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RESEARCH REPORT

A COLLABORATIVE AGREEMENT FOR BERTH SCHEDULING UNDER EXCESSIVE DEMAND

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Abstract: International seaborne trade has increased significantly during the last three decades and this growth is expected to continue at similar rates. To address the growing demand, terminal operators seek to improve productivity with the minimum capital investment. This report proposes a berth scheduling policy, where demand can be diverted from a dedicated marine container terminal to a multi-user one at an additional cost. The objective of the dedicated marine terminal operator is to minimize the total vessel handling costs. Due to complexity of the proposed mathematical formulation, a Memetic Algorithm is developed to solve the resulting problem. A number of numerical experiments are presented to evaluate efficiency of the new berthing policy and the solution algorithm. Results indicate that the suggested berthing policy yielded substantial cost savings to the dedicated marine container terminal operator during high demand periods.

Keywords: Marine container terminals, collaborative agreement, shared capacity, service time windows, Memetic Algorithm, cost savings.

INTRODUCTION

Maritime transportation is critical for international trade with approximately 90% of the global trade volume carried by vessels (Journal of Commerce, 2014). To meet the growing demand while facing capacity expansion limitations (e.g., lack of land, high cost of expansion, etc.) marine container terminal operators have emphasized on the importance of planning and operations' optimization as a means to increase productivity. Terminal capacity can be increased by upgrading the existing or constructing new infrastructure, but this requires significant capital investments. Alternatives to construction of new infrastructure include improvement of conventional equipment and productivity by introducing new forms of technology, information systems, and work organization. One approach that can increase productivity without a capital investment is better utilization of the existing capacity between terminal operators through collaborative agreements (Cargo Business, 2014). One may view such agreements as the answer of port operators to alliances formed by liner shipping companies that allow vessels from different liner shipping companies to be served at different terminals of the same port.

Various studies have been published that discuss collaborative agreements between liner shipping companies, including formation of alliances (Panayides and Wiedmer, 2011); selection of strategic alliance partners (Ding and Liang, 2005); liner shipping alliance stability (Yang et al., 2011); and collaborative vs. non-collaborative policies comparison between liner shipping companies (Lei et al., 2008). A few studies have explored collaborative agreements between liner shipping companies and marine container terminal operators (Golias and Haralambides, 2011; Wang et al., 2015). In this report we propose a berth scheduling policy, where based on a contractual agreement the dedicated (or private) container terminal (DCT) may divert vessels to a multi-user (or public) container terminal (MUT). To the authors' knowledge, only one other study to date has been published (Imai et al., 2008a), explicitly modeling collaborative agreements between marine container terminal operators. The policy proposed in that study diverted vessels with excessive waiting times to an external terminal with the objective to minimize the total diverted vessel service time. The problem, studied in this report, extends that policy as follows:

i) The DCT operator diverts vessels based on a more generalized cost function, as it is unlikely that terminal operators will base service decisions solely on the vessel waiting times;

ii) For each diverted vessel the proposed optimization model will select the optimal TW and handling rate among the available ones, offered by the MUT operator (i.e., the handling rate and TW allocation for each diverted vessel is a decision made by the DCT operator), and

iii) A service time window (TW) constraint is applied to each diverted vessel, as a terminal operator (i.e., the multi-user terminal) will not accept a vessel at any time during the planning horizon (as such action may disrupt service of its own customers).

The rest of the paper is organized as follows. The next two sections describe the problem and present the mathematical formulation, aiming to model the proposed DCT berth scheduling policy. The fourth section describes the solution algorithm, and the fifth one presents results from numerical experiments, performed to evaluate the solution algorithm and the proposed berth scheduling policy. The last section concludes the paper and outlines future research directions.

PROBLEM DESCRIPTION

In this report we consider a seaport with two container terminals (DCT and MUT). DCT serves vessels from one liner shipping company and MUT from various ones. The latter assumptions do not limit the applicability of the proposed model for other cases and they can be relaxed as needed (e.g., DCT serves vessels from multiple liner shipping companies). The DCT operator has a contractual agreement of diverting vessels to MUT. Since MUT also provides service to its own vessels, diverted vessels (from DCT) can only be handled during particular TWs. For each TW, the MUT operator offers various vessel handling rates (measured in TEUs/hr.) and charges (measured in USD/TEU). We assume that both DCT and MUT operators have incorporated concession fees and tariffs in the handling costs used in the model (Psaraftis, 2005; Saeed and Larsen, 2010). All three parameters (i.e., TWs, handling rates, and charges) are known in advance and are fixed for each berth planning period (usually one to two weeks). The DCT operator is able to request one of the available handling rates for each diverted vessel (i.e., vessel handling time at MUT is a decision variable, given that the MUT operator needs to serve, as efficiently as possible, its own vessels). This decision allows the DCT operator and the carrier to weigh delayed departure costs, if a vessel is served at the DCT, vs. increased handling costs (and reduced or no delayed departure costs), if the same vessel is served at MUT. The proposed policy assumes a one way demand diversion (i.e., from DCT to MUT) and is only applicable in the cases, where MUT (after its berth planning has been established) has capacity to accommodate additional demand. The proposed model can be applied in the reverse direction, but not in cases, where demand is shared among both terminals (i.e., two way diversion).

Furthermore, it is assumed that the MUT operator will not alter its berth schedule to better accommodate the diverted demand (i.e., change the duration of a TW by delaying start of service of other vessels or divert resources (cranes) from other vessels/berths to increase handling rates). If a vessel service is completed on time, no penalties/premiums are imposed to the DCT operator. A vessel cannot be diverted for service, if service cannot be completed within the TW under the highest available handling rate. Note that the same waiting and delayed/early departure costs are applied to vessels served at DCT. We assume that both terminals have discrete berth layouts, and only one vessel can be served at each berth at any given time. Note that vessel handling time at DCT varies by its berth assignment (see Beirwirth and Meisel, 2010 for a description of the "*preferred berth*" concept).

MATHEMATICAL FORMULATION

The DCT berth scheduling policy, described in the previous section, is formulated as a non-linear mixed integer mathematical model (from now on referred to as *BSDM*). Next we present the basic notations used throughout the paper, followed by the mathematical formulation of *BSDM*. Additional notations will be defined throughout the paper as needed.

Nomenclature

Sets

$V = \{1, \dots, n\}$	Set of vessels requesting service at DCT
$B = \{1, \dots, m\}$	Set of berths
$T = \{1, \dots, k\}$	Set of available TWs at MUT

$R_t = \{1, \dots, q\}, t \in T$	Set of available handling rates during TW t at MUT

Decision variables

$x_{vb}, v \in V, b \in B$	=1 if vessel v is served at berth b and zero otherwise (at DCT)
$d_{vt}, v \in V, t \in T$	=1 if vessel v is diverted for service at MUT during TW t and zero otherwise
$y_{ps}, p, s \in V, p \neq s$	=1 if vessel s is served at the same berth as vessel p as its immediate successor and zero otherwise (at DCT)
$f_v, v \in V$	=1 if vessel v is served as the first vessel at the assigned berth and zero otherwise (at DCT)
$l_v, v \in V$	=1 if vessel v is served as the last vessel at the assigned berth and zero otherwise (at DCT)
$SR_{vt}, v \in V, t \in T$	requested handling rate for diverted vessel v during TW t (TEUs/hr.)

Auxiliary variables

$t_v, v \in V$	start time of service for vessel v (at either terminal)
$LD_{v,}\ v \in V$	hours of late departure for vessel v
$ED_v, v \in V$	hours of early departure for vessel v
$H_{vt} = \dfrac{NC_v}{SR_{vt}}, v \in V, t \in T$	handling time of vessel v during TW t at MUT (hrs.)

Parameters

$A_v, v \in V$	arrival time of vessel v (hrs.)
$NC_v, v \in V$	number of containers (un)loaded from/to vessel v (TEUs)
$D_{vb}, v \in V, b \in B$	handling rate of vessel v at berth b at DCT (TEUs/hr.)
$S_{vb} = \dfrac{NC_v}{D_{vb}}, v \in V, b \in B$	handling time of vessel v at berth b at DCT (hrs.)
$RD_v, v \in V$	requested departure time of vessel v (hrs.)
$PS_{vt}, v \in V, t \in \mathrm{T}$	=1 if vessel v can finish service during TW t under the highest handling rate available and zero otherwise
$hc_v, v \in V$	handling cost for vessel v at DCT (USD/hr.)
$hc_t^r, t \in T, r \in R_t$	handling cost at MUT during TW t under handling rate r (USD/TEU)
$dc_v, v \in V$	late departure penalty for vessel v (USD/hr.)
$ep_v, v \in V$	early departure premium for vessel v (USD/hr.)
$[st_t; ft_t], t \in T$	start and end of TW t
M	large positive number

BSDM:

$$min[\sum_{v \in V} \sum_{t \in T} (NC_v d_{vt} hc_t^r) + \sum_{v \in V} \sum_{b \in B} (S_{vb} x_{vb} hc_v) + \sum_{v \in V} (dc_v LD_v) - \sum_{v \in V} (ep_v ED_v)] \tag{1}$$

Subject to:

$$\sum_{b\in B} x_{vb} + \sum_{t\in T} d_{vt} = 1\ \forall v \in V \quad (2)$$

$$f_s + \sum_{p\in V\neq s} y_{ps} + \sum_{t\in T} d_{st} = 1\ \forall s \in V \quad (3)$$

$$l_p + \sum_{s\in V\neq p} y_{ps} + \sum_{t\in T} d_{pt} = 1\ \forall p \in V \quad (4)$$

$$f_p + f_s + d_{pt} + d_{st} \leq 3 - x_{pb} - x_{sb}\ \forall p, s \in V, p \neq s, b \in B, t \in T \quad (5)$$

$$l_p + l_s + d_{pt} + d_{st} \leq 3 - x_{pb} - x_{sb}\ \forall p, s \in V, p \neq s, b \in B, t \in T \quad (6)$$

$$y_{ps} - 1 \leq x_{pb} + d_{pt} - x_{sb} - d_{st} \leq 1 - y_{ps}\ \forall p, s \in V, p \neq s, b \in B, t \in T \quad (7)$$

$$t_v \geq A_v\ \forall v \in V \quad (8)$$

$$t_v \geq \sum_{t\in T} (st_t d_{vt})\ \forall v \in V \quad (9)$$

$$ft_t \geq t_v + H_{vt} - M(1 - \sum_{t\in T} d_{vt})\ \forall v \in V, t \in T \quad (10)$$

$$t_s \geq t_p + \sum_{b\in B} (S_{pb} x_{pb}) - M(1 - y_{ps})\ \forall p, s \in V, p \neq s \quad (11)$$

$$LD_v \geq t_v + \sum_{b\in B} (S_{vb} x_{vb}) - RD_v - M(1 - \sum_{b\in B} x_{vb})\ \forall v \in V \quad (12)$$

$$LD_v \geq t_v + \sum_{t\in T} (H_{vt} d_{vt}) - RD_v - M(1 - \sum_{t\in T} d_{vt})\ \forall v \in V \quad (13)$$

$$LD_v \geq 0\ \forall v \in V \quad (14)$$

$$ED_v = max(0;\ RD_v - [t_v + \sum_{b\in B} (S_{vb} x_{vb})] - M(1 - \sum_{b\in B} x_{vb}))\ \forall v \in V \quad (15)$$

$$ED_v = max(0;\ RD_v - [t_v + \sum_{t\in T} (H_{vt} d_{vt})] - M(1 - \sum_{t\in T} d_{vt}))\ \forall v \in V \quad (16)$$

$$d_{vt} \leq PS_{vt}\ \forall v \in V, t \in T \quad (17)$$

$$x_{vb} \in \{0,1\}\ v \in V, b \in B \quad (18)$$

$$d_{vt} \in \{0,1\}\ v \in V, t \in T \quad (19)$$

$$PS_{vt} \in \{0,1\}\ v \in V, t \in T \quad (20)$$

$$y_{ps} \in \{0,1\}\ p, s \in V \quad (21)$$

$$f_v, l_v \in \{0,1\}\ v \in V \quad (22)$$

$$LD_v, t_v, ED_v, NC_v, A_v, D_{vb}, S_{vb}, H_{vt}, RD_v, SR_{vt}, hc_v, hc_t^r, dc_v, ep_v, st_t, ft_t \in R^+\ \forall v \in V, t \in T, r \in R_t \quad (23)$$

The objective function (1) minimizes the total handling cost of vessels calling at DCT. The first component of the objective function estimates handling costs for vessels calling and served at DCT. The second component of the objective function estimates handling costs for vessels calling at DCT but served at MUT. The third and fourth components estimate penalties/premiums due to late/early departures of vessels calling at DCT (served at DCT or MUT). Constraints set (2) ensure that a vessel is served once either at DCT or MUT. Constraints set (3) indicate that a vessel is either served first or after another vessel at DCT, or it can be diverted for service at MUT.

Constraints set (4) ensure that a vessel is either served last or before another vessel at DCT, or it can be diverted for service at MUT. Constraints set (5) indicate that only one vessel is served first at each berth at DCT. Constraints set (6) ensure that only one vessel is served last at each berth at DCT. Constraints set (7) indicate that a vessel can be served after another, if they are both assigned to the same berth at DCT. Constraints set (8) ensure that handling of a vessel starts only after its arrival. Constraints set (9) indicate that handling of a diverted vessel cannot start before the beginning of a TW. Constraints set (10) ensure that service of a diverted vessel, assigned at a TW under selected handling rate, should be completed before the end of the TW. Constraints set (11) compute service times of vessels at DCT. Constraints sets (12) through (14) estimate late departures, while constraints sets (15) and (16) estimate early departures. Constraints set (17) ensure that a vessel will not be diverted to a TW at MUT, if it cannot be served there during that TW length. Constraints sets (18) through (23) define the decision variables and parameters. Next we present a procedure, used to select handling rates for each available TW at MUT for a diverted vessel.

Optimal handling rate at MUT for diverted vessels

In *BSDM* the optimal handling rate (SR_{vt}) and time (H_{vt}) for a diverted vessel are decision and auxiliary variables respectively. In this subsection we propose a procedure (Procedure 1) to select the optimal handling rate and estimate the handling time of any diverted vessel, before the optimization model is executed. This is possible because, if the decision is made to divert a vessel, the optimal handling rate only depends on the finish time and handling costs. Let VFT_{vt}^{r} and $OCDV_{vt}^{r}$ denote the finish time and handling cost (handling and delayed/early departure) of vessel v, served at MUT during TW t under handling rate r. The proposed procedure loops through all the vessels and TWs and selects the optimal handling rate (SR_{vt}) for each vessel and TW combination by minimizing the handling cost ($OCDV_{vt}^{r}$). The vessel handling rate estimation (*VHRE*) procedure is presented next. Note that: i) PS_{vt} is also calculated as part of *VHRE*, and ii) pseudocode conventions from Smed and Hakonen (2006) are used throughout this report.

Procedure 1. Vessel Handling Rate Estimation (*VHRE*)

$\boldsymbol{VHRE}(V, T, R_t, A_v, NC_v, RD_v, ft_t, hc_t^r, hr_t^r, dc_v, ep_v)$
in: $V = \{1, \dots, n\}$ - set of vessels; $T = \{1, \dots, k\}$ - set of TWs; $R_t = \{1, \dots, q\}$ - set of available handling rates during TW t; A_v - arrival time of vessel v; NC_v - number of containers assigned to vessel v; RD_v - requested departure time of vessel v; ft_t - end of TW t; hc_t^r - handling cost at TW t under handling rate r; hr_t^r - value of handling rate r at TW t; dc_v - late departure penalty for vessel v; ep_v - early departure premium for vessel v
out: SR – the optimal handling rate for each vessel at each available TW

$|VFT| \leftarrow n \cdot k \cdot q$; $|OCDV| \leftarrow n \cdot k \cdot q$; $|SR| \leftarrow n \cdot k$; $|PS| \leftarrow n \cdot k$ ◁ Initialization
$v \leftarrow 1; t \leftarrow 1; r \leftarrow 1$
for all $v \in V$ **do**
  for all $t \in T$ **do**
    for all $r \in R_t$ **do**

$VFT_{vt}^{r} \leftarrow max(st_t; A_v) + \left(\frac{NC_v}{hr_t^r}\right)$ ⊲ Estimate vessel finish time

$OCDV_{vt}^{r} \leftarrow (NC_v \cdot hc_t^r) + max(VFT_{vt}^{r} - RD_v; 0) \cdot dc_v - max(RD_v - VFT_{vt}^{r}; 0) \cdot ep_v$

$PS_{vt} = max[0, \frac{VFT_{vt}^{r} - ft_t}{abs(VFT_{vt}^{r} - ft_t)}]$ ⊲ Assess feasibility of serving a vessel during the given TW

$r \leftarrow r + 1$

end for

$SR_{vt} \leftarrow \underset{r}{argmin}(OCDV_{vt}^{r})$ ⊲ Estimate the optimal handling rate

$t \leftarrow t + 1$

end for

$v \leftarrow v + 1$

end for

return SR

SOLUTION ALGORITHM

As the berth scheduling problem is known to be NP-Hard (Bierwirth and Meisel, 2015), a Memetic Algorithm (*MA*) is developed to obtain good quality solutions within acceptable computational time. *MAs* employ local search heuristics and (often) provide higher quality solutions and faster convergence as compared to Evolutionary Algorithms - *EAs* (Eiben and Smith, 2003; Arivudainambi and Rekha, 2013). The main steps of the proposed *MA* are summarized in Procedure 2 and explained in detail throughout this section.

Procedure 2. Memetic Algorithm (*MA*)

$\boldsymbol{MA}(V, B, T, PopSize, MutRate, StopCriterion)$

in: $V = \{1, \dots, n\}$ - set of vessels; $B = \{1, \dots, m\}$ - set of berths at DCT; $T = \{1, \dots, k\}$ - set of TWs; $PopSize$ – population size; $MutRate$ – mutation rate; $StopCriterion$ – stopping criterion

out: $BestChrom$ – the best vessel assignment at DCT and MUT

$|Pop| \leftarrow PopSize$; $|Fit| \leftarrow PopSize$; $|Parents| \leftarrow PopSize$; $|Offspring| \leftarrow PopSize$

$Chrom \leftarrow \boldsymbol{InitChrom}(V, B, T)$ ⊲ Chromosome initialization

$gen \leftarrow 0$

$Pop_{gen} \leftarrow \boldsymbol{InitPop}(Chrom, PopSize)$ ⊲ Population initialization

$Fit_{gen} \leftarrow \boldsymbol{Evaluate}(Pop_{gen})$ ⊲ Initial population fitness evaluation

while $StopCriterion \leftarrow FALSE$ **do**

$gen \leftarrow gen + 1$

8: $Parents_{gen} \leftarrow \boldsymbol{SelectParents}(Pop_{gen})$ ⊲ Select parents

9: $Offspring_{gen} \leftarrow \boldsymbol{MAoperation}(Parents_{gen}, MutRate, V_{DCT}, V_{MUT})$ ⊲ Produce offspring

10: $Fit_{gen} \leftarrow \boldsymbol{Evaluate}(Offspring_{gen})$ ⊲ Offspring fitness evaluation

11: $Pop_{gen+1} \leftarrow \boldsymbol{Select}(Offspring_{gen}, Fit_{gen})$ ⊲ Define population in the next generation

12: **end while**

13: **return** $BestChrom$

In steps 1- 4 the chromosomes and population are initialized. In step 5, fitness functions values of the initial population chromosomes are estimated. Then, the algorithm enters the main loop (steps 7 through 11). In step 8, function $SelectParents(Pop_{gen})$ identifies parents from the current population (i.e., variable $Parents_{gen}$) to be used in step 9 and produce new offspring. In step 9, function $MAoperation(Parents_{gen}, MutRate, V_{DCT}, V_{MUT})$ applies the stochastic operator and two groups of local search heuristics (*LSHs*) to produce new offspring (i.e., variable $Offspring_{gen}$). The first group of *LSHs* is directed to improve the DCT vessel schedule (will be referred to as V_{DCT}) after applying the stochastic operator. The second group of *LSHs* is directed to improve the MUT vessel schedule (will be referred to as V_{MUT}) after applying the stochastic operator. In step 10, function $Evaluate(Offspring_{gen})$ calculates fitness function values (i.e., variable Fit_{gen}) for the offspring, and in step 11, function $Select(Offspring_{gen}, Fit_{gen})$ selects individuals, based on their fitness, to become candidate parents in the next generation. *MA* exits the loop, when a termination criterion is satisfied. The algorithm was coded in MATLAB 7.11.0 (R2010b). Next we present in detail each of the components of the developed *MA*.

Chromosome representation

An integer chromosome was adopted to represent a solution (i.e., vessel assignment at both DCT and MUT). Note that terms solution, individual, and vessel assignment will be used interchangeably throughout the paper. Each chromosome is composed of genes (Eiben and Smith, 2003). Genes are represented by vessels, assigned for service at DCT and MUT. Position and value of a gene along the chromosome will be referred to as locus and allele respectively (Eiben and Smith, 2003). An example of a chromosome for a small problem instance is shown in Figure 1, where six vessels request service at DCT, which has two berths. In this example MUT has six available TWs, dedicated to serve the diverted vessels from DCT. In this example vessel "6" is diverted for service at MUT during the third TW. As for DCT, vessels "2", "4", and "5" are served (in that order) at berth "1", while vessels "1" and "3" are served (in that order) at berth "2".

Chromosome Representation

	The DCT												The MUT				
Vessel/Order	2	4	5	0	0	0	1	3	0	0	0	0	0	0	6	0	0
Berth/TW	Berth 1						Berth 2						1	2	3	4	5
													TWs				

Figure 1: Chromosome representation example.

Population initialization

During initialization all vessels are assigned for service at DCT based on a First Come First Served with Earliest Finish Time Policy (*FCFS_EFTP*) rule. Other heuristics or exact methods can be applied to initialize the chromosomes but are left as future research. Note that randomly initialized populations are not advisable, as they will contain a significant number of infeasible and low-quality individuals, negatively affecting convergence patterns and the final solution quality (Eiben and Smith, 2003; Sivanandam and Deepa, 2008). In this report various sizes of the initial population ($PopSize$) will be evaluated and details are presented in the numerical experiments section. The population size remains constant and equal to the initial population size throughout the *MA* evolution.

Parent selection

Parent selection determines individuals from the current population that will be allowed to produce offspring via the *MA* operations at a given generation. The proposed *MA* applies a deterministic parent selection scheme (i.e., all survived offspring become parents), as this strategy is widely used in Evolutionary Programming and Genetic Algorithms (Eiben and Smith, 2003).

MA operations

Crossover and mutation are common *EA/MA* operators. However, for the chromosome structure, proposed in this report, typical crossover operators (e.g., one-point crossover, two-point crossover) will result in a complex infeasibility, as each offspring may inherit combinations of parent genes, representing the same vessels. Such individuals may be repaired; however, computational efforts will be much more significant as compared to repairing infeasibility, caused by mutation. Several types of mutation operations have been presented in the literature (Eiben and Smith, 2003), and in this study swap mutation was applied because of its efficiency (Golias et al., 2009). Other mutation operators (e.g., insert, invert, scramble, etc.) are replaced by more efficient *LSHs*, described in the next section. The Swap Mutation Operator (SMO) randomly swaps genes along the chromosome, representing both groups of vessels served at DCT and MUT respectively (an example of swap mutation is shown in Figure 2, where vessels 5 and 6 swap terminals). The number of genes, swapped in each chromosome, is defined by the mutation rate ($MutRate$). Various $MutRate$ values will be examined in the numerical experiments section. Before any *MA* operations are performed, the Elitist strategy is employed to store the best individual to be used as a parent in the next generation.

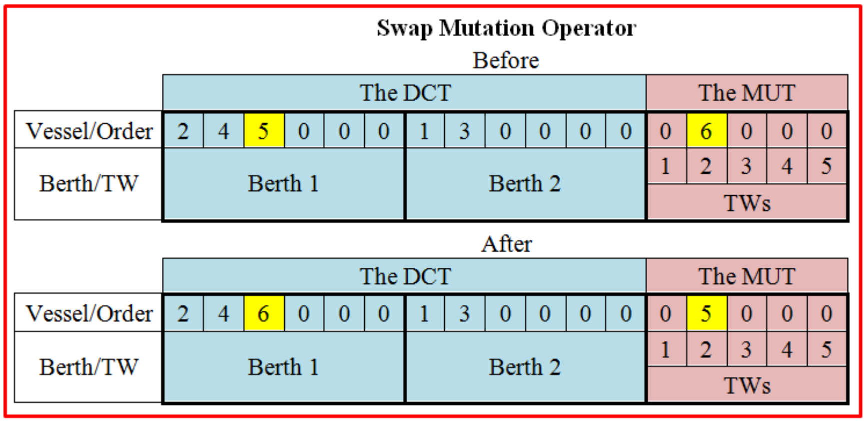

Figure 2: Swap mutation operator example.

Local search heuristics (LSHs)

In this section two *LSHs* that improve DCT vessel assignment during *MA* operations are described. Additionally, an optimization model is developed to schedule vessels at MUT after swap mutation operations have been performed (i.e., after the sets of vessels served at each terminal have been selected). Performance of the heuristics and the optimization model in terms of computational time and solution quality are evaluated in the numerical experiments section. The local search heuristics and optimization model substitute other stochastic operators (e.g., crossover) and are applied after the swap mutation operations (see Figure 3).

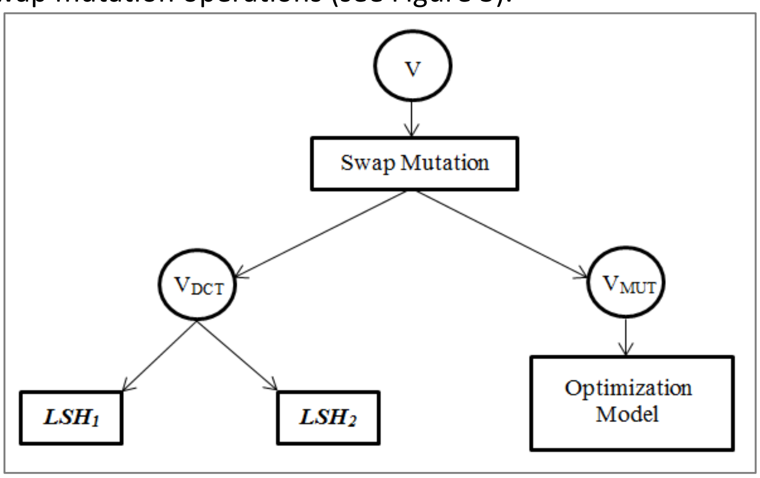

Figure 3: Local Search Heuristics.

Dedicated container terminal local search heuristics

Single Berth Dispatch Heuristic

The first heuristic (from now on referred to as the Single Berth Dispatch Heuristic or *SBDH*) belongs to the family of dispatch heuristics for the unrelated machine scheduling problem (Pinedo, 2008). Once jobs are assigned to each machine, dispatch heuristics are applied to refine the initial schedule based on attributes of each job (e.g., assigning jobs of the same family in a batch requires a machine set up only for the first job, which will reduce the total set up costs).

SBDH estimates vessel service order at each berth (without considering vessels at the other berths) and is based on two parameters: arrival ($A_v \; \forall v \in V_{DCT}$) and handling times ($S_{vb} = \frac{NC_v}{D_b} \; \forall v \in V_{DCT}, b \in B$). Depending on the average arrival and handling times, *SBDH* sorts DCT vessels either based on their arrival or handling time, or based on the sum of their arrival and handling times. In case of a static berth allocation problem, where all vessels are already at the port in the beginning of the planning horizon, vessels are sorted only based on their handling times. Note that hours of early and late departures (i.e., components of the objective function) are dependent on the departure time request of each vessel: $LD_v = f(RD_v), ED_v = f(RD_v)$. In this study the requested departure time of each vessel was assigned based on the vessels' arrival and handling times (i.e., $RD_v = f(A_v, S_{vb}) \; \forall v \in V_{DCT}, b \in B$). Hence, both *SBDH* attributes directly account for the problem's objective. Denote BA_b as the time when the berth b becomes idle at the first time in the planning horizon (in this study $BA_b = 0 \; \forall b \in B$); TH as a pre-specified threshold value. The steps of *SBDH* can be described in Procedure 3.

Procedure 3. Single Berth Dispatch Heuristic (*SBDH*)

$\boldsymbol{SBDH}(V_{DCT}, B, A_v, S_{vb}, x_{vb}, VP_b, BA_b, TH)$
in: $V_{DCT} = \{1, \dots, n\}$ - set of vessels assigned to DCT; $B = \{1, \dots, m\}$ - set of berths; A_v - arrival time of vessel v; S_{vb} - handling time of vessel v at berth b; x_{vb} - vessel to berth assignment; VP_b - vessel positions at berth b; BA_b - time when the berth b becomes idle at the first time in the planning horizon; TH - pre-specified threshold
out: Ω – refined vessel to berth assignment at DCT
1: $|\Omega| \leftarrow n \cdot m$ ⊲ Initialization
2: $b \leftarrow 1$
3: **for all** $b \in B$ **do**
4: $v \leftarrow 1$
5: **for all** $v \in V_{DCT}$ **do** ⊲ Determine vessel arrival times at the given berth
6: **if** $x_{vb} = 1$ **then**
7: $A_{vb} \leftarrow A_v$
8: **end if**
9: $v \leftarrow v + 1$
10: **end for**
11: $avga_b \leftarrow (\sum_{v=1}^{n} A_{vb}) / (\sum_{v=1}^{n} x_{vb})$ ⊲ Estimate the average vessel arrival time at the berth
12: $avgs_b \leftarrow (\sum_{v=1}^{n} S_{vb}) / (\sum_{v=1}^{n} x_{vb})$ ⊲ Estimate the average vessel handling time at the berth
13: **if** $BA_b < min(A_{vb})$ **and** $[avga_b - min(A_{vb})] > avgs_b + TH$ **then**
14: $\Omega_b \leftarrow \boldsymbol{Sort}(VP_b, A_{vb})$ ⊲ Sort vessels based on their arrival times
15: **else if** $BA_b < min(A_{vb})$ **and** $[avga_b - min(A_{vb})] + TH < avgs_b$ **then**
16: $\Omega_b \leftarrow \boldsymbol{Sort}(VP_b, S_{vb})$ ⊲ Sort vessels based on their handling times

else if $BA_b < min(A_{vb})$ **and** $|[avga_b - min(A_{vb})] - avgs_b| \leq TH$ **then**
$\Omega_b \leftarrow \boldsymbol{Sort}(VP_b, A_{vb} + S_{vb})$ ⊲ Sort vessels based on sum of their arrival and handling times
else if $BA_b \geq max(A_{vb})$ **then**
$\Omega_b \leftarrow \boldsymbol{Sort}(VP_b, S_{vb})$ ⊲ Sort vessels based on their handling times
end if
$b \leftarrow b + 1$
end for
return Ω

A sensitivity analysis for the threshold value (TH) was conducted and results are presented in the numerical experiments section.

Epochal EA (EEA)

The second heuristic employs an *EA* as means to improve vessel assignment at each DCT berth (from now on referred to as the Single Berth *EA* or *SBEA*). Chromosome representation for *SBEA* is depicted in Figure 4A, where six vessels "2", "5", "4", "7", "9", and "8" request service at berth b of DCT. *SBEA* has features similar to *MA*: a) deterministic parent selection, b) swap mutation for the *SBEA* operations (Figure 4B), and c) offspring selection (discussed later in section). The main drawback of using an additional *EA* within the proposed *MA* is an increased computational time. To address this issue *SBEA* is applied periodically after a pre-specified number of generations (a.k.a., epoch), and only to a group of individuals within the population. The notion of "*epoch*" is widely used in Island *EA* models (Eiben and Smith, 2003).

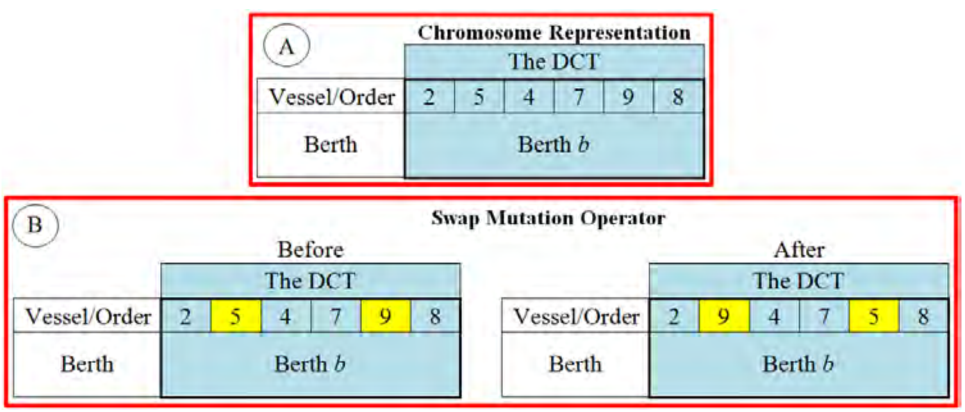

Figure 4: *SBEA* features.

Multi-user terminal vessel assignment

A mathematical model was developed to assign the diverted vessels to the available MUT TWs during each generation. The model formulation (which is a relaxation of *BSDM* and referred to as *P1*) is as follows.

$$P1: min[\sum_{v\in V_{MUT}} \sum_{t\in T}(NC_v d_{vt} hc_t^r) + \sum_{v\in V_{MUT}}(dc_v LD_v) - \sum_{v\in V_{MUT}}(ep_v ED_v)] \quad (24)$$

Subject to:

(8), (9), (10), (13), (14), (16), (17), (19), (20), (23)

$$\sum_{t\in T} d_{vt} = 1 \ \forall v \in V_{MUT} \quad (25)$$

$$\sum_{v\in V_{MUT}} d_{vt} \leq 1 \ \forall t \in T \quad (26)$$

The objective function (24) minimizes the total handling cost of diverted vessels, i.e. handling costs at MUT, penalties due to late vessel departures, and premiums due to early vessel departures. Constraints set (25) ensure that each diverted vessel is served only once. Constraints set (26) indicate that no more than one diverted vessel can be served at each TW. *P1* includes one decision variable ($d_{vt}\ \forall v \in V_{MUT}, t \in T$), several auxiliary variables (i.e., $t_v, LD_v, ED_v\ \forall v \in V_{MUT}$), and non-linear constraints set (16). In *P1* handling costs at MUT for a given set of diverted vessels are already known (i.e., estimated by *VHRE)*. *P1* can thus be reduced to *P2* as follows.

$$P2: min \sum_{v\in V_{MUT}} \sum_{t\in T} c_{vt} d_{vt} \quad (27)$$

Subject to:

(19), (25), (26)

where c_{vt} is the total cost of vessel service during a TW at MUT, estimated by *VHRE*.

Even though *P2* is unimodular (Rader, 2010), the solution time complexity depends on the approach used. In this study three solution approaches were evaluated to solve *P2*: a) A binary programming formulation using MATLAB's optimization solver (this solution approach will be referred to as OVA_{BP} – optimal vessel assignment via binary programming), b) A linear relaxation of *P2* (i.e., relaxation of the integrality constraints) using GAMS optimization solver (this solution approach will be referred to as OVA_{LP} – optimal vessel assignment via linear programming), and c) A heuristic solution algorithm (this solution approach will be referred to as *IVAH* – improved vessel assignment heuristic). GAMS was used as a solver for the second approach due to the inability of MATLAB linear optimization solver to produce an integer solution. Next we describe *IVAH* in more detail.

IVAH heuristic

Let $V_{MUT} = \{1,2,\ldots,m\}$ and $T = \{1,2,\ldots,t\}$ be the set of vessels diverted to MUT, and available TWs respectively. Also let t_v be a TW, to which vessel v is assigned for service. For each diverted vessel at MUT we can calculate the total handling cost (c_{vt}) for each TW, associated with service of a given vessel. If a vessel cannot finish service at TW, then that cost is set equal to a large positive number *M*. Let $C_{vt} = \min_{t\in T}(c_{vt})\ \forall v \in V_{MUT}$ be the minimum handing cost of vessel v during TW t. We define priority of a vessel to occupy a TW as the sum of additional costs, endured by the vessel, if it is not served at the TW with the minimum handling cost: $p_v = \sum_{t\in T}(c_{vt} - C_{vt})\ \forall v \in V_{MUT}$. Once these inputs are calculated, *IVAH* selects the vessel with the highest priority and assigns it to the TW with the minimum handling cost. That vessel and the

TW, it occupies, are removed from the list of vessels (V_{MUT}) and available TWs (T) respectively, and priorities for the remainder of the vessels are recalculated. The procedure continues until each vessel has been assigned to a TW. The *IVAH* heuristic is described in Procedure 4.

Procedure 4. Improved Vessel Assignment Heuristic (*IVAH*)

$\boldsymbol{IVA}(V_{MUT}, T, c_{vt})$
in: $V_{MUT} = \{1, \dots, m\}$ - set of diverted vessels; $T = \{1, \dots, k\}$ - set of TWs; ; c_{vt} - total cost of serving vessel v during TW t
out: Ψ – refined vessel to TW assignment at MUT

$|\Psi| \leftarrow k$ ⊲ Initialization
while $V_{MUT} \neq \emptyset$ **do**
  $v \leftarrow 1$
  for all $v \in V_{MUT}$ **do**
    $C_{vt} \leftarrow \min_{t \in T}(c_{vt})$ ⊲ Determine the minimum cost of vessel service
    $p_v \leftarrow \sum_{t \in T}(c_{vt} - C_{vt})$ ⊲ Define vessel priority
    $v \leftarrow v + 1$
  end for
  $v \leftarrow \underset{v}{argmax}(p_v)$ ⊲ Find the vessel with the highest priority
  $t_v \leftarrow \underset{t}{argmin}(c_{vt})$ ⊲ Find the TW with the minimum service cost
  $V_{MUT} \leftarrow V_{MUT} - \{v\}$
  $\Psi_t \leftarrow \Psi_t \cup \{v\}$ ⊲ Assign the vessel with the highest priority
  $T \leftarrow T - \{t\}$
end while
return Ψ

A computational time analysis of the three proposed solution approaches for *P2* and the optimality gap analysis for *IVAH* are presented in the numerical experiments section.

Fitness function

For *EAs*/*MAs* the fitness function is usually associated with the objective function (Sivanandam and Deepa, 2008). In the proposed *MA* the fitness function value was set equal to the objective function value without applying any scaling mechanisms.

Offspring selection

Offspring selection at a given generation of *MA* chooses the strongest individuals that will be able to adapt to the environment and become competent parents, while at the same time allows for a small number of weak individuals to move on (Sivanandam and Deepa, 2008). In this report we developed a selection procedure based on the Roulette Wheel Selection *RWS* (Goldberg, 1989). Probabilistic selection mechanisms (like *RWS*) do not necessarily keep the best individuals and do not necessarily exclude the worst individuals, resulting in a genetic drift (Eiben and Smith, 2003). A Modified *RWS* (*MRWS*) was developed in this study, which addresses the first issue (i.e., keep the best individuals) by applying the Elitist Strategy and the second issue (i.e., excluding the worst individuals and avoiding the genetic drift) by setting an upper bound on the cumulative normalized fitness value. *MRWS* was validated against the Tournament Selection mechanism, and provided better solution quality and faster convergence.

Stopping criterion

If the optimal objective function value or a lower bound is known a priori, the algorithm can be stopped once a specified optimality gap is reached. *BSDM* is NP-hard, and the optimal solution (or a strict lower bound) is not known in advance. In this report the algorithm was terminated, if no change in the objective function value occurred after a pre-specified number of generations (*MaxNumGen* of 3,000 generations) or the maximum number of generations is reached (*LimitGen* of 10,000 generations).

NUMERICAL EXPERIMENTS

This section presents numerical experiments performed to evaluate the proposed *MA* and to quantify benefits from the DCT berth scheduling policy. Numerical data used (shown in Table 1) were generated based on available port operations literature (Imai et al., 2008a-b; Golias et al., 2009; Carlo et al., 2013). Three exponentially distributed vessel interarrival time (IAT) patterns with mean of 2, 3, and 4 hours were considered to evaluate the proposed berth scheduling policy under high, medium, and low demand respectively. Based on the available literature (Trade Fact of the Week, 2014; TRP, 2013) and assuming a mix of vessel operations that include mooring, loading and discharge of containers, type of container (empty, loaded, size, reefer), re-stowing (on-board the vessel or via quay), the DCT handling cost was set equal to $650 per container. The DCT handling rate at the “preferred berth” was set equal to 125 TEUs/hr. (e.g., five QCs with average productivity of 25 TEUs/hrs. are assigned to each berth). The “preferred berth” was identified for each vessel based on *FCFS_EFTP*. Handling time of vessels at the other berths was generated in relation to the berth with the minimum handling time (Golias et al., 2009). Handling charges at MUT, as previously discussed, were dependent on the handling rate requested, and were assumed to be higher than the handling charges at DCT (Ballis et al., 2010). The range of MUT handling rates was selected based on data published in Journal of Commerce (2015). It was assumed that the MUT operator could provide 4 different handling rates for each TW. The number of available TWs varied from zero (the DCT operator cannot divert any vessels to MUT) to twenty. Hourly late/early departure penalties/premiums were also based on the available literature (Zampelli, 2013). Four vessel departure time requests were considered (ranging from very strict to very soft) using uniform distributions (denoted as U) and were dependent on the vessels' arrival and handling times.

Table 1: Numerical data.

Planning horizon	1 week
Vessel interarrival patterns (exponential)	2, 3, and 4 hrs.
Requested vessel departure $[RD_v\ \forall v \in V]$ – RD1, RD2, RD3, RD4	Arrival time + Handling Time × [U(1.0-1.2), U(1.2-1.4), U(1.4-1.6), U(1.6-1.8)]
Containers assigned to each vessel $[NC_v\ \forall v \in V]$	U(750-3000) TEUs
Handling rate at DCT preferred berth $[D_{vb}\ \forall v \in V, b \in B]$	125 TEUs/hr.
DCT number of berths	[4, 6, 8]
MUT number of available TWs	[0, 5, 10, 15, 20]
TW duration	10÷20 hrs.
MUT available handling rates $[r \in R_t]$	[75; 125; 150; 250] TEUs/hr.
Charge at MUT $[hc_t^{rt}\ \forall t \in T, t \in R_t]$	[750; 1000; 1200; 2000] USD/TEU
Late departure penalty $[dc_v\ \forall v \in V]$	7000 USD/hr.
Early departure premium $[ep_v\ \forall v \in V]$	5000 USD/hr. (70% of the penalty)

Using data presented in Table 1 two subsets of datasets were developed. The first subset was used for the evaluation of the berth scheduling policy and consisted of 180 instances of all possible combinations of vessel arrival types, vessel departure time requests, DCT berth capacity, and number of available TW shown in Table 1 (i.e., [3 vessel arrival types] × [4 vessel departure time requests] × [3 DCT berth capacities] × [5 TW availabilities at MUT]). The second subset was used for the evaluation of the *MA* and *LSHs* and calibration of their parameters. The rational of using two different groups of datasets is to avoid bias in the evaluation of the DCT berth scheduling policy (i.e., evaluate the berth scheduling policy with datasets that were used to calibrate parameters of *MA* and *LSHs*). All numerical experiments were conducted on a Dell T1500 Intel(T) Core i5 Processor with 1.96 GB of RAM.

MA parameter tuning

Population size ($PopSize$) and mutation rate ($MutRate$) were selected based on preliminary *MA* runs. Three candidate values were considered for $MutRate$ - {2, 4, 6}. Five candidate values were considered for $PopSize$ - {20, 30, 40, 50, 60}. Results of the conducted analysis indicated that *MA* with $PopSize$ of 30 and $MutRate$ of 2 demonstrated the best trade-off between the solution quality and the computational time.

Evaluation of *LSHs* at DCT

Additional computational experiments were performed to select values for parameters of *SBDH* and *EEA*. While *SBDH* has only one parameter (threshold TH), *EEA* has four parameters: 1) *Epoch*, 2) $q \in Q$ – the quantity of individuals selected for improvement, 3) population size of *SBEA* – $PopSizeSBEA$, and 4) mutation rate of *SBEA* – $MutRateSBEA$. A total of seven TH values were considered: $TH = \{0, 5, 10, 15, 20, 30, 40\}$. Results of the analysis indicated that *SBDH* with

$TH = 40$ demonstrated the best trade-off between the solution quality and the computational time. As for *EEA*, preliminary experiments suggested *Epoch* = 100, $PopSizeSBEA = 10$, and $MutRateSBEA = 2$. The quantity of individuals ($q \in Q$), chosen for improvement by *EEA*, will be uniformly distributed between 10% and 20% of the *MA* population. *SBEA* will be terminated if no improvement in the objective function was observed after *MaxNumGenSBEA* = 100 generations.

Evaluation of *LSHs* at MUT

A comparative analysis was conducted to evaluate the three approaches to solve *P2* (OVA_{LP}, OVA_{BP}, and *IVAH*). Twenty instances with different TWs, ranging from 2 to 40 with an increment of two, were developed. For each instance 500 cases were created with different number of containers per vessel, uniformly distributed between 750 and 3,000 TEUs. It was assumed that the number of diverted vessels was equal to the number of available TWs (i.e., the worst complexity for the MUT scheduling that may occur during *MA* evolution), while IAT was set equal to 2 hours. The rest of the parameters were adopted from Table 1. Five replications for each solution approach were performed for each case to estimate the average computational time (the objective function values did not change from replication to replication). Results of the time complexity analysis for OVA_{LP}, OVA_{BP}, and *IVAH* are presented in Figure 5 for each one of the twenty instances (average values over 500 cases and five replications for each case).

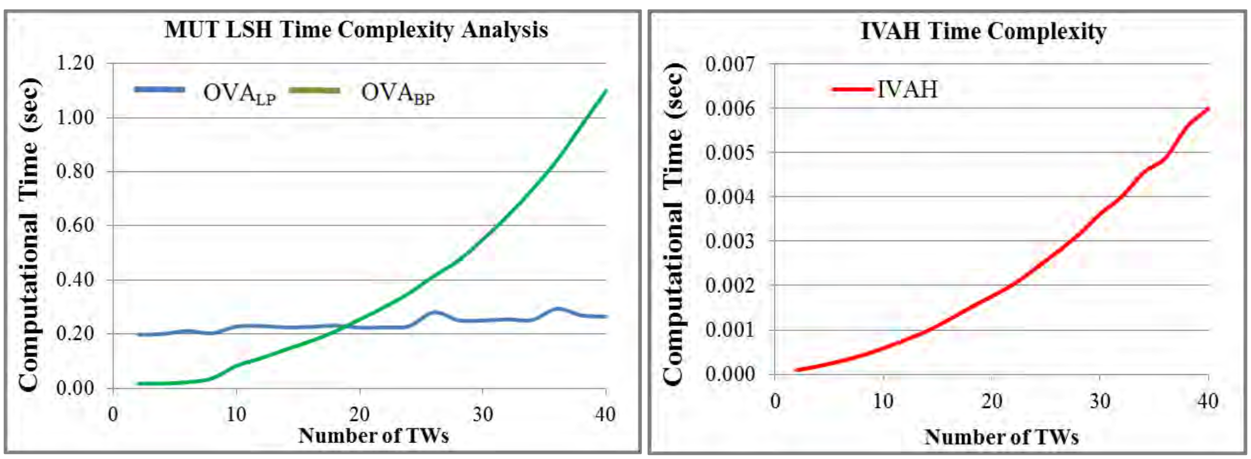

Figure 5: MUT *LSH* time complexity analysis.

IVAH substantially outperformed OVA_{LP} and OVA_{BP} in terms of computational time (e.g., 0.006 sec vs. 0.265 sec vs. 1.010 sec respectively for TWs = 40). OVA_{BP} was more efficient than OVA_{LP} for scenarios with TWs < 20. This can be explained by OVA_{LP} requiring an additional time for exchanging data between MATLAB and the external optimization solver (GAMS). However, when the number of available TWs exceeds 20, OVA_{LP} is recommended to determine the optimal MUT vessel assignment.

Computational experiments demonstrated that *IVAH* optimality gap (Δ) did not exceed 7% over all cases and instances. The maximum average optimality gap $\Delta = 3.73\%$ was observed for the instance with 40 TWs. Based on *IVAH* time complexity and optimality gap analysis, the heuristic was found to be applicable as the least time consuming with acceptable optimality gaps.

MA stability and performance

The next step in the analysis was to evaluate the *MA* stability and performance. Let *MA*(LSH_i) be the *MA* that applies LSH_i (i = 1, 2) to improve the DCT vessel assignment. Each *MA*(LSH_i) used *IVAH* as the solution approach for *P2* (i.e., to improve the MUT vessel assignment). The analysis was conducted using four problem instances, generated using the data shown in Table 1. Ten replications with different starting berth schedules were performed to evaluate the stability and performance of both *MAs*. Difference in the objective function value at termination from replication to replication did not exceed 1% for both *MA*(*SBDH)* and *MA*(*EEA)*, which showcases stability of both algorithms. *MA*(*EEA)* outperformed *MA*(*SBDH)* in terms of the solution quality (on average 2.8% lower objective function values) but underperformed in terms of computational time (12.4 vs. 16.3 minutes on average). As the latter was not significant, *MA(EEA)* was selected as the solution algorithm. Note that OVA_{BP} was applied upon *MA* convergence to the best individual (i.e., to ensure optimality of the final MUT vessel assignment) and provided the cost reduction for the majority of cases.

Berthing policy evaluation

Two performance measures were chosen to evaluate the proposed berth scheduling policy: i) total savings over the planning horizon (i.e., 1 week), and ii) TW utilization (i.e., how many vessels were diverted to MUT). All 180 instances described in the beginning of this section were used as the input data.

Total Savings

Total savings (shown in Table 2) were estimated as the difference in the objective function value for the case where all vessels are handled at DCT under *FCFS_EFTP* rule (i.e., TWs = 0) and the cases where a subset of vessels are diverted for service at MUT (i.e., TWs > 0). As expected, higher cost savings are observed for high demand/low capacity at the DCT (e.g., for the case of five available TWs (TWs = 5), high demand period (IAT = 2 hrs.), and 4 DCT berths, monetary benefits (for the DCT operator) from diverting vessels to MUT range from $1.25 to $1.57 million). Total cost savings increased with the number of available TWs under high demand. As expected, no significant savings are observed for low demand periods (e.g., IAT = 4 hrs.) and high DCT berth capacity (e.g., 8 berths). Note that for low demand or high capacity cases savings do not continue to increase with the number of TWs. For example, in the case of IAT = 4 hrs. and 4 berths at the DCT the optimal number of TWs is five (increasing the number of TWs beyond this point does not provide additional cost savings). Results from the proposed policy and model can thus be used to negotiate the number of TW requested by the DCT operator.

Time Window Utilization

Another important step during evaluation of the berthing policy was comparing the amount of diverted vessels to the number of available TWs. The TW utilization increased with more frequent vessel arrivals and lower DCT berth capacity. The number of diverted vessels decreases (as expected) during low demand periods (e.g., IAT = 4 hrs.) and high DCT berth capacity (e.g., 8 berths). In this study TW duration was relatively tight (between 10 hrs. and 20 hrs.), since MUT was assumed to have frequent arrivals of its own vessels. From these results we can anticipate that the number of diverted vessels should increase with the TW duration since: i) the number of vessels that can request service (i.e., "*fit*" within a TW) will increase, and ii) diverted vessels will be able to request lower handling rates and still complete service within the allocated TW (reducing the cost of service at MUT). Modeling negotiations of the TW duration is left as future research.

Table 2: Berthing policy total savings per planning period ($US x 1,000).

		4 Berths (@ DCT)				6 Berths (@ DCT)				8 Berths (@ DCT)			
IAT	TW	RD1	RD2	RD3	RD4	RD1	RD2	RD3	RD4	RD1	RD2	RD3	RD4
2 hrs.	5	1,248	1,393	1,415	1,575	93	567	837	949	-	-	-	-
	10	3,096	3,529	2,364	2,675	298	567	860	949	57	42	29	23
	15	4,509	4,337	4,226	4,198	665	567	1,086	1,059	57	42	29	23
	20	6,110	5,216	5,565	5,001	809	645	1,086	1,059	57	42	29	23
3 hrs.	5	149	-	685	686	-	-	-	-	-	-	-	-
	10	595	362	685	686	-	-	-	-	-	-	-	-
	15	740	362	937	937	-	-	-	-	-	-	-	-
	20	740	362	976	937	-	-	-	-	-	-	-	-
4 hrs.	5	27	11	4	-	-	-	-	-	-	-	-	-
	10	27	11	4	-	-	-	-	-	-	-	-	-
	15	27	11	4	-	-	-	-	-	-	-	-	-
	20	27	11	4	-	-	-	-	-	-	-	-	-

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CONCLUSIONS AND FUTURE RESEARCH

In this report a berth scheduling policy for a dedicated marine container terminal with excessive demand was proposed, where vessels can be diverted for service to another terminal during negotiated time windows. A Memetic Algorithm that utilized two groups of local search heuristics was developed to solve the mathematical formulation modeling the berthing policy. The proposed policy showed greater savings for scenarios with higher demand and lower capacity at the dedicated marine container terminal. Savings of the dedicated marine container terminal operator increased with the number of available time windows, while no substantial savings were observed for low demand periods and high capacity at the dedicated marine container terminal. The developed model can also be used as a tool to assist terminal operators in price setting and negotiations of container handling rates during high/medium demand periods. Future research may focus on: a) cost functions for penalties/premiums based on vessel size and load, b) vessel priorities, c) multiple vessel service per time window, d) adaptive mutation operators to improve solution quality and convergence rates, e) vessel assignment heuristics during mutation, and f) negotiation of time windows start and end times.

REFERENCES

1. Arivudainambi, D. and Rekha, D. (2013). Memetic algorithm for minimum energy broadcast problem in wireless ad hoc networks. *Swarm and Evolutionary Computation* 12: 57–64.
2. Ballis, A., Golias, J., C. and Abakoumkin, A. (1997). A comparison between conventional and advanced handling systems for low volume container maritime terminals. *Maritime Policy and Management* 24(1): 73-92.
3. Ballis, A., Dimitriou, L. and Paravantis, J. (2010). Quay to Storage Area Container Transfer: Critical Review of Modeling Techniques and Practical Outcomes. 89th Annual Meeting of the Transportation Research Board, 2010.
4. Bierwirth, C. and Meisel, F. (2015). A follow-up survey of berth allocation and quay crane scheduling problems in container terminals. *European Journal of Operational Research* 244(3): 1-15.
5. Cargo Business. (2014). Report: Container shipping vulnerable at Puget Sound ports. http://www.cargobusinessnews.com/news, accessed 23 May 2014.
6. Carlo, H., Vis, I. and Roddbergen, K. (2013). Seaside operations in container terminals: literature overview, trends, and research directions. *Flexible Services and Manufacturing Journal*: 1-39.
7. Ding, J. and Liang, G. (2005). Using fuzzy MCDM to select partners of strategic alliances for liner shipping. *Information Sciences* 173(1): 197–225.
8. Eiben, A.E. and Smith, J.E. (2003). *Introduction to Evolutionary Computing*. Springer-Verlag, Berlin/Heidelberg.
9. Goldberg, D.E. (1989). *Genetic algorithms in search, optimization, and machine-learning*. Addison-Wesley.
10. Golias, M., Saharidis, G., Boile, M., Theofanis, S. and Ierapetritou, M. (2009). The berth allocation problem: Optimizing vessel arrival time. *Maritime Economics & Logistics* 11(4): 358-377.
11. Golias, M. and Haralambides, H. (2011). Berth scheduling with variable cost functions. *Journal of Maritime Economics and Logistics* 13(2): 174-189.
12. Imai, A., Nishimura, E. and Paradimitriou, S. (2008a). Berthing ships at a multi-user container terminal with a limited quay capacity. *Transportation Research Part E* 44(1): 136–151.
13. Imai, A., Chen, H., Nishimura, E. and Paradimitriou, S. (2008b). The simultaneous berth and quay crane allocation problem. *Transportation Research Part E* 44(5): 900–920.
14. Journal of Commerce. (2014). Maritime news, 2014. https://www.joc.com/maritime-news, accessed on 26 January 2015.

15. Journal of Commerce. (2015). New operational methods improving port productivity. www.joc.com, accessed on 26 January 2015.
16. Lei, L., Fan, C., Boile, M. and Theofanis, S. (2008). Collaborative vs. non-collaborative container-vessel scheduling. *Transportation Research Part E* 44(3): 504–520.
17. Panayides, P. and Wiedmer, R. (2011). Strategic alliances in container liner shipping. *Research in Transportation Economics* 32(1): 25-38.
18. Pinedo, M. (2008). *Scheduling: Theory, Algorithms, and Systems*. Springer Science + Business Media, LLC.
19. Psaraftis N.H. (2005). Tariff Reform in the Port of Piraeus: a Practical Approach. *Maritime Economics & Logistics* 7: 356–381.
20. Rader, D. J. (2010). *Deterministic Operations Research: Models and Methods in Linear Optimization*. Wiley.
21. Saeed N. and Larsen I. O. (2010). Container terminal concessions: A game theory application to the case of the ports of Pakistan. *Maritime Economics & Logistics*. 12: 237–262.
22. Sivanandam, S. and Deepa, S. (2008). *Introduction to Genetic Algorithms*. Springer Berlin Heidelberg New York.
23. Smed, J. and Hakonen, H. (2006). *Algorithms and Networking for Computer Games*. John Wiley & Sons, Ltd. ISBN: 0-470-01812-7
24. Trade Fact of the Week. (2014). Cost to export one container of goods, New York to London: ~$3,000. http://progressive-economy.org/2013/02/06/cost-to-export-one-container-of-goods-new-york-to-london-3000, accessed on 10 June 2014.
25. TRP. (2013). General Schedule of Rates and Services. www.trp.com.ar, accessed on 12 June 2014.
26. Wang, S., Liu, Z. and Qu, X. (2015). Collaborative mechanisms for berth allocation. *Advanced Engineering Informatics*, in press.
27. Yang, D., Liu, M. and Shi, X. (2011). Verifying liner Shipping Alliance's stability by applying core theory. *Research in Transportation Economics* 32(1): 15-24.
28. Zampelli, S., Vergados, Y., Schaeren, R., Dullaert, W. and Raa, B. (2013). The berth allocation and quay crane assignment problem using a CP approach. www.ua.ac.be, accessed on 26 January 2015.