Berth Allocation and Scheduling at Dedicated Marine Container Terminals with Excessive Demand

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ABSTRACT

International seaborne trade significantly increased during the last decades and this growth is expected to continue at similar rates. To address growing demand terminal operators seek to improve productivity with minimal capital investment. This paper introduces a new berth scheduling policy for a dedicated marine container terminal that diverts demand to a multi-user terminal. The objective of the dedicated container terminal operator is to minimize the total 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 the efficiency of the new berthing policy and solution algorithm.
INTRODUCTION

Maritime transportation is crucial for international trade with roughly 90% of the global trade volume carried by vessels (1). According to data by the United Nations Conference on Trade and Development (UNCTAD), a significant increase of dry (5.3% in tonnage), containerized (6.6% in tonnage), and major bulk cargo (4.5% in tonnage) was observed from 2012 to 2013, while similar future growth was projected for 2014 (2). The US Army Corp of Engineers (3) expects that US imports will grow at an average rate of 5.0% per year, reaching 60 million TEUs by 2037. During the same time period exports are forecasted to increase at an average rate of 5.5% per year and will grow up to 52 million TEUs. The overall international seaborne trade reached 9.6 billion tons in 2013 (4.2% increase from 2012). The majority of high value cargo and general consumption goods are shipped in containerized form. Liner shipping companies, looking for transport efficiency and economies of scale, have increased vessel size on the most of trade routes. The World Shipping Council (4) indicates that “it would require hundreds of freight aircrafts, many miles of rail cars, and fleets of trucks to carry the goods that can fit on one large liner ship”. Maersk, the biggest liner shipping company in the world, recently ordered 20 Triple E vessels with estimated capacity of 18,000 twenty foot equivalent units (TEUs). Triple E vessels are designed to reduce CO₂ emissions by 20% per container (5).

To meet the growing demand, and facing capacity expansion limitations (e.g., lack of land, high cost of expansion, etc.), marine container terminal operators have emphasized on the improvement of planning and operations as means to increase productivity. Terminal capacity can be increased by upgrading existing or constructing new infrastructure but requires significant capital investment (6). Alternatives that do not involve construction, such as improvement of conventional equipment and productivity by introducing new forms of technology (7), information systems (8), and work organization (9), are also available options. One approach that can increase productivity without capital investment is collaborative agreements1 between terminal operators (10). In this paper we present a mathematical model for a berth scheduling policy that is based on a contractual agreement between two terminals for shared capacity of the seaside. The contractual agreement allows a dedicated (or private) container terminal (DCT) to divert vessels to a multi-user (or public) container terminal (MUT). The problem is formulated as a non-linear mixed integer mathematical programming model and a Memetic Algorithm is proposed as the solution algorithm. The objective of the proposed model is to determine vessel assignment (calling at DCT) at both DCT and MUT and minimize handling and delayed departure vessel costs for the DCT operator.

The rest of the paper is organized as follows. The next section describes the problem and briefly discusses the relevant literature. The third section presents the mathematical formulation, proposed to model the berth scheduling policy. The fourth section describes the solution algorithm. The fifth section presents results from numerical experiments to evaluate the proposed solution algorithm and berth scheduling policy. The last section concludes the paper and provides future research directions.

PROBLEM DESCRIPTION

Marine container terminal operations and decision problems have kept the interest of numerous researches over the last two decades. For excellent reviews of the literature we refer (in chronological order) to Steenken, et al. (11), Stahlbock and Vos (12), Theofanis et al. (13), Beirwirth and Meisel (14), and Carlo et al. (15). These studies presented a detailed description of container terminal operations, overview of international seaborne trade history, outline of the major decision problems, and classification of various scientific publications by different topics. The problem, studied in this paper, is essentially an extension of the idea, proposed by Imai et al. (16), where vessels with excessive waiting times were diverted from a multi-user terminal to an external terminal. Unlike the study by Imai et al. (16), where decision on vessel diversion was based on waiting time, the berth scheduling policy proposed herein diverts vessels based on a more generalized cost function (that can include waiting time).

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1 On March, 2014 the Federal Maritime Commission sanctioned a request from the ports of Tacoma and Seattle to begin information exchanges aimed at boosting container traffic in the Puget Sound region.
Furthermore, the proposed berth scheduling policy imposes a service time window (TW) constraint for each diverted vessel. These TW constraints are suggested to better portray real world operations, where it is highly unlikely, that a terminal operator will accept any vessel from another terminal at any time. Adopting the latter policy may result in service disruption of MUT customers. Thus, it is more likely that the two terminals will enter an agreement similar to the one described next.

**Contractual Agreement Description**

We consider a marine port with two container terminals: DCT and MUT. The former serves vessels from a particular liner shipping company, while the latter from various liner shipping companies. DCT operator has a contractual agreement and can divert vessels to MUT. Since MUT also provides service to vessels of other liner shipping companies, diverted vessels (from DCT) can only be handled during particular TWs (see Figure 1A). For each TW MUT operator can offer to DCT various handling rates. MUT vessel handling charges are proportional to the handling rate (i.e., higher price for higher productivity, usually measured in TEUs/hr (un)loaded from/to the vessel). DCT operator is able to request one of the available handling rates (TEUs/hr), which is a function of QCs that MUT operator will employ during a given TW at the assigned berth. The latter option allows DCT operator to weigh different options of delayed departure costs if a vessel is served at its facility vs. handling costs (and reduced or no delayed departure costs) if a vessel is served at MUT. Note that MUT operator will not alter its berth schedule to better accommodate the diverted demand (i.e., delay start of service of other vessels or divert resources from other vessels/berths to increase handling rates during a TW). We assume that both (DCT and MUT) have discrete berth layouts and that 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 Theofanis et al. (13), Beirwirth and Meisel (14), for an excellent description of the “preferred berth”, vessel service time, location of containers at the storage yard and QC allocation/scheduling). Next we elaborate on the concept of vessel service at MUT during TWs.

**Service at MUT**

If a diverted vessel can be served within a TW at MUT there are two possible alternatives for its service completion time (see Figure 1B cases 1 and 2 respectively):

1. Vessel service is completed before the requested departure time, and the total service cost is equal to the handling cost and premium (negative cost) due to early vessel departure, and
2. Vessel service is completed after the requested departure time, and the total service cost is equal to the handling cost plus a penalty due to late vessel departure.

If vessel service is completed on time, no penalties/premiums are imposed. It is assumed that a vessel cannot be diverted for service at MUT (see case 3 in Figure 1B), if its service cannot be completed by the end of the TW under the highest available handling rate (for that TW). Note that similar waiting and delayed/early departure costs are applied to vessels served at DCT.

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2 These assumptions do not limit the generality of the proposed model and can be relaxed as needed (e.g., DCT serves vessels from multiple liner shipping companies)
3 Without loss of generality premiums from early departures can be excluded (i.e., set equal to zero). As will be discussed in the fourth section, excluding premiums from early departures reduces the models’ complexity
4 Premiums and penalties refer to DCT operator costs
MATHEMATICAL FORMULATION

The berth scheduling policy described in section 2 is formulated as a mixed-integer mathematical model (from now on referred to as BSDM) and is based on the generalized berth allocation and scheduling model, presented by Golias et al. (17). BSDM takes into account existence of an additional terminal (MUT) for handling diverted vessels, where DCT vessel handling rates at MUT are considered as parameters and are estimated using a heuristic algorithm (details are discussed later in this section). Next we present the basic notations used throughout the paper, followed by BSDM. Additional notations will be defined as needed.

Nomenclature

Sets

\[ V \] Set of vessels requesting service at DCT

\[ V_{DCT}, V_{MUT} \] Dynamic sets of vessels served at DCT and MUT respectively where

\[ V_{DCT} \cup V_{MUT} = V, V_{DCT} \cap V_{MUT} = \emptyset \]

\[ B \] Set of berths
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 \( t \)
- \( y_{ps}, p, s \in V, p \neq s \) =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)

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 the vessel \( v \)
- \( ED_v, v \in V \) hours of early departure for the vessel \( v \)

Parameters

- \( A_v, v \in V \) arrival time of vessel \( v \) (hours)
- \( NC_v, v \in V \) 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/hour)
- \( S_{vb} = \frac{NC_v}{D_{vb}}, v \in V, b \in B \) handling time of vessel \( v \) at berth \( b \) at DCT (hours)
- \( H_{vt}, v \in V, t \in T, r \in R_t \) handling time of vessel \( v \) during a TW \( t \) under handling rate \( r \) at MUT (hours)
- \( RD_v, v \in V \) requested departure time of vessel \( v \) (hours)
- \( hc_v, v \in V \) handling cost of vessel \( v \) at DCT (USD/hour)
- \( hc_r, t \in T, r \in R_t \) handling cost at MUT during a TW \( t \) under handling rate \( r \) (USD/TEU)
- \( dc_v, v \in V \) late departure penalty for vessel \( v \) (USD/hour)
- \( ep_v, v \in V \) early departure premium for vessel \( v \) (USD/hour)
- \([st_t, ft_t], t \in T \) start and end of a TW \( t \)
- \( M \) large positive number

BSDM:

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

Subject to:

\[
\sum_{b \in B} x_{vb} + \sum_{t \in T} d_{vt} = 1 \forall v \in V \tag{2}
\]

\[
f_p + \sum_{p \in V \setminus s} y_{ps} + \sum_{t \in T} d_{st} = 1 \forall s \in V \tag{3}
\]

\[
l_p + \sum_{s \in V \setminus p} y_{ps} + \sum_{t \in T} d_{pt} = 1 \forall p \in V \tag{4}
\]

\[
f_p + f_s + d_{pt} + d_{st} \leq 3 - x_{pb} - x_{sb} \forall p, s \in V, p \neq s, b \in B, t \in T \tag{5}
\]
\[ l_p + l_s + d_{pt} + d_{st} \leq 3 - x_{pb} - x_{sb} \forall p, s \in V, p \neq s, b \in B, t \in T \]

\[ y_{ps} - 1 \leq x_{pb} + d_{pt} - x_{sb} - d_{st} \leq 1 - y_{ps} \forall p, s \in V, p \neq s, b \in B, t \in T \]

\[ t_v \geq A_v \forall v \in V \]

\[ t_v \geq \sum_{t \in T} (s_t \times d_{vt}) \forall v \in V \]

\[ f_t \times d_{vt} \leq t_v + H_{vt}^r \forall v \in V, t \in T \]

\[ t_s \geq t_p + \sum_{b \in B} (S_{sb} \times x_{sb}) - M \times (1 - y_{ps}) \forall p, s \in V, p \neq s \]

\[ LD_v \geq t_v + \sum_{b \in B} (S_{vb} \times x_{vb}) - RD_v - M \times (1 - \sum_{b \in B} x_{vb}) \forall v \in V \]

\[ LD_v \geq t_v + (H_{vt}^r \times d_{vt}) - RD_v - M \times (1 - \sum_{t \in T} d_{vt}) \forall v \in V \]

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

\[ ED_v = \max(0, RD_v - [t_v + (H_{vt}^r \times d_{vt})] - M \times (1 - \sum_{t \in T} d_{vt})) \forall v \in V \]

\[ x_{vb} \in \{0,1\} \forall v \in V, b \in B \]

\[ d_{vt} \in \{0,1\} \forall v \in V, t \in T \]

\[ y_{ps} \in \{0,1\}, p, s \in V \]

\[ f_t, l_v \in \{0,1\}, v \in V \]

\[ LD_v, t_v, ED_v, N_C_v, A_v, D_v, S_v, h_r, RD_v, h_c, h_c^r, d_v, ep_v, st_v, f_t \in R^+ \forall v \in V_{MUT}, t \in T, r \in R_t \]

The objective function (1) minimizes the overall vessel handling cost, initially calling at DCT, i.e., handling cost either at DCT or MUT (first and second component respectively), and penalties/premiums due to late/early vessel departures (third and fourth component respectively). Constraints set (2) ensure that a vessel is served once either at DCT or at MUT. Constraints set (3) indicate that a vessel can either be served first or after another vessel at DCT, or it can be diverted to MUT. Constraints set (4) ensure that a vessel can either be served last or before another vessel at DCT, or it can be diverted to MUT. Constraints set (5) indicate that only one vessel can be served first at each berth of DCT. Constraints set (6) ensure that only one vessel can be served last at each berth of DCT. Constraints set (7) indicate that a vessel can be served after another, if they are both assigned to the same berth of 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 during a TW under handling rate \( r \in R_t \), 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 departure (hrs). Constraints sets (15) and (16) estimate early departures (hrs). Constraints sets (17) through (21) define the decision variables and parameters. Next we present a heuristic used to select handling rates for a diverted vessel for each available TW.

**Handling Rates Heuristic (HRH)**

HRH estimates optimal handling rates for all vessels, if they are served at MUT. Denote \( V_{FVT}^t \) and \( O_{CDV}^r \) as the finish time and service (handling and delayed/early departure) cost of vessel \( v \in V \), served at MUT during time window \( t \in T \) under handling rate \( r \in R_t \). Let \( S_{R_v}^t \) be the handling rate with the minimal cost \( O_{CDV}^r \) for vessel \( v \). Let \( Poss \) be a binary \( v \times t \) matrix, where \( Poss(v,t) = 1 \) if a vessel \( v \in V \) can be served during \( t \in T \), and = 0 otherwise. **HRH** pseudocode is presented next.
**HRH Pseudocode**

1. Set $V FT_{vt}^r = 0; O CDV_{vt}^r = 0; S R_{vt}^r = 0; Poss(v,t) = 0; \forall v \in V, t \in T, r \in R_t$

2. for $\forall v \in V, t \in T, r \in R_t$ set

   $V FT_{vt}^r = \max (s_{vt}; A_v) + \left( \frac{NC_v}{r} \right)$

3. $O CDV_{vt}^r = (NC_v \times h_{v t}) + \max (V FT_{vt}^r - RD_v; 0) \times d c_v - \max (RD_v - V FT_{vt}^r; 0) \times e p_v$

4. $S R_{vt}^r = \arg \min_r (O CDV_{vt}^r)$

5. if $V FT_{vt}^r \leq f t_t$

6. else

7. $Poss(v,t) = 1$

8. $Poss(v,t) = 0$

9. end

**SOLUTION APPROACH**

Even simple discrete berth scheduling (DBSP) formulations are difficult to solve (15) as they belong to the NP class problems (relaxed formulations result to the machine scheduling, knapsack, etc.). In this study a Memetic Algorithm (MA) was developed to obtain good quality solutions within acceptable computational time. MAs belong to the group of Evolutionary Algorithms (EAs), and are widely used for solving complex problems in different fields (16-20, 22-24). However, while EAs construct individuals using stochastic operators, MAs employ along with the stochastic operators local search heuristics and provide higher quality solutions and faster convergence (18, 20).

The main steps of the proposed MA are presented in Figure 2. In the first two steps, the chromosome and population are initialized. Then, the algorithm enters the main loop. In step 3 function \textit{SelectParents}(Pop(gen)) identifies parents in the population (i.e., variable Parents(gen)), while in step 4, function \textit{MAoperation}(Parents(gen)) applies stochastic operators and local search heuristics to produce the new offspring (i.e., variable Offspring(gen)). In step 5, function \textit{Evaluate}(Offspring(gen)) calculates fitness values (i.e., variable Fitness(gen)) for the offspring, and in step 6, function \textit{Select}(Fitness(gen)) selects individuals, based on their fitness, to become parents in the next generation (step 7). MA exits the loop, when a termination criterion is satisfied. The algorithm was coded using Matlab 7.11.0 (R2010b) on Dell T1500 Intel(T) Core™ with 1.96 GB of RAM. Next we present the main features of the suggested MA in more details.
Chromosome Representation
An integer chromosome was used in the developed MA to represent a solution. An example for a small problem instance is shown in Figure 3A, where six vessels request service at DCT which has two berths. MUT has six available TWs. In the example chromosome, vessel “6” was 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”.
FIGURE 3 MA Features.

Population Initialization
During initialization all vessels are assigned for service to DCT based on a First Come First Served with Earliest Finish Time Policy (FCFS_EFTP). Other heuristics or exact methods can be applied for more efficient initialization at both terminals 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 (20, 22). In this paper various sizes of the initial population (PopSize) have been evaluated (details are presented in the next section). The population size remains constant throughout MA (and equal to the initial population size). FCFS_EFTP is outlined next.

**FCFS_EFTP Pseudocode**

1. Sort vessels by their arrival times \( A_v \forall v \in V \)
2. Set \( BerthAvailability_b = 0 \forall b \in B \)
3. Assign vessel \( v \in V \) with the earliest arrival time \( A_v \) to the first available berth \( b \)
4. Compute Start Time \( ST_v = \max[A_v, BerthAvailability_b] \)
5. Calculate Service Finish Time \( FT_v = ST_v + S_{vb} \) (where \( S_{vb} \) - Handling Time)
6. Determine Position where a vessel \( v \in V \) is served along the berth \( b \)
7. Set \( BerthAvailability_b = FT_v \)
8. If all vessels are assigned \( \rightarrow \) Finish, else go to the Step 3

Parent Selection
Parent selection determines individuals from the current population that will be allowed to produce offspring, via 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 (20).

MA Operations
Crossover and mutation are common EA/MA operators. However, for the chromosome structure proposed in this paper, typical crossover operators (e.g., one-point crossover, two-point crossover) will result in infeasible offspring that require substantial computational effort to repair and were not adopted. Several types of mutation operations have been presented in the literature (20), and in this study swap

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5 No vessels are assumed present at any berth or TW at DCT and MUT respectively at the beginning of the planning horizon.
mutation was applied due to its efficiency (17-19). The Swap Mutation Operator (SMO) randomly swaps genes along the chromosome, representing both vessels served at DCT and MUT (an example of Swap Mutation is shown in Figure 3B). The number of genes selected for each chromosome is defined by the Mutation Rate (MutRate). Various MutRate values will be tested during MA evaluation in the next section. Before any further MA operations are performed, the Elitist strategy is employed to store the best individual and use as a parent in the next generation. Note that other mutation operators (e.g., insert, invert, scramble, etc.) were replaced by more efficient local search heuristics (described later in this section).

Feasibility during EA Evolution

A crucial feature of MA design is to ensure feasibility of individuals at each generation. In the problem studied herein an individual may become infeasible, if service of a vessel, diverted to the MUT TW, cannot be completed even under the highest available handling rate (case 3, Figure 1B). In the proposed MA, HRH identifies vessels that cannot be diverted and passes the information to SMO (i.e., genes identified by HRH will not be selected as swapping candidates). Other strategies can be used, such as assigning penalties to infeasible individuals (20). However, low penalties may increase the probability of infeasible individual to survive, and high penalties can negatively affect the computational time, when probabilistic offspring selection schemes are applied (as the one used in the proposed algorithm and described later in this section).

Local Search Heuristics (LSH)

Two local search heuristics were developed to improve vessel assignment during MA operations after SMO. The first focused on vessels served at MUT, and the second on vessels served at DCT. Next we describe both heuristics.

LSH at MUT

A mathematical model was developed to assign diverted vessels to the available TWs at MUT during each generation for each chromosome. The problem formulation (from now on referred to as relaxed BSDM or BSDM-R) is as follows.

**BSDM-R:**

\[
\begin{align*}
\text{min} & \quad \sum_{v \in V_{MUT}} \sum_{t \in T} (NC_v \times d_{vt} \times hc_f^t) + \sum_{v \in V_{MUT}} (dc_v \times LD_v) - \sum_{v \in V_{MUT}} (ep_v \times ED_v) \\
\text{Subject to:} & \\
\sum_{t \in T} d_{vt} &= 1 \quad \forall v \in V_{MUT} \quad (23) \\
\sum_{v \in V_{MUT}} d_{vt} &\leq 1 \quad \forall t \in T \quad (24) \\
t_v &\geq A_v \quad \forall v \in V_{MUT} \quad (25) \\
t_v &\geq \sum_{t \in T} (st_t \times d_{vt}) \quad \forall v \in V_{MUT} \quad (26) \\
f t_t \times d_{vt} &\leq t_v + H_t^v \quad \forall v \in V_{MUT}, t \in T \quad (27) \\
LD_v &\geq t_v + \sum_{t \in T} (H_t^v \times d_{vt}) - RD_v - M \times (1 - \sum_{t \in T} d_{vt}) \quad \forall v \in V_{MUT} \quad (28) \\
LD_v &\geq 0 \quad \forall v \in V_{MUT} \quad (29)
\end{align*}
\]
The objective function (22) minimizes the overall service cost of diverted vessels, i.e., handling costs, penalties due to late vessel departures, and premiums due to early vessel departures. Constraints set (23) ensure that each diverted vessel is served only once. Constraints set (24) indicate that no more than one diverted vessel can be served. Constraints set (25) ensure that handling of vessel starts only after its arrival. Constraints set (26) indicate that service of a vessel cannot start before the beginning of a TW. Constraints set (27) ensure that service of a vessel under handling rate \( r \in R_t \), should be completed before the end of the TW. Constraints sets (28) and (29) estimate hours of late departure of a vessel. Constraints sets (30) and (31) define the decision variables and parameters. 

BSDM-R includes one decision variable (\( d_{vt} \forall v \in V_{MUT}, t \in T \)), several auxiliary variables (i.e., \( t_v, L_D, E_D, N_C, A, H_v^r, R_D, h_c^r, d_v, e_p, s_t, f_t \in R^+ \forall v \in V_{MUT}, t \in T, r \in R_t \)) and a non-linear constraint (30). BSDM-R can be reduced to a less complex problem, when we consider that given a set of diverted vessels, service costs at MUT are computed by HRH. Thus, BSDM-R is reformulated as follows.

Reformulated BSDM-R or RBSDM-R:

min \( \sum_{v \in V_{MUT}} \sum_{t \in T} c_{vt} \times d_{vt} \)  

Subject to:

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

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

Where \( c_{vt} \) is the total cost of vessel service during a TW at MUT, estimated by HRH.

Objective (33) and constraints sets (34) and (35) are similar to the ones, used in BSDM-R. RBSDM-R is unimodular (i.e., relaxing the integrality constraints will produce an integer solution) and can be solved efficiently using CPLEX. The procedure of finding the optimal vessel assignment at MUT (from now on referred to as MUT Optimal Vessel Assignment or OVA) was coded and embedded in MA.

LSH at DCT

A local search heuristic was developed to improve vessel scheduling at DCT after SMO application. The proposed 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 (21). SBDH estimates the 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 (\( S_{vb} = \frac{N_C}{D_b} \ \forall v \in V_{DCT}, b \in B \)). Next we present the steps of SBDH.

SBDH Pseudocode

for \( \forall b \in B \) refine the vessel service order

if \( T_{lb} < \min(A_v) \& [\text{mean (A_v) - min(A_v)}] \gg \text{mean (S_{vb})} \) \( \rightarrow \) sort based on \( A_v \); 

else if \( T_{lb} < \min(A_v) \& [\text{mean (A_v) - min(A_v)}] \ll \text{mean (S_{vb})} \) \( \rightarrow \) sort based on \( S_{vb} \);
elseif $T_{IB} < \min(A_v)$ & $[\text{mean}(A_v) - \min(A_v)] \approx \text{mean}(S_{vb})$ \, sort based on $A_v + S_{vb}$; \
elseif $T_{IB} \geq \max(A_v)$ \, sort based on $S_{vb}$; 
end if

Note: $T_{IB}$ – time when the berth $b \in B$ becomes idle at the first time in the planning horizon.

$SBDH$ was evaluated using small to medium size instance problems (i.e., one berth and 5 to 10 vessels), and results where compared to schedules, obtained using CPLEX. The optimality gap was less than 5% and was considered as acceptable.

**Fitness Function**

For EAs/MAs the fitness function is usually associated with the objective function (22). In the proposed MA the fitness function value was set equal to the objective function value without applying any scaling mechanisms.

**Offspring Selection**

The offspring selection at a given generation of a MA is an important part of its design. It allows choosing the strongest individuals that will be able to adapt to the environment and reproduce competent parents, while at the same time allowing for a small number of weak individuals to move on (22-23). In this paper we developed a selection procedure based on the Roulette Wheel Selection (RWS, [24]). 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 (20). To address the first issue (i.e., keep the best individuals) we apply the Elitist Strategy. To address the second issue (i.e., excluding the worst individuals and avoid genetic drift) we designed a Modified RWS (MRWS) outlined next.

**MRWS Pseudocode**

Step 1: Calculate normalized fitness values for each individual
Step 2: Sort mutated individuals by normalized fitness values in the ascending order
Step 3: Estimate cumulative fitness values
Step 4: Flip the coin and get the value between 0 and $SelectPar$ ("rotate the wheel")
Step 5: Identify the individual with cumulative fitness value, close to the one obtained from Step 4. Select this individual for the next generation
Step 6: Repeat Steps 4 and 5 until the desired population size is reached

The main difference between RWS and MRWS is that mutated individuals are sorted by normalized fitness values in ascending order, and an additional parameter $SelectPar$ (with values between 0 and 1), defines the "wheel’s rotation". Depending on the search objectives, $SelectPar$ values may vary (high for exploration and low for exploitation). Based on preliminary MA runs, $SelectPar = 0.20$ was found to be efficient (i.e., demonstrated faster convergence and lower objective function values). Lower values of $SelectPar$ are not recommended, as they potentially result in premature convergence. MRWS was validated against the Tournament Selection mechanism, and provided better solution quality and faster convergence.

**Stopping Criterion**

If the optimal value of the objective function value or a lower bound is known a priori, the algorithm can be stopped once an optimality gap is reached. BSDM is NP-hard, and the optimal solution (or a strict lower bound) is not known in advance. In this paper the algorithm was terminated, if no change in the
objective function value occurred after a pre-specified number of generations (MaxNumGen of 3000
generations).

NUMERICAL EXPERIMENTS
This section presents a number of numerical experiments to assess benefits of the proposed berthing
policy and to evaluate performance of the proposed MA. Numerical data were generated based on the
available literature (15-19, 25) and are presented in Table 1. Three vessel arrival patterns are considered
to evaluate the proposed berth scheduling policy under high, medium, and low demand (average vessel
inter-arrival times of 2, 3, and 4 hours respectively). Based on the available literature (26, 27) and
assuming a mix of vessel operations that include mooring, loading and discharge of containers, type of
container (empty, loaded, size, refer), re-stowing (on-board the vessel or via quay), the handling cost was
set equal to $650 per container. Handling charges at MUT, as previously discussed, depend on the
handling rate requested, and are assumed higher than the handling charges at DCT (25). MUT operator
can provide 4 possible handling rates at each TW. The number of available TWs varies from 2 to 10 to
evaluate the efficiency of the proposed berthing strategy. Hourly late/early departure penalties/premiums
were defined based on the available literature (28). A strict departure time request, equal to the arrival
plus handling time at DCT was assumed for each vessel.

<table>
<thead>
<tr>
<th>TABLE 1 Numerical Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of calls</td>
</tr>
<tr>
<td>Vessel inter-arrival patterns</td>
</tr>
<tr>
<td>Requested vessel departure $[RD_v \forall v \in V]$</td>
</tr>
<tr>
<td>Containers assigned to each vessel $[NC_v \forall v \in V]$</td>
</tr>
<tr>
<td>Handling rate at DCT $[D_{vb} \forall v \in V, b \in B]$</td>
</tr>
<tr>
<td>Number of berths at DCT</td>
</tr>
<tr>
<td>Number of available TWs</td>
</tr>
<tr>
<td>TW duration</td>
</tr>
<tr>
<td>Available handling rates at MUT $[t \in R_t]$</td>
</tr>
<tr>
<td>Charge at MUT $[hc_t^v \forall t \in T, t \in R_t]$</td>
</tr>
<tr>
<td>Late departure penalty $[dc_v \forall v \in V]$</td>
</tr>
<tr>
<td>Early departure premium $[ep_v \forall v \in V]$</td>
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</tbody>
</table>

MA Performance
MA was compared to six EAs, developed using the methodology in section 4, and various mutation rates
(MutRate = [0.01, 0.005, 0.002], which corresponds to [6, 4, 2] swapped genes), and population sizes
(PopSize = [20, 40, 60]). The main difference between EAs and MA is that during step 4 (Figure 2) EAs
do not employ OVA and SBDH to improve vessel assignment at the terminals. A total of six EAs were
considered and are listed next:

- EA1 – EA with PopSize = 40 and MutRate = 0.01
- EA2 – EA with PopSize = 40 and MutRate = 0.005
- EA3 – EA with PopSize = 40 and MutRate = 0.002
- EA4 – EA with PopSize = 20 and MutRate = 0.002
- EA5 – EA with PopSize = 60 and MutRate = 0.002
- EA6 – EA with PopSize = 40, MutRate = 0.002, and PermRate = 0.002

EA6 applies an additional Permutation Operator that randomly picks several genes (PermRate)
and randomly changes their positions. The main difference between the Permutation Operator and SMO
is that in the former case genes will alter their loci at each DCT berth of every individual. Multiple
replications were performed for each algorithm. It was found that differences in the objective function
values, obtained from 10 replications for EAs and MA, didn’t vary significantly (less than 0.2%), which indicates stability of the algorithms. EA and MA replications, which provided the lowest objective function values, were selected for the analysis. The convergence pattern and the objective function value at termination for each algorithm are presented in Figure 4.

We observe that low mutation rates returned better objective function values. Increasing population size improved the objective value at termination. A large population size allows exploring different domains of the search space. However, computational time increases with population size. In this study EAs with $PopSize = 40$ provided a good trade-off between solution quality and computational time. The Permutation Operator produced worse quality individuals, as it introduced randomness in the vessel assignment at DCT. MA provided the best objective function value and converged faster than the other heuristics.

![Figure 4 MA and EA Comparison.](image)

**FIGURE 4 MA and EA Comparison.**

**Berthing Policy Evaluation**

The proposed berth scheduling policy was evaluated by changing the number of available TWs from zero to ten with an increment of two. MA was used as a solution algorithm with parameter values set equal to $PopSize = 40$, $MutRate = 0.002$, $MaxNumGen = 200$, and $MRWS$ with $SelectPar = 0.20$. Results are shown in Figure 5, where it can observed that:

- Increasing number of TWs reduces the service cost for all scenarios with higher demand, exhibiting higher savings;
- Increasing number of TWs at MUT for cases with low demand does not affect the service cost significantly (e.g., instances with TWs = 6, 8, and 10 for the terminal with IAT3);
- The proposed strategy will be efficient at busy container terminals with frequent vessel arrivals;
- Cost improvement decreases with TW increase (e.g., the difference in cost from zero to two TWs is $17, $16, and $16 per TEU, while from eight to ten TWs is $9, $7, and $1 per TEU for the high, medium and small problem instances respectively).

Note that results presented herein could assist DCT operator to develop pricing schemes for different demand periods. For example, if 2 TWs are available at MUT then the smallest handling charge
per container that DCT operator can implement (and be profitable) is $920, $804, and $776 for high, medium, and low demand periods respectively. Furthermore, the suggested model can assist DCT operator in negotiating additional TWs at MUT based on marginal handling costs. The proposed model can also assist DCT operator during negotiations on handling rates at MUT TWs. The proposed model can also assist DCT operator during negotiations on handling rates at MUT TWs. The proposed model can also assist DCT operator during negotiations on handling rates at MUT TWs. The proposed model can also assist DCT operator during negotiations on handling rates at MUT TWs.

![FIGURE 5 Berthing Policy Efficiency.](image)

**CONCLUSIONS AND FUTURE RESEARCH AVENUES**

In this paper a berth scheduling policy for marine container terminals with excessive demand was proposed, where vessels can be diverted from one terminal to another. A Memetic Algorithm was developed to solve the mathematical model of the berthing policy. The proposed MA employed local search heuristics and provided better solutions when compared to other EAs. The suggested policy showed greater savings under frequent vessel arrivals (lower vessel inter-arrival rates). Savings also increased with the number of available TWs at the terminal, where vessels were diverted (although marginal gains decreased). The proposed model can also be used as a tool to assist terminal operators in price setting/negotiating of container handling rates during at different demand periods (both at DCT and MUT). Future research is focusing on: a) cost functions for penalties/premiums based on vessel size or load; b) vessel priorities; c) adaptive Mutation Operators to improve solution quality and convergence rates; and d) development of vessel assignment heuristics during mutation.
REFERENCES


