\neq i) \in V, \tag{3}$$

$$\delta_{ij}^p + \delta_{ij}^t \geq 1 \qquad \forall i, j (\neq i) \in V, \tag{4}$$

$$p_i - \frac{L_i}{2} \geq 0 \qquad \forall i \in V, \tag{5}$$

$$p_i + \frac{L_i}{2} \leq Q \qquad \forall i \in V, \tag{6}$$

$$t_i^B \geq \max(A_i, 0) \qquad \forall i \in V, \tag{7}$$

$$t_i^F = t_i^B + C_i \qquad \forall i \in V, \tag{8}$$

$$p_i, t_i^B \geq 0 \text{ and are integer} \qquad \forall i \in V, \tag{9}$$

$$\delta_{ij}^p, \delta_{ij}^t \in \{0,1\} \qquad \forall i, j (\neq i) \in V, \tag{10}$$

Where δ_{ij}^p and δ_{ij}^t are the variables defined as :

$\delta_{ij}^p := 1$ if non-overlapping restriction in quay axis is applied for ships *i* and *j*,
$= 0$ Otherwise.

$\delta_{ij}^t := 1$ if non-overlapping restriction in time axis is applied for ships *i* and *j*,
$= 0$ Otherwise.

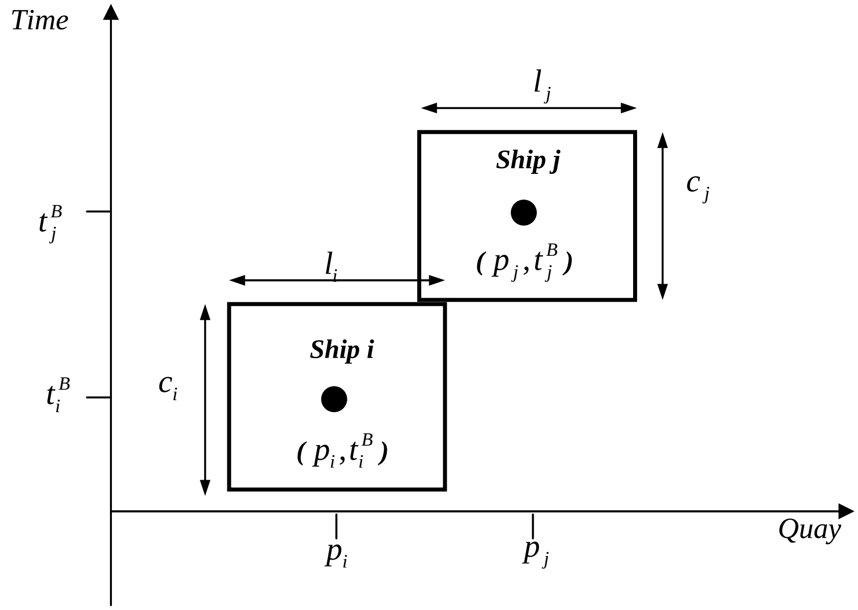

Figure 1 Structure of CBAP

Table 1 Different data sets

Ship lengths								
	*Ship **1***	*Ship **2***	*Ship **3***	*Ship **4***	*Ship **5***	*Ship **6***	*Ship **7***	*Ship **8***
*Data sets **1***	150	200	250	150	200	250	150	200
*Data sets **2***	200	300	200	250	250	200	300	300
*Data sets **3***	350	250	400	350	200	400	450	400
*Data sets **4***	250	550	400	300	500	350	450	400
*Data sets **5***	400	500	450	550	600	350	550	600
Best handling times								
*Data sets **1***	5.00	7.00	9.00	5.00	7.00	9.00	5.00	7.00
*Data sets **2***	7.75	11.50	7. 50	8.00	8.50	7.25	10.50	11.00
*Data sets **3***	10.25	7.25	11.25	10.00	6.25	11.00	12.25	11.75
*Data sets **4***	6.00	14.25	12.75	7.25	13.50	7.75	13.50	13.00
*Data sets **5***	11.50	13.75	13.00	14.25	15.00	7.75	14.00	14.75
arrival time to the port (hr: min)								
*Data sets **1***	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00
*Data sets **2***	6:00	7:15	8:30	9:45	11:00	13:00	14:30	16:00
*Data sets **3***	6:00	7:00	7:30	10:00	12:45	14:30	17:45	19:00
*Data sets **4***	6:00	8:45	10:30	13:00	15:45	18:15	19:30	21:00
*Data sets **5***	6:00	9:00	11:45	12:15	16:15	18:30	21:15	23:00

Table 2 The sizes of Imai and PMs for problems with 6, 7 and 8 ships

Number of Ships	**Number of nonlinear variables**	**Number of nonlinear constraints**	**Number of nonlinear variables**	**Number of nonlinear constraints**
6	84	66	6	1
7	112	91	7	1
8	144	120	8	1

Table 3 The results of the computational experiment for set data 1

$\gamma_i = 0.005$						
	Problem sizes		**IM**		**PM**	
Problem No.	**Number of Ships**	**Quay length**	**Objective function (hr)**	**Solution Time (sec)**	**Objective function (hr)**	**Solution Time (sec)**
1	6	700	Not available *		54.500	26
2		800	Not available		49.750	16
3		900	Not available		49.000	15
4		1000	Not available		48.250	15
5		1100	46.500	194	46.500	13
6		1200	45.750	93	45.750	13
7		1300	45.000	45	45.000	13
8		1400	45.000	30	45.000	13
9	7	800	Not available		58.125	26
10		900	Not available		56.500	26
11		1000	Not available		53.375	20
12		1100	Not available		53.000	15
13		1200	Not available		51.125	15
14		1300	50.000	291	50.000	14
15		1400	50.000	48	50.000	14
16	8	1000	Not available		63.625	77
17		1100	Not available		62.500	44
18		1200	Not available		59.125	24
19		1300	Not available		58.250	17
20		1400	Not available		58.125	13
21		1500	Not available		58.000	15
22		1600	58.000	771	58.000	12
23		1700	58.000	563	58.000	12

* ***Not available*** means that the instance was not solved in acceptable time (less than 1200 sec).

Table 4 The results of the computational experiment for set data 2

$\gamma_i = 0.05$						
	Problem sizes		**IM**		**PM**	
Problem No.	**Number of Ships**	**Quay length**	**Objective function (hr)**	**Solution Time (sec)**	**Objective function (hr)**	**Solution Time (sec)**
1		600	Not available*		88.500	69
2		700	Not available		81.500	16
3		800	Not available		76.500	16
4		900	Not available		71.500	12
5		1000	Not available		66.500	11
6		1100	Not available		65.250	13
7		1200	Not available		65.250	28
8	**7**	800	Not available		98.000	21
9		900	Not available		91.750	17
10		1000	Not available		85.500	36
11		1100	Not available		83.000	34
12		1200	Not available		83.000	14
14	8	1100	Not available		106.500	19
15		1200	Not available		105.250	12
16		1300	Not available		105.250	21
17		1400	Not available		105.250	21
18		1500	Not available		104.75	19
19		1600	Not available		103.500	21
20		1700	Not available		103.500	18

* ***Not available*** means that the instance was not solved in acceptable time (less than 1200 sec).

Table 5 The results of the computational experiment for set data 3

$\gamma_i = 0.1$						
	Problem sizes		**IM**		**PM**	
Problem No.	**Number of Ships**	**Quay length**	**Objective function (hr)**	**Solution Time (sec)**	**Objective function (hr)**	**Solution Time (sec)**
2	**6**	800	Not available		103.250	31
3		900	Not available		103.250	29
4		1000	Not available		87.250	15
5		1100	Not available		77.250	13
6		1200	Not available		70.500	13
7		1300	68.000	326	68.000	13
8	**7**	1000	Not available		108.000	19
9		1100	Not available		98.000	28
10		1200	Not available		91.250	23
11		1300	Not available		88.750	16
12		1400	Not available		88.750	11
13	**8**	1000	Not available		63.625	77
14		1100	Not available		62.500	44
15		1200	Not available		122.500	20
16		1300	Not available		120.000	18
17		1400	Not available		115.500	51
19		1600	Not available		104.500	24
20		1700	Not available		102.000	11
21		1800	Not available		102.000	12

* ***Not available*** means that the instance was not solved in acceptable time (less than 1200 sec).

Table 6 The results of the computational experiment for set data 4

$\gamma_i = 0.08$						
	Problem sizes		**IM**		**PM**	
Problem No.	**Number of Ships**	**Quay length**	**Objective function (hr)**	**Solution Time (sec)**	**Objective function (hr)**	**Solution Time (sec)**
2		800	Not available		116.000	13
3		900	Not available		114.000	27
4		1000	Not available		112.000	27
5		1100	Not available		110.000	27
6		1200	Not available		108.000	14
7		1300	Not available		106.000	12
8		1400	Not available		99.750	15
9		1500	Not available		91.750	11
10		1600	Not available		83.750	15
11		1700	Not available		77.750	10
12		1800	Not available		75.750	14
13		1900	Not available		73.750	12
14		2000	Not available		80.250	13
15		2100	Not available		73.750	13
16		800	Not available		139.250	17
17		900	Not available		137.250	16
18		1000	Not available		137.250	16
19		1300	Not available		161.250	40
20		1400	Not available		147.250	23
21		1500	Not available		137.250	27
22		1600	Not available		129.250	20
23		1700	Not available		123.250	16
24		1800	Not available		121250	15
25		1900	Not available		118.000	19
26		2000	Not available		116.000	18
27		2100	Not available		116.000	14

* ***Not available*** means that the instance was not solved in acceptable time (less than 1200 sec).

Table 7 The results of the computational experiment for set data 5

$\gamma_i = 0.2$						
	Problem sizes		**IM**		**PM**	
Problem No.	**Number of Ships**	**Quay length**	**Objective function (hr)**	**Solution Time (sec)**	**Objective function (hr)**	**Solution Time (sec)**
1		800	Not available		148.7500	15
2		900	Not available		148.7500	15
3		1000	Not available		140.2500	12
4		1100	Not available		138.750	13
5		1200	Not available		140.000	11
6		1300	Not available		140.2500	14
7		1400	Not available		138.750	12
8		1500	Not available		138.750	12
9		1400	Not available		200.000	20
10		1500	Not available		196.250	116
11		1600	Not available		188.500	52
12		1700	Not available		178.500	17
13		1800	Not available		169.500	27
14		1900	Not available		156.750	13
15		2000	Not available		151.750	14
16		2100	Not available		138.500	13
17		2200	Not available		131.500	12
18		2300	Not available		126.500	14
19		2400	Not available		126.500	14
20		1900	Not available		199.750	82
21		2000	Not available		189.750	54
22		2100	Not available		176.000	44
23		2200	Not available		166.000	44
24		2300	Not available		156.000	34
25		2400	Not available		156.000	15

* ***Not available*** means that the instance was not solved in acceptable time (less than 1200 sec).

Table 8 The results of sample 1

Objective function = 59.125 hr									
berthing time (hr:min)	t_i^B	6:00	7:00	8:00	9:00	10:00	11:00	12:00	14:00
berthing location(m)	p_i	225	600	1075	75	400	825	225	600
Ship delay (hr)	5.125	0.375	0.000	0.875	1.125	1.000	0.375	0.375	1.000

Table 9 Results of sample 2

Objective function = 76.500 hr							
Best berthing location (m)	M_i	200	400	600	200	400	600
Berthing time (hr : min)	t_i^B	6:00	7:15	8:30	13:45	18:45	16:00
Berthing location (m)	p_i	150	200	650	125	400	650
Ship delay (hr)	***26.000***	2.500	0.000	2.500	7.750	7.750	5.500

Table 10 Results of sample 3

Objective function = 102.000 hr									
Best berthing location (m)	M_i	450	900	1350	450	900	1350	450	900
Berthing time (hr : min)	t_i^B	6:00	7:00	7:30	16:15	14:15	18:45	26:15	20:30
Berthing location (m)	p_i	450	900	1350	450	900	1350	450	900
Ship delay (hr)	***22.000***	0.000	0.000	0.000	6.250	1.500	4.250	8.500	1.500

Table 11 Results of sample 4

Objective function = 121.250 hr									
Best berthing location (m)	M_i	450	900	1350	450	900	1350	450	900
Berthing time (hr : min)	t_i^B	6:00	8:45	10:30	13:00	36:00	23:15	23:00	23:00
Berthing location (m)	p_i	450	900	1375	450	900	1350	450	900
Ship delay (hr)	***33.250***	0.000	0.000	2.000	0.000	20.75	5.000	3.500	2.000

Table 12 Results of sample 5

Objective function = 166.000 hr									
Best berthing location (m)	M_i	550	1100	1650	550	1100	1650	550	1100
Berthing time (hr : min)	t_i^B	6:00	9:00	11:45	31:30	22:45	24:45	17:30	37:75
Berthing location (m)	p_i	550	1100	1650	550	1125	1650	550	1125
Ship delay (hr)	***62.000***	0.000	0.000	0.000	24.250	11.500	6.250	5.250	14.750

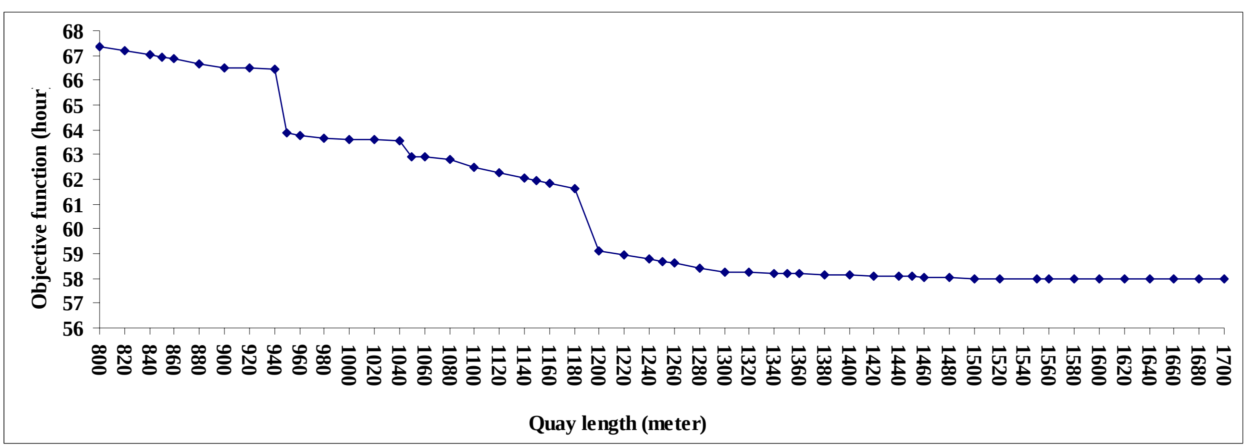

Figure 2 The changes of objective function of 8 ships problem against the length of quay

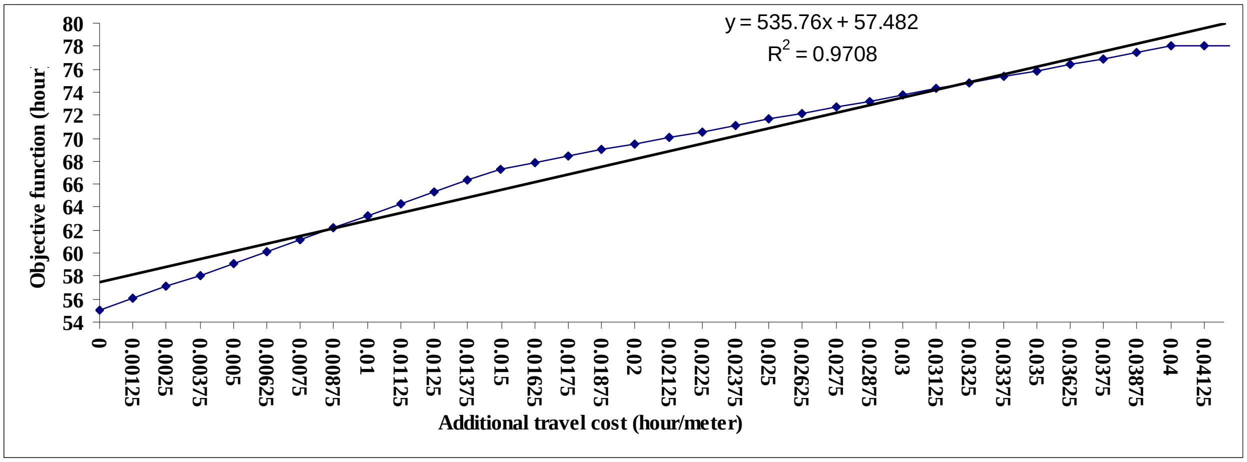

Figure 3 The changes of objective function of 8 ships problem to increasing γ_i