A Metaheuristic Approach for the Seaside Operations in Maritime Container Terminals

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Abstract. The service time of the container vessels is the main indicator of the competitiveness of a maritime container terminal. This work proposes two Variable Neighbourhood Searches (VNS) in order to tackle the Tactical Berth Allocation Problem and the Quay Crane Scheduling Problem, which are the main operational problems in the seaside. These metaheuristics are integrated into a framework that provides an overall planning for the vessels arrived to port within a given time horizon. The performance of the proposed VNSs is compared with the most highlighted solution methods published in the related literature. In addition, the effectiveness of the framework is assessed in real size environments.

Keywords: Metaheuristic, Container Terminal, Seaside Operations.

1 Introduction

The maritime container terminals are core elements within the international sea freight trade (Vis and de Koster [10]). These facilities are open systems dedicated to the exchange of containers in multimodal transportation networks. In general terms, a container terminal is split into three different functional areas (Petering [7]). Firstly, the quay area is the part of the port in which the container vessels are berthed in order to load and unload containers to/from them. Secondly, the yard area is aimed at storing the containers until their later retrieval. Lastly, the mainland interface connects the terminal with the road transportation.

The most widespread indicator concerning the competitiveness of a maritime container terminal is the service time required to serve the container vessels arrived to the port (Yeo [4]). The seaside operations are those arising in the quay area of a maritime container terminal and directly related to the service of container vessels. The operational decisions stemming from the service of container vessels can be modeled through a well-defined sequence of steps. Once the container vessel arrives to the port, a berthing position in the quay is assigned to it on the basis of its particular characteristics (dimensions, stowage plan, etc.). A subset of the available quay cranes at the terminal is allocated to the vessel. These quay cranes perform the loading and unloading operations associated

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with the containers of the vessel. An in-depth survey on the seaside operations is conducted by Meisel [6].

The Tactical Berth Allocation Problem (TBAP) pursues to determine the berthing position, berthing time and allocation of quay cranes for the container vessels arrived to the port over a well-defined time horizon. In the TBAP, we are given a set of incoming container vessels V, a set of berths B and a maximum number of available quay cranes Q. Each container vessel $v \in V$ must be assigned to an empty berth $b \in B$ within its time window $[t_v, t'_v]$. The berthing position of a vessel should be close to the departure position of its containers. In this regard, the housekeeping cost, $h_{ss'}$, represents the effort associated with moving a given container between the berthing positions s and s' of the quay (Giallombardo et al. [2]). For each container vessel $v \in V$, the service time, s_v, is defined according to the containers included into its stowage plan. That is, the number of containers to be loaded and unloaded to/from the vessel at hand. A quay crane profile determines the distribution of quay cranes used during the service time of a given container vessel. The set of available quay crane profiles is denoted by P. The usage cost of each profile $p \in P$ is denoted by c_p. The main goal of the TBAP is to maximize the usage cost of the quay crane profiles used to serve the vessels and minimize the housekeeping costs derived from the transshipment of containers among container vessels. A comprehensive description of the TBAP is provided by Vacca et al. [9].

The Quay Crane Scheduling Problem (QCSP) is aimed at scheduling the loading and unloading operations of containers to/from a given container vessel. We are given a set of tasks, $\Omega = \{1, ..., n\}$, and the quay cranes with similar technical characteristics allocated to the vessel, $Q' = \{1, ..., q\}$, where $Q' \subseteq Q$. Each task $t \in \Omega$ represents the loading or unloading operations of a group of containers located in the same bay of the vessel, l_t. The time required by a quay crane in order to perform the task t is denoted by w_t. Furthermore, each quay crane $q \in Q'$ is ready after time r_q and is initially located in the bay l_q. All the quay cranes can move between two adjacent bays at speed $\hat{t}$. The QCSP introduces particular constraints concerning its application scope. The quay cranes move on rails and, therefore, they cannot cross each other. In addition, they have to keep a safety distance, δ (expressed as a number of bays), between them in order to minimize potential collisions. This fact avoids that the quay cranes perform at the same time tasks located at a distance lower than δ bays. Lastly, there are precedence relationships among tasks located in the same bay (Kim and Park [5]). For instance, unloading tasks have to be performed before loading operations. The objective of the QCSP is to determine the processing time of each task in such a way that the finishing time of the last performed task (makespan) is minimized. The makespan of a given schedule is the service time of the associated vessel. A mathematical formulation for the QCSP is proposed by Meisel. [6].

In spite of the great deal of attention gathered by these operational problems over the last years (Steenken et. al [8]), there is a lack of integration approaches in which the interactions between them are considered. In this work we address the integration of the seaside operations in a maritime container terminal. In this context, we propose two VNS algorithms in order to individually tackle the TBAP and the QCSP, respectively. These metaheuristics are integrated into an effective framework with the goal of providing an overall planning for serving incoming container vessels within a given time horizon.

The remainder of this work is structured as follows. Section 2 introduces a framework based on metaheuristics aimed at tackling the main seaside operations and the interactions between them. Finally, Section 3 analyzes the performance of the proposed metaheuristics compared to other approaches from the related literature and assesses the effectiveness of the integration strategy. In addition, some general guidelines for further research are presented.

2 Metaheuristic Approach

A Variable Neighbourhood Search (VNS) is a metaheuristic that has demonstrated to be competitive in a large number of practical scopes. It is based upon the systematic change of several neighbourhood structures (Hansen and Mladenović [3]). In this work we develop two VNSs in order to address the TBAP and the QCSP, respectively. Later, these metaheuristics are integrated into a framework.

2.1 VNS Algorithm for Solving the TBAP

Algorithm 1 depicts the pseudocode of the proposed VNS aimed at solving the TBAP. The VNS uses two neighbourhood structures based upon the reinsertion movement $N_a(\gamma, \lambda)$, namely, λ vessels and their assigned profiles are removed from the berth $b \in B$ and reinserted in another berth b', where $b \neq b'$, and the interchange movement $N_b(\gamma)$, which consists in exchanging a vessel $v \in V$ assigned to berth $b \in B$ with another vessel v' assigned to berth b', where $b \neq b'$.

The starting solution of the VNS, γ, is generated by assigning the profile $p \in P$ with the highest usage cost to each vessel. The berthing position of each vessel is selected at random, whereas the starting of its service time is selected as the earliest possible within its time window (line 1). The value of the parameter k is set to 1 (line 2). The shaking process (line 4) allows to escape from those local optima found along the search by using the neighbourhood structure N_a. The solution exploitation phase of the VNS algorithm is based on a Variable Descent Neighbourhood Search (VND) (lines $5-14$). Given a solution γ', it explores one neighbourhood at time until a local optimum with respect to the neighbourhood structures N_a and N_b is found. The application of the neighbourhoods structures in the VND is carried out according to the value of the parameter k_1, initially set to 1 (line 6). The first neighbourhood structure explored is N_a and later N_b. The best solution found by means of the VND is denoted by γ'. The objective function value of γ' allows to update the best solution found along the search (denoted by γ) and restart k (lines $15-17$). Otherwise, the value of k is increased (line 19). These steps are carried out until $k = k_{max}$ (line 21).

```
γ ← Generate initial solution
k ← 1
repeat
   γ′ ← Shake(γ, k)
   repeat
      k1 ← 1
      γ″ ← Local Search(γ, k1)
      if f(γ″) > f(γ′) then
         γ′ ← γ″
         k1 ← 1
      else
         k1 ← k1 + 1
      end if
   until k1 = k1max
   if f(γ′) > f(γ) then
      γ ← γ′
      k ← 1
   else
      k ← k + 1
   end if
until k = kmax
```

Algorithm 1. VNS for the TBAP

```
1: σ ← Generate initial solution
2: ES ← ∅
3: repeat
4:    k ← 1
5:    repeat
6:       σ′ ← Shake(σ, k)
7:       σ″ ← Local Search(σ′)
8:       Update ES
9:       if f(σ″) < f(σ) then
10:         σ ← σ″
11:         k ← 1
12:      else
13:         k ← k + 1
14:      end if
15:   until k = kmax
16:   σ′, σ″ ← Select schedules from ES
17:   σ ← Combine(σ′, σ″)
18: until Stopping Criteria
```

Algorithm 2. VNS for the QCSP

2.2 VNS Algorithm for Solving the QCSP

The pseudocode of the proposed VNS for the QCSP is depicted in Algorithm 2. It is based upon two neighbourhood structures, namely, reassignment (N_1) and interchange of tasks (N_2). The search starts generating an initial schedule, σ, by assigning each task $t \in \Omega$ to its nearest quay crane (line 1). The value of the parameter k is also set to 1 (line 4). A shaking procedure allows to reach unexplored regions of the search space by means of the reassignment of k tasks to another quay crane. The reassigned tasks are selected on the basis of a frequency memory. In this way, at each step, a neighbour schedule, σ', is generated at random from σ within the neighbourhood structure N_k (line 6). A local optimum, σ'', is reached through a local search based on the proposed neighbourhood structures (line 7). An improvement in the value of σ'' allows to update σ and restart k (lines 9, 10 and 11). Otherwise, the value of k is increased (line 13). These steps are carried out until $k = k_{max}$ (line 15).

An elite set, ES, is included into the VNS with the goal of collecting the promising schedules found along the search. It is composed of the fittest schedules and those local optima with the highest diversity in ES. The diversity of two schedules is measured as the number of tasks performed by different quay cranes. At each step, ES provides a pair of schedules σ and σ' selected at random (line 16) in order to be combined (line 17) and restart the search. The combination process keeps those tasks performed by the same quay crane, whereas the remaining tasks are randomly assigned to one quay crane.

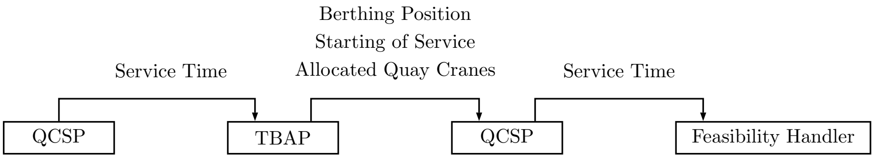

Fig 1. Structure of the metaheuristic-based framework for the seaside operations

2.3 Integrated Approach

The service time of a given vessel is directly derived from the number and schedule of its allocated quay cranes. As indicated in the introduction, the TBAP assumes an estimation of this time in order to determine the berthing position and the starting of the service time of each vessel. However, the real service time is only known during the schedule of its tasks, which is defined by the QCSP.

In this work we propose a functional integration approach aimed at providing an overall service planning for container vessels arrived to port. The TBAP and the QCSP are integrated into a framework that allows to tackle the dependencies between both. The structure of the proposed framework is depicted in Figure 1. Firstly, an estimation of the service time for each vessel within the time horizon is pursued. In this regard, the QCSP is solved for each vessel by means of some domain-specific solver for it, for example, the proposed VNS. In all the cases, the number of considered quay cranes is the maximum allowed according to the dimensions of the vessel at hand. Short computational times should be used in this step due to the fact that it is intended to get an estimation of the service time. Once the service time of each vessel is estimated, the TBAP is solved through some optimization technique. The TBAP provides the berthing position, berthing time and the subset of quay cranes allocated to each vessel. However, the service time is estimated so far. Hence, the QCSP is solved for each vessel using the real subset of allocated quay cranes. It is worth mentioning that the real service time can be different to the estimated one and, therefore, it can produce overlap in the service of the vessels. In order to avoid this fact, the last stage of the framework (denoted by *Feasibility Handler*) adjusts the berthing time of the involved vessels.

3 Discussion and Further Research

This section is devoted to individually assess the performance of the VNSs proposed in order to solve the TBAP and the QCSP, respectively. In addition, the effectiveness of the developed framework is analyzed in real size instances. All the computational experiments reported in this work have been carried out on a computer equipped with a CPU Intel 3.16 GHz and 4 GB of RAM.

Table 1 presents a comparison among CPLEX, the Tabu Search combined with Branch and Price (TS-BP) developed by Giallombardo et al. [2] and the

Table 1. Comparison between VNS and TS-B&P (Giallombardo et al. [2]) for the TBAP

Instance				*CPLEX*	*TS-BP*		*VNS*	
Name	*V*	*B*	*P*	UB_{CPLEX}	f_{BP-TS}	t. (s)	f_{VNS}	t. (s)
A_{p10}	20	5	10	1383614	97.26	81	97.25	4.86
A_{p20}	20	5	20	1384765	97.19	172	96.99	10.49
A_{p30}	20	5	30	1385119	97.37	259	96.94	12.23
B_{p10}	30	5	10	1613252	95.68	308	96.66	12.46
B_{p20}	30	5	20	1613769	95.12	614	96.20	26.55
B_{p30}	30	5	30	1613805	—	920	96.33	59.71
C_{p10}	40	5	10	2289660	97.41	1382	97.50	68.47
C_{p20}	40	5	20	2290662	97.37	3144	97.62	99.04
C_{p30}	40	5	30	2291301	96.60	4352	96.72	223.1

proposed VNS. The first column (*Instance*) shows the instances to solve. For each instance, the name (*Name*), the vessels (V), the berths (B) and the profiles (P) are presented. Column *CPLEX* shows the results obtained by CPLEX with a maximum computational time of 2 hours. The next columns (*TS-BP* and *VNS*) show the results obtained by TS-BP and VNS with $k_{max} = 5$ and $k_{1max} = 2$, respectively. In each case, the objective function value scaled up to 100 with respect to UB_{CPLEX} and the computational time (in seconds) are reported, respectively.

The computational results illustrated in Table 1 indicate that the proposed VNS is highly competitive for the wide range of problem instances at hand. It reports the best-known solutions by means of short computational times, less than 225 seconds in the worst case. This fact motivates its use within integration strategies such as that proposed in Section 2.3. Furthermore, it is worth pointing out that TS-BP requires larger times to provide solutions with similar quality.

Table 2 shows a comparison for the QCSP between the proposed VNS and the exact technique called UDS proposed by Bierwirth and Meisel [1]. The execution

Table 2. Comparison between VNS and UDS (Bierwirth and Meisel [1]) for the QCSP

Instance			*UDS*		*VNS*		
Set	*n*	q	f_{UDS}	t. (m)	f_{VNS}	t. (m)	Gap (%)
A	10	2	459.9	1.12 E-5	459.9	0.001	0.00
B	15	2	666.6	3.68 E-5	666.6	0.017	0.00
C	20	3	604.8	6.26 E-4	604.8	0.096	0.00
D	25	3	804.6	3.43 E-3	804.6	0.254	0.00
E	30	4	730.2	0.10	730.2	0.570	0.00
F	35	4	863.7	1.08	865.5	1.140	0.24
G	40	5	753.0	2.37	759.0	1.930	0.89
H	45	5	889.8	19.16	891.0	3.240	0.15
I	50	6	817.8	23.97	818.1	4.780	0.07

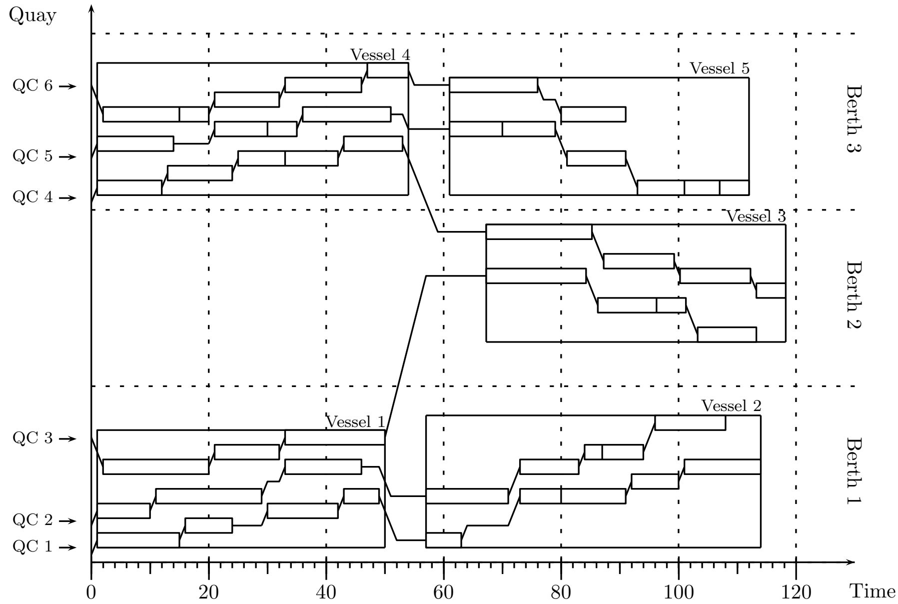

Fig 2. Example of solution reported by the metaheuristic-based framework

of the VNS is stopped when 20 iterations are performed. In addition, we set $k_{max} = 5$ and an elite set with 10 solutions (5 by quality and 5 by dispertion). Column *Instance* shows the name of the group of instances (*Set*), number of tasks (n) and number of quay cranes (q) to solve. There are 10 instances in each group. Next columns (*UDS* and *VNS*) present the average objective function value and the average computational time (in minutes) required by both methods. In the case of VNS, the gap between both solution methods is also reported.

There are no differences in the quality of the solutions found by both methods in small instances. The time used by the VNS is slightly larger than the UDS. However, there are relevant differences between the times for large instances. In those cases, the VNS is also high effective. The reported solutions are optimal or near-optimal in all the cases (with a gap below 1%).

We illustrate in Figure 2 a complete example of the solution reported by the developed metaheuristic-based framework. We have $V = 5$ vessels, $B = 3$ berths and $Q = 6$ quay cranes. In this case, the berthing position and berthing time of each vessel is defined within its time window by means of the VNS for the TBAP. The tasks of each vessel (represented as small rectangles) are performed by one quay crane (defined by the VNS for the QCSP). It is worth pointing out that the interferences between quay cranes give rise to waiting times within each vessel. In addition, the quay cranes have to wait for some vessel because it is not already berthed, see vessel 3. Finally, as indicated in Subsection 2.3, after knowing the real service time of each vessel, overlaps between vessels can appear, for instance, between vessels 4 and 5. In those cases, the *Feasibility Handler* is devoted to appropriately delay the berthing time of the vessel 5.

The proposed metaheuristic-based framework is able to tackle high-dimension instances. Its effectiveness is directly founded on the performance of the domain-specific methods used to solve the TBAP and the QCSP. However, some directions can be followed for further research. First, container terminal managers are highly interested on having a suitable management of the vehicles used to transport the loaded and unloaded containers to/from the vessels. Our framework will be extended for this purpose. Future works must address the dynamic nature of the environment. For instance, the quay cranes are subject to breakdowns.

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