THE TACTICAL BERTH ALLOCATION PROBLEM WITH QUAY CRANE ASSIGNMENT AND TRANSSHIPMENT-RELATED QUADRATIC YARD COSTS

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Abstract

In this paper we integrate two decision problems arising in container terminals: the berth allocation problem, which consists of assigning and scheduling incoming ships to berthing positions, and the quay crane assignment problem, which assigns to incoming ships a certain QC profile (i.e. number of quay cranes per working shift). They are indeed strictly correlated, as the QC profile assigned to the ships affects the handling times and therefore it has impact on the berth allocation. We present two formulations for the integrated problem: a mixed integer quadratic program and a linearization which reduces to a mixed integer linear program. The objective function aims, on the one hand, to maximize the total value of chosen QC profiles and, on the other hand, to minimize the housekeeping costs generated by transshipment flows between ships. An economical analysis of the value of QC assignment profiles and of yard-related costs in a transshipment context is provided. Both models have been validated on instances based on real data; computational results are presented and discussed.

1 INTRODUCTION

Maritime transportation has gained a crucial role in the exchange of goods between continents and containerization enforced this trend (UNCTAD, 2007). Containers possess several advantages: they require less product packaging, they help reducing damage, and they yield higher productivity during the various handling phases. Moreover containers allow for inter-modal transportation because transshipment between ships, trucks or trains is easily performed. In order to cut down transportation costs, container traffic asks for ultra-large containerships and thus for terminals with facilities and technologies able to handle them (mega-terminals), and for a maritime transportation system, which can reduce transportation costs. This system is known as *hub and spoke*: deep sea containerships (*mother vessels*) operate between a limited number of transhipment terminals (*hubs*), and smaller vessels (*feeders*) link the hubs with the other ports (*spokes*). The need for an optimal management of logistic activities at modern container terminals is well recognized. For an overview and classification of the various equipments and decision problems in such systems, see (Vis and de Koster, 2003), (Steenken et al., 2004), and (Stahlbock and Voss, 2008).

This paper deals with the Tactical Berth Allocation Problem (TBAP) in a transshipment container terminal. The TBAP differs from the Operational Berth Allocation Problem (OBAP) in many substantial ways other than the length of the planning horizon. Since in the scientific literature the operational problem has been by far more studied and it is usually refereed to as BAP, in the following we keep this convention and we will simply indicate the OBAP as BAP.

The TBAP planning consists of months while the BAP considers few days (typically one week). Basically, both the tactical and the operational problems deal with assigning and scheduling ships to berthing positions, i.e. deciding where and when the ships should moor. Both the TBAP and the BAP strives to balance terminal costs and service quality. However, the different decisional levels and time frames induce different problems. In the TBAP service quality depends upon the negotiation between the terminal and the shipping lines regarding the terminal resources, mainly berths and quay cranes. A higher service quality occurs when the terminal can accommodate shipping lines requests in term of expected berthing times, and assigned quay cranes. In the BAP service quality is measured by adherence to a schedule, e.g. ideally zero waiting time to moor.

The TBAP, thanks to the longer planning horizon, can integrate terminal's costs in a more comprehensive way with respect to the BAP. In a transshipment terminal, containers arrive and depart by vessels while being temporarily stored in the yard. When unloading a vessel, the discharged containers must be allocated to yard positions close enough to the vessel berthing point in order to speed up the vessel handling. However, when the departure position of a container is far from its yard position, the container must be reallocated before the arrival of the outbound vessel. Therefore, the yard management deals with a dynamic allocation of containers through their duration-of-stay inside the terminal. The operational

BAP considers this aspect penalizing mooring far from the most favorable berth with respect to the yard positions of outbound containers. It should be noted that is the tactical berth allocation that determines the long-term favorite berth (*home berth*) for each vessel, thus inducing container flows inside the yard. In the BAP the yard related costs can be modeled by a vessel specific penalty function increasing from the favorite berth. Instead, in the TBAP the yard costs are an effect of the simultaneous assignment of vessels to home berths, i.e. we have a quadratic yard-related cost function.

Vessel arrival times have different meanings in the operational and in the tactical problems. In the TBAP shipping lines indicate time ranges for the expected arrival times, e.g. monday morning with a weekly frequency. The tactical berth plan must accommodate for such arrival times or an alternative agreement should be searched. In the BAP we assume to know exactly the vessel arrival times and a berth plan is drawn such that the waiting times to moor are minimized. Service quality objectives are usually achieved by imposing time windows for the berthing times that begins at the expected arrival times. According to the terminal practice we can have hard time windows, i.e. a maximum feasible berth waiting time, or soft ones with a vessel specific penalty function for these delays, or a combination of both. Synthetically, while the BAP focuses on minimization of berth waiting times, in the TBAP we want to know if accommodating a customer request is feasible and how it impacts on the whole terminal performances such as yard costs and quay cranes utilization.

The temporal aspect of the berth allocation problems depends not only on arrival times but also on the expected handling times. Handling times are influenced by many factors such as the amount of loading and unloading containers, the distribution of these containers inside the vessels, the number of quay cranes assigned to each work shift, etc. In fact, the vessel handling does not decrease proportionally augmenting the number of assigned quay cranes. This happens because of QC interferences due to safety distance when moving along a unique rail. Of course, the distribution of work-load inside the vessel is relevant too: a more even distribution is more favorable to the deployment of more QCs. A detailed forecast can be obtained by solving the Quay Crane Scheduling Problem (QCSP), see e.g. (Kim and Park, 2004), and (Moccia et al., 2006), which requires a considerable amount of data available few days before vessel arrival. Therefore, at the operational level the forecast about the handling time becomes more accurate as the berthing time approaches. The BAP, thus, assumes deterministic handling times or, by integration with a QCSP module, chooses between different loading and unloading plans. The TBAP, instead, deals with the negotiation between the terminal and the shipping lines about reserved assignment of quay cranes along work shifts. For a given amount of requested quay crane hours it could be possible to propose different profiles. For example, assume that we have a request for a vessel that requires six QCs work shifts and the customer acknowledges to evaluate both an intensive QC profile (for example three QCs on two work shifts) and a longer one (two QCs on three work shifts). The terminal managers want to know the trade-off between the two profiles. The faster one will be likely more satisfying for the customer because of the smaller handling time; on the contrary, the slower one will put less pressure on the quay cranes availability, which could be a bottleneck at some periods. However, the relations are by far more complicated because if the quay cranes are not a limiting factor on the vessel expected processing time, then a faster handling time is advantageous for the terminal too because it augments berth availability. Similarly, customers can be extremely sensitive to faster handling times regarding mother vessels and less demanding for feeders. It appears clear that the so called Quay Crane Assignment Problem (QCAP), i.e. deciding how many QCs to assign and for how long, has a relevant impact on the berth allocation. In this work, we aim to combine berth allocation with QCAP and solve this new integrated problem at the tactical level from the point of view of a transshipment terminal. The purpose is to support the terminal in its negotiation process with analytic tools and quantitative results.

The remainder of this paper is organised as follows. A literature review is provided in Section 2 while the problem description as well as two formulations for the TBAP with QCs assignment are presented in Section 3. The objective function is analyzed from an economical point of view in Section 4. Computational results are discussed in Section 5, followed by conclusions in Section 6.

2 LITERATURE REVIEW

The operational berth allocation problem has received so far a larger attention than the tactical one in the scientific literature. Therefore, our literature review is mainly referred to the BAP. However, we point at the shared issues between operational and tactical levels and we discuss in more detail the articles relevant to the TBAP.

The BAP consists in allocating ships to berths along a time axis. Usual side constraints are berth's allowable draft (depth of the water), time windows and priorities assigned to the ships, favorite berthing areas, etc. The BAP can be modeled as a discrete problem if the quay is viewed as a finite set of berths. In this case the berths can be described as fixed length segments, or, if the spatial dimension is ignored, as points. Continuous models consider that ships can berth anywhere along the quay. While continuous models are more realistic, discrete ones can be very useful to study relaxed problems in order to devise efficient algorithms for them.

Imai et al. (2001) have proposed the *Dynamic Berth Allocation Problem* (DBAP) formulation in which the quay is represented as a finite set of berthing points. This formulation is called "dynamic" as opposed to a previous one called the *Static Berth Allocation Problem* (SBAP), see (Imai et al., 1997), which considers the case where all ships are already in the port when the berths become available. The SBAP is solvable in polynomial time with the Hungarian method since it is reducible to an assignment problem. In their paper, the authors take advantage of this characteristic. They propose a suitable Lagrangean relaxation for the DBAP where the subproblem is an assignment problem. Their computational results show that the DBAP is easy to solve as long as the instances are "close" to the static case, in the sense that most ships are already in the port when the berths become available. The objective function is the sum of the ship service times. As the authors point out, this objective function does not consider ship priorities.

Nishimura et al. (2001) have presented a non-linear integer program and a genetic algorithm based on a different representation of the spatial dimension in which the quay is a collection of segments and up to two ships can share the same segment at the same time if their lengths are compatible with the length of the berth segment. Additional constraints relative to the water depth of the berths are also introduced.

The DBAP formulation was extended in Imai et al. (2003) to consider service priorities which are handled by introducing in the objective function a term corresponding to service time. Priorities, based for example on volumes, can also be incorporated in the model. The resulting formulation is non-linear. The authors show that with a suitable Lagrangean relaxation, the subproblem becomes a quadratic assignment problem. Since this problem is not well solved by exact methods, the authors have developed a genetic heuristic.

In Lim (1998) the quay is represented as a continuous line. A heuristic solves the problem of deciding the berthing points given the berthing time of the ships, assuming constant handling times. This approach does not solve the general problem in which the berthing time is a decision variable and the handling time varies along the quay.

Imai et al. (2005) address the continuous BAP with the purpose of minimizing the total service time of ships, when handling time of a ship depends on the quay location assigned to it. They present a heuristic algorithm which solves the problem in two stages, by improving the solution for the discrete case. Tests are performed on generated instances with quay-length up to 1600m and up to 60 ships to be allocated.

Cordeau et al. (2005) consider both the discrete and the continuous BAP. Two formulations and two tabu search heuristics are presented and tested on realistic generated instances derived by a statistical analysis of traffic and berth allocation data of the port of Gioia Tauro (Italy).

Cordeau et al. (2007) can be regarded as introductory to the TBAP. The paper deals with the Service Allocation Problem (SAP), a tactical problem arising in the yard management of a container transhipment terminal. A *service,* also called *port route*, is the sequence of ports visited by a vessel. Shipping companies plan their port routes in order to match the demand for freight transportation. A shipping company will usually ask the terminal management to dedicate specific areas of the yard and the quay (home berths) to their services. The SAP objective is the minimization of container rehandling operations inside the yard choosing the home berth for each service. The SAP is formulated as a Generalized Quadratic Assignment Problem (GQAP, see e.g. Cordeau et al. (2006), and Hahn et al. (2008)) with side constraints, and solved by an evolutionary heuristic. The SAP can be seen as a relaxed TBAP when collapsing the temporal dimension. The SAP output consists in reference home berths that planners consider when drawing the TBAP.

Moorthy and Teo (2006) address the design of a berth template, a tactical planning problem that arises in transshipment hubs and concerns the allocation of favorite berthing locations (home berths) to vessels which periodically call at the terminal. The problem is modeled as a bicriteria optimization problem, which reflects the trade-off between service levels and costs. The authors propose two procedures able to build good and robust templates, which are evaluated by simulating their performances; robust templates are also compared with optimal templates on real-life generated instances. The paper approach builds on a heuristic algorithm for the BAP presented in Dai et al. (2007).

Imai et al. (2007) consider the case of indented berths, where multiple small ships can be served by the same berth simultaneously. The problem is formulated as an integer linear problem and solved by genetic algorithms. Solutions are evaluated by comparing the indented terminal with a conventional terminal of the same size: tests on generated instances show that the total service time for all ships is longer in indented terminals, although mega-ships are served faster.

Wang and Lim (2007) propose a stochastic beam search scheme for the BAP.

The implemented algorithm is tested on real-life data from the Singapore Port Terminal (the size of instances is up to 400 vessels); it outperforms state-of-the-art metaheuristics, providing better solutions in shorter running times.

Monaco and Sammarra (2007) propose a strong formulation for the discrete BAP as a dynamic scheduling problem on unrelated parallel machines and develop an efficient Lagrangean heuristic algorithm. Instances up to 30 ships and 7 berthing points are solved reaching near-optimal solutions in short computational time.

The integration of berth allocation and quay cranes assignment has received less attention in the scientific literature; however, a few studies on this specific topic have been recently published.

Park and Kim (2003) have firstly integrated the BAP in the continuous case with the QCAP, also considering the scheduling of quay cranes. The integrated problem is formulated as an integer program and a two-phase solution procedure is presented to solve the model. In the first phase, the berthing time and position of vessels and the number of quay-cranes assigned to each vessel at each time step are determined using Lagrangean relaxation and a subgradient optimization technique; the objective is to minimize the sum of penalty costs over all ships. In the second phase, cranes are scheduled along the quay via dynamic programming, with the objective of minimizing the number of setups. Up to 40 vessels are scheduled over a time horizon of one week, with a berth of 1200m and 11 QCs available. With respect to the problem formulation, authors take into account some practical aspects such as favourite berthing positions of vessels, maximum and minimum number of cranes to be assigned to each vessel, penalty costs due to earlier or later berthing time, and later departure time (with respect to previously committed time).

Meisel and Bierwirth (2006) investigate the simultaneous allocation of berths and quay cranes, focusing on the reduction of QCs idle times, which significantly impact on terminal's labor costs. A heuristic scheduling algorithm based on priority-rules methods for the resource-constrained project scheduling is proposed and tested on six instances, based on real data, which consider up to 18 vessels to be served in two days. Preliminary results, compared to the manually generated schedules which have been used in practice, are encouraging. In this approach, each vessel represents an activity which can be performed in 8 different modes, each mode representing a given QC-to-Vessel assignment over time. The concept of "mode" seems analogous to the concept of profile we have introduced so far; however, no detailed description of these modes is available in the paper.

Imai et al. (2008) address the simultaneous berth-crane allocation and scheduling problem, taking into account physical constraints of quay cranes, which cannot move freely among berths as they are all mounted on the same track and cannot bypass each other. A MIP formulation which minimizes the total service time is proposed and a genetic algorithm-based heuristic is developed to find an approximate solution. Computational experiments have been performed on generated instances, which consider between 34 and 88 ships calling over a period of one week, with 4-5 berths and between 8 and 18 QCs available. As authors recognize, the relationship between the number of cranes and the handling time is not investigated in the paper; indeed, a reference number of cranes needed by each ship is assumed to be given as input of the problem.

Meisel and Bierwirth (2008) study the integration of BAP and QCAP with a focus on quay cranes productivity. An integer linear model is presented and a construction heuristic, local refinement procedures and two meta-heuristics are developed to solve the problem. Authors compare their approach to the one proposed by Park and Kim (2003) over the same set of instances and they always provide better solutions. More complex instances are generated, taking into account a time horizon of one week, a berth length of 1000m and 10 QCs available to serve up to 40 vessels. Vessels are divided in 3 classes (Feeder, Medium and Jumbo) with different technical specifications and cost rates. Only small instances (20 vessels) are near-optimally solved by a commercial solver, whereas the proposed heuristics perform relatively well also on bigger instances. An analysis of quay crane's productivity losses, mainly due to interference among QCs and to the distance of the vessel berthing position from the yard areas assigned to this vessel, is also presented and their impact on the terminal's service cost is evaluated.

3 MATHEMATICAL MODEL

In this section we firstly provide a compact description of the problem and motivate our modeling choices; in particular, in Section 3.1, we illustrate the concept of QC assignment profiles. We then present a mixed integer quadratic programming formulation (MIQP) for the TBAP with integrated QCs assignment in Section 3.2 as well as a linearization of the MIQP model which results in a mixed integer linear program (MILP) in Section 3.3.

With respect to the BAP, we start considering the discrete case. Given a set N of ships and a set M of berths, we aim to assign, over a certain time horizon, a home berth and a QC profile to each ship as well as schedule incoming ships according to time windows on their arrival time and on berths' availabilities, in order to, on the one hand, maximize the total value of chosen QC assignment profiles and, on the other hand, minimize the housekeeping costs generated by transshipment flows between ships.

The integrated problem presents increased complexity because the ship handling time is not constant but depends on the number of quay cranes assigned to the ship. With respect to the classical BAP, this implies additional decision variables and constraints.

3.1 QC assignment profiles

The use of QC profiles to handle the assignment of quay cranes to ships is firstly motivated by the practice: at the tactical level and, in particular, in the context of a negotiation process between the terminal and the shipping companies, terminal's managers need to be aware of the trade-off among the different QC profiles they may propose to the counterpart.

Concerning the mathematical model, the concept of QC profiles presents several advantages with respect to the ability to capture real-world issues and with respect to the control that the terminal can have on several aspects during the optimization process. These are the main reasons why we have explicitly introduced this feature in the formulation.

We assume to have a set of feasible QC profiles P_i for every ship $i \in N$, which are decided by the terminal according to the specific amount of QC hours requested by the ship (and usually legally bound by contracts) as well as internal rules and good practices related to the efficiency of operations in the terminal.

Our approach differs from the traditional modeling choice present in the literature, e.g. Park and Kim (2003), Imai et al. (2008), Meisel and Bierwirth (2008), which usually assigns quay cranes hour by hour, without any control on the final outcome in terms of QC profiles, according to their models. As mentioned, the concept of "mode" in Meisel and Bierwirth (2006) is somehow similar to our concept of QC profile, but the authors do not provide enough details to allow comparisons.

For a given vessel, feasible QC profiles usually vary in length (number of shifts) as well as in the distribution of QC cranes over the active shifts, in order to ensure the requested amount of QC hours.

Some operational constraints, which are usually not taken into account by other models, can be directly integrated in the definition of the set of feasible profiles. A common rule, for instance, is that quay cranes are assigned to vessels and placed on the corresponding quay segment shift by shift: this means that a quay crane cannot be moved from one vessel to another at whatever moment, but only between two shifts. This constraint can be easily handled by forcing profiles to maintain exactly the same number of quay cranes during a shift. Another good practice is to keep the distribution of quay cranes as much regular as possible among active shifts; a variance of one or at most two QCs can be considered acceptable, although high variability should be avoided as much as possible. Also this feature can be included in our profile set definition easily.

In addition to these general rules, the terminal can manage more directly some priority-related issues. Since the set of feasible QC profiles is defined for every ship, managers can assign different minimum and maximum handling times not only depending on the ship's size and the traffic volume but also depending on the ship's relative importance for the terminal. This also applies for the minimum and maximum number of quay cranes allowed to be assigned to a given ship. We would like to remark that this is an important advantage provided by our approach, compared to other models in the literature where handling time is either considered an input of the problem or barely controlled by time windows on the vessel's arrival and departure, in addition to some priority-related weights in the objective function, which usually aim to serve faster vessels with high priority. Furthermore, each QC profile has an associated "value" which reflects technical aspects such as the resources utilized by the profile itself but which is also computed by taking into account the specific vessel which will use the profile; in other words, the same QC profile i.e. same length and QCs distribution over time, can have different values associated to different ships, according indeed to their priority or importance.

With respect to productivity losses due to quay cranes interference, recently studied by Meisel and Bierwirth (2008), we can easily include this feature in the definition of the feasible set of profiles. Indeed, we can use the approach suggested by the authors to compute, for each profile, the actual quay crane productivity instead of the theoretical one.

Last but not least, a remark concerning the time: in our model the time horizon, and thus every working shift, is discretized in time steps and we allow a profile to start at every time step of the shift. However, since we assume that a vessel starts to be operated when it arrives at the port, the profile assigned to the vessel by any feasible solution must comply with the arrival time of the vessel itself at the port (which is also a decision variable of the problem).

3.2 MIQP Formulation

In this section we present a mixed integer quadratic programming formulation for the TBAP with QCs assignment. Input data for this problem are:

N	set of vessels;
M	set of berths;
H	set of time steps;
S	set of the time step indexes $\{1, ..., \bar{s}\}$ relative to a work shift; $\bar{s}$ represents the number of time steps in a work shift;
H^s	subset of H which contains all the time steps corresponding to the same time step $s \in S$ within a work shift;
P_i^s	set of feasible quay crane assignment profiles for the vessel $i \in N$ when vessel arrives at a time step with index $s \in S$ within a work shift;
P_i	set of quay crane assignment profiles for vessel $i \in N$; $P_i = \cup_{s \in S} P_i^s$;
t_i^p	handling time of ship $i \in N$ under the QC profile $p \in P_i$ expressed as multiple of the time step length;
v_i^p	the value of serving the ship $i \in N$ by the quay crane profile $p \in P_i$;
q_i^{pu}	number of quay cranes assigned to the vessel $i \in N$ in profile $p \in P_i$ at time step $u \in (1, ..., t_i^p)$;
Q^h	maximum number of quay cranes available at the time step $h \in H$;
f_{ij}	flow of containers exchanges between vessels $i, j \in N$;
d_{kw}	housekeeping cost per unit of container between yard slots corresponding to berths $k, w \in M$;
$[a_i, b_i]$	[earliest, latest] feasible arrival time of ship $i \in N$;
$[a^k, b^k]$	[start, end] of availability time of berth $k \in M$;
$[a^h, b^h]$	[start, end] of the time step $h \in H$.

We define a graph $G^k = (V^k,\ A^k)\ \ \forall k \in M$, where $V^k = N \cup \{o(k),\ d(k)\}$, with $o(k)$ and $d(k)$ additional vertices representing berth k, and $A^k \subseteq V^k \times V^k$. The following decision variables are defined:

- $x_{ij}^k \in \{0, 1\}\ \ \forall k \in M, \forall (i, j) \in A^k$, set to 1 if ship j is scheduled after ship i at berth k and 0 otherwise;

- $y_i^k \in \{0, 1\}\ \ \forall k \in M, \forall i \in N$, set to 1 if ship i is assigned to berth k and 0 otherwise;

- $\gamma_i^h \in \{0, 1\}\ \ \forall h \in H, \forall i \in N$, set to 1 if ship i arrives at time step h and 0 otherwise;

- $\lambda_i^p \in \{0,1\} \;\; \forall p \in P_i, \forall i \in N$, set to 1 if ship i is served by the profile p and 0 otherwise;

- $\rho_i^{ph} \in \{0,1\} \;\; \forall p \in P_i, \forall h \in H, \forall i \in N$, set to 1 if ship i is served by profile p and arrives at time step h and 0 otherwise;

- $T_i^k \geq 0 \;\; \forall k \in M, \, \forall i \in N$, representing the berthing time of ship i at the berth k i.e. the time when the ship moors;

- $T_{o(k)}^k \geq 0 \;\; \forall k \in M$, representing the starting operation time of berth k i.e. the time when the first ship moors at the berth;

- $T_{d(k)}^k \geq 0 \;\; \forall k \in M$, representing the ending operation time of berth k i.e. the time when the last ship departs from the berth.

The TBAP with QC assignment can therefore be formulated as follows:

$$\max \; \sum_{i \in N} \sum_{p \in P_i} v_i^p \lambda_i^p - \frac{1}{2} \sum_{i,j \in N} \sum_{k,w \in M} f_{ij} d_{kw} y_i^k y_j^w \tag{1}$$

$$\text{s.t.} \; \sum_{k \in M} y_i^k = 1 \qquad \forall i \in N, \tag{2}$$

$$\sum_{j \in N \cup \{d(k)\}} x_{o(k),j}^k = 1 \qquad \forall k \in M, \tag{3}$$

$$\sum_{i \in N \cup \{o(k)\}} x_{i,d(k)}^k = 1 \qquad \forall k \in M, \tag{4}$$

$$\sum_{j \in N \cup \{d(k)\}} x_{ij}^k - \sum_{j \in N \cup \{o(k)\}} x_{ji}^k = 0 \qquad \forall k \in M, \, \forall i \in N, \tag{5}$$

$$\sum_{j \in N \cup \{d(k)\}} x_{ij}^k = y_i^k \qquad \forall k \in M, \, \forall i \in N, \tag{6}$$

$$T_i^k + \sum_{p \in P_i} t_i^p \lambda_i^p - T_j^k \leq (1 - x_{ij}^k) M \qquad \forall k \in M, \, \forall i \in N, \; \forall j \in N \cup \{d(k)\}, \tag{7}$$

$$T_{o(k)}^k - T_j^k \leq (1 - x_{o(k),j}^k) M \qquad \forall k \in M, \, \forall j \in N, \tag{8}$$

$$a_i y_i^k \leq T_i^k \qquad \forall k \in M, \, \forall i \in N, \tag{9}$$

$$T_i^k \leq b_i y_i^k \qquad \forall k \in M, \, \forall i \in N, \tag{10}$$

$$a^k \leq T_{o(k)}^k \qquad \forall k \in M, \tag{11}$$

$$T_{d(k)}^k \leq b^k \qquad \forall k \in M, \tag{12}$$

$$\sum_{p \in P_i} \lambda_i^p = 1 \qquad \forall i \in N, \tag{13}$$

$$\sum_{h \in H^s} \gamma_i^h = \sum_{p \in P_i^s} \lambda_i^p \qquad \forall i \in N, \forall s \in S, \tag{14}$$

$$\sum_{k \in M} T_i^k - b^h \leq (1 - \gamma_i^h) M \qquad \forall h \in H,\ \forall i \in N, \tag{15}$$

$$a^h - \sum_{k \in M} T_i^k \leq (1 - \gamma_i^h) M \qquad \forall h \in H,\ \forall i \in N, \tag{16}$$

$$\rho_i^{ph} \geq \lambda_i^p + \gamma_i^h - 1 \qquad \forall h \in H, \forall i \in N, \forall p \in P_i, \tag{17}$$

$$\sum_{i \in N} \sum_{p \in P_i} \sum_{u = max\{h - t_i^p + 1; 1\}}^{h} \rho_i^{pu} q_i^{p(h-u+1)} \leq Q^h \qquad \forall h \in H^{\bar{s}}, \tag{18}$$

$$x_{ij}^k \in \{0, 1\} \qquad \forall k \in M,\ \forall (i, j) \in A^k, \tag{19}$$

$$y_i^k \in \{0, 1\} \qquad \forall k \in M,\ \forall i \in N, \tag{20}$$

$$\gamma_i^h \in \{0, 1\} \qquad \forall h \in H, \forall i \in N, \tag{21}$$

$$\lambda_i^p \in \{0, 1\} \qquad \forall p \in P_i, \forall i \in N, \tag{22}$$

$$\rho_i^{ph} \in \{0, 1\} \qquad \forall p \in P_i, \forall h \in H, \forall i \in N, \tag{23}$$

$$T_i^k \geq 0 \qquad \forall k \in M,\ \forall i \in N \cup \{o(k), d(k)\}. \tag{24}$$

The objective function (1) maximizes the sum of the values of the chosen quay crane assignment profiles over all the vessels and simultaneously minimizes the yard-related housekeeping costs generated by the flows of containers exchanged between vessels. Constraints (2) state that every ship i must be assigned to one and only one berth k. Constraints (3) and (4) define the outcoming and incoming flows to the the depots, while flow conservation for the remaining vertices is ensured by constraints (5). Constraints (6) state the link between variables x_{ij}^k and y_i^k, while precedences in every tour are ensured by constraints (7) and (8), which coherently set time variables T_i^k. Time windows on the arrival time are stated for every ship by constraints (9) and (10), while time windows on berths' availabilities are stated by constraints (11) and (12). Constraints (13) ensure that one and only one QCs profile is assigned to every ship. Constraints (14) define the link between variables γ_i^h and λ_i^p while constraints (15) and (16) link binary variables γ_i^h to the arrival time T_i^k. Observe that constraints (10) imply $T_i^k = 0$ when ship $i \in N$ does not moor at berth $k \in K$. Variables ρ_i^{ph} are linked to variables λ_i^p and γ_i^h by constraints (17): in particular, ρ_i^{ph} is equal to 1 if and only if $\lambda_i^p = \gamma_i^h = 1$. Finally, constraints (18) ensure that, at every time step, the total number of assigned quay cranes does not exceed the number of quay cranes which are available in the terminal.

	h=1	h=2	h=3	h=4	h=5	h=6	h=7	h=8
	Ship 1				Ship 2			
berth 1	3	2	2		4	4	5	5
		Ship 3				Ship 4		
berth 2		4	5			3	3	3
			Ship 5					
berth 3			3	3	3	2	2	
QCs TOT	**3**	**6**	**10**	**3**	**7**	**9**	**10**	**8**

Figure 1: *Example of a Berth & Quay Cranes Allocation Plan.*

To better illustrate capacity constraints (18), we use as running example the plan shown in Figure 1, which refers to the scheduling and assignment of $|N| = 5$ vessels to $|M| = 3$ berths over a time horizon of $|H| = 8$ time steps. From the plan we can infer the following non-zero data:

$$
\begin{array}{llll}
i=1 & \rho_1^{p1}=1 & t_1^p=3 & q_1^{p1}=3,\ q_1^{p2}=2,\ q_1^{p3}=2 \\
i=2 & \rho_2^{p5}=1 & t_2^p=4 & q_2^{p1}=4,\ q_2^{p2}=4,\ q_2^{p3}=5,\ q_2^{p4}=5 \\
i=3 & \rho_3^{p2}=1 & t_3^p=2 & q_3^{p1}=4,\ q_3^{p2}=5 \\
i=4 & \rho_4^{p6}=1 & t_4^p=3 & q_4^{p1}=3,\ q_4^{p2}=3,\ q_4^{p3}=3 \\
i=5 & \rho_5^{p3}=1 & t_5^p=5 & q_5^{p1}=3,\ q_5^{p2}=3,\ q_5^{p3}=3,\ q_5^{p4}=2,\ q_5^{p5}=2
\end{array}
$$

For each time step $h = 1, ...8$, the corresponding constraint in (18) counts the number of active quay cranes. Let us consider the case $h = 3$: the index u changes its range for each vessel, because, starting from $h = 3$, it goes backwards until the beginning of the profile. Therefore we have:

$$
\begin{array}{ll}
i=1 & u=1,2,3 \\
i=2 & u=1,2,3 \\
i=3 & u=2,3 \\
i=4 & u=1,2,3 \\
i=5 & u=1,2,3
\end{array}
$$

We remark that vessels $i = 2, 4$ do not contribute to the sum, since $\rho_2^{pu} = \rho_4^{pu} = 0$

$\forall\, u = 1, 2, 3$ and this is coherent with the plan. For the remaining vessels, ρ_i^{pu} is not zero only for one value u^*:

$$
\begin{array}{lll}
i = 1 & u^* = 1 & \Longrightarrow q_1^{p(3-1+1)} = q_1^{p3} = 2 \\
i = 3 & u^* = 2 & \Longrightarrow q_3^{p(3-2+1)} = q_3^{p2} = 5 \\
i = 5 & u^* = 3 & \Longrightarrow q_5^{p(3-3+1)} = q_5^{p1} = 3
\end{array}
$$

Therefore the sum in (18) reduces to:

$$q_1^{p3} + q_3^{p2} + q_5^{p1} = 2 + 5 + 3 = 10$$

which is indeed the total number of quay cranes which are active at time step $h = 3$.

Finally, we observe that the TBAP formulation (1)–(24) can be interpreted as a Multi-Depot Vehicle Routing Problem with Time Windows (MDVRPTW), see e.g. Cordeau et al. (2005), with an additional quadratic component in the objective function and side constraints.

3.3 MILP Formulation

The quadratic objective function (1) can be linearized by defining an additional decision variable $z_{ij}^{kw} \in \{0, 1\}\ \forall i, j \in N,\ \forall k, w \in M$, which is equal to 1 if $y_i^k = y_j^w = 1$ and 0 otherwise. Variables z_{ij}^{kw} are linked to variables y_i^k by the following additional constraints:

$$\sum_{k \in K} \sum_{w \in K} z_{ij}^{kw} = g_{ij} \qquad \forall i, j \in N, \tag{25}$$

$$z_{ij}^{kw} \leq y_i^k \qquad \forall i, j \in N, \forall k, w \in M \tag{26}$$

$$z_{ij}^{kw} \leq y_j^w \qquad \forall i, j \in N, \forall k, w \in M \tag{27}$$

where g_{ij} is a constant which is equal to 1 if $f_{ij} > 0$ and 0 otherwise.

TBAP can therefore be formulated as a mixed integer linear program as follows:

$$
\begin{array}{ll}
\max & \displaystyle\sum_{i \in N} \sum_{p \in P_i} v_i^p \lambda_i^p - \frac{1}{2} \sum_{i \in N} \sum_{j \in N} \sum_{k \in M} \sum_{w \in M} f_{ij} d_{kw} z_{ij}^{kw} \\
\text{s.t.} & (2) - (24)\,, (25) - (27).
\end{array} \tag{28}
$$

4 Economical analysis

In this section we provide additional details regarding the two components of our objective function, the value of QCs assignment profiles, and the transshipment-related yard costs. The cost figures and the operational parameters described in the following were provided by the Medcenter Container Terminal (MCT), port of Gioia Tauro, Italy.

4.1 Value of QCs assignment profiles

The terminal faces different customer sensitivities to the QC intensity of contracted profiles. In fact, given two reference profiles for a mother vessel and for a feeder, the added value of shortening the same handling time by selecting more QC intensive profiles is higher (double as order of magnitude) for a mother vessel than for a feeder. A similar pattern exists when considering less QC intensive profiles, i.e. longer handling times, of course in term of reduced values. Furthermore, the feasible profiles span different ranges for the two classes of vessels: with respect to the same reference handling volume, we can have acceptable slower profiles for the feeders than for a mother vessel. Figure 2 illustrates these patterns assuming that the reference profile extends on five work shifts (30 hours) for a mother vessel and on three work shifts (18 hours) for a feeder.

4.2 Transshipment-related housekeeping costs

When loading (or unloading) a vessel the containers must be at (or allocated to) yard positions close enough to the vessel berthing point in order to speed up the vessel handling. Usually, a yard position is evaluated as satisfyingly close to a berth if the distance along the quay axis is less than 600 meters. We remark that this maximal close distance value can be lowered for higher priority workloads. Furthermore, when we estimate yard-related transshipment costs induced by berth allocation, we do not consider the real yard position of the loading and unloading containers. In fact, we assume that the expected travelled distance along the quay axis is given by the distance between the incoming and outgoing berths. If this distance is lower than the threshold value of 600 meters, then a container will likely move from the quay to its assigned yard position when unloading and from this yard position to the quay when loading. However, in a large transshipment terminal, the distance between the unloading berth and the loading one is often larger

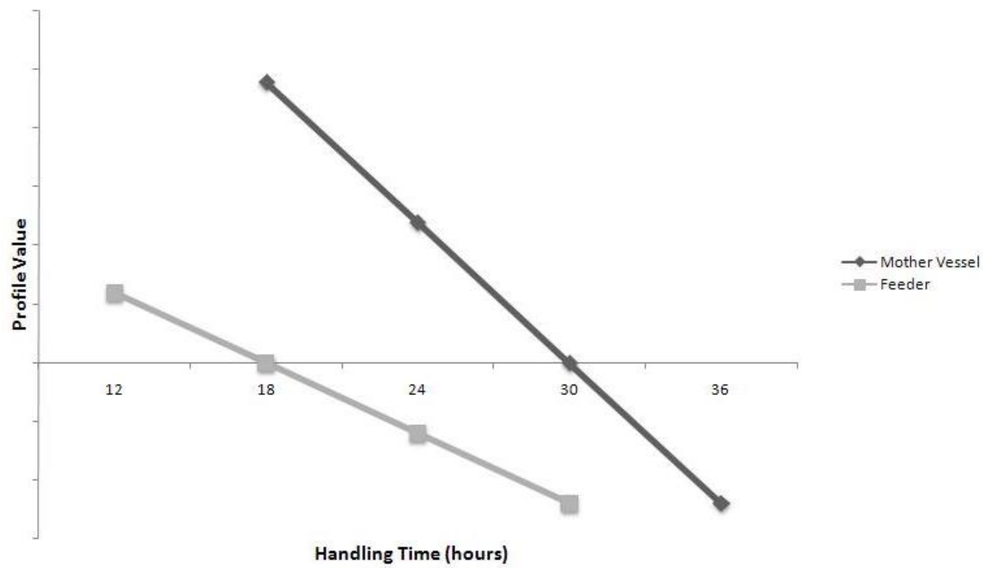

Figure 2: *QC profile range and value variation according to the handling time and class of vessel.*

than 600 meters. Therefore, containers are moved before the arrival of the outgoing vessel from their current yard positions to new ones closer to the outgoing berth. This process is called *housekeeping* and requires a dedicated management in order to accommodate operational constraints like the capacity of the yard positions, the maximum container handling workload for a given work shift, etc. A rule motivated by cost minimization enforces that whenever the distance along the quay axis is larger than 1100 meters, the yard-to-yard transfer is operated by deploying multi trailer vehicles instead of straddle carries. Therefore we have a yard cost function that depends upon the distance between the incoming and outgoing berths according to three transport modalities:

- the distance is below 600 meters: no housekeeping is performed, the unitary transport cost, euro/(meter x container), depends upon straddle carriers cost figures only;
- the distance is between 600 and 1100 meters: a housekeeping process is activated by deploying straddle carriers only, however we face a transport cost larger than in the previous distance range;

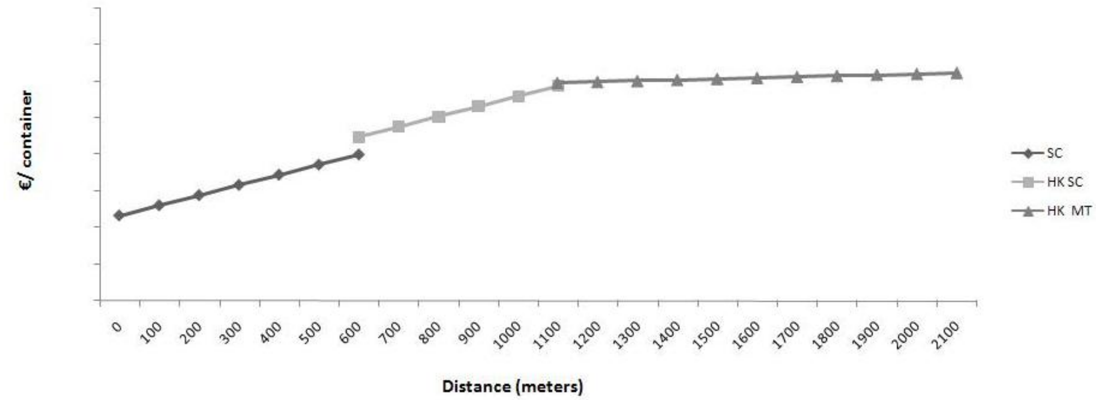

Figure 3: *Yard costs according to the distance between the incoming and outgoing berths.*

- the distance is larger than 1100 meters: the housekeeping is performed by using the less expensive multi trailer vehicles (higher capacity than the straddle carriers).

The qualitative pattern of this piecewise linear cost function is given in Figure 3, where we indicate by SC the direct transfer with straddle carriers, by HK SC the housekeeping with straddle carriers, and by HK MT the housekeeping with multi trailer vehicles.

5 Preliminary results

In this section we describe the validation process of our models. We firstly illustrate how realistic test instances have been generated and we then present and analyse some preliminary results obtained through a commercial solver.

5.1 Generation of test instances

Our tests are based on real data provided by MCT. We had access to historical berth allocation plans and quay cranes assignment plans concerning about 60 vessels per week over a time horizon of one month; specific information on vessels such as the arrival time and the total number of containers to be handled were also provided. Furthermore, data referring to the flows of containers exchanged between ships as well as a study on the yard-related transshipment costs were available (cf. Section 4).

Instances generated to validate our models rely on these real data. The quay, which is 3395 m long, can be partitioned in 13 berthing points, which are equipped with 25 quay cranes (22 gantry cranes and 3 mobile cranes). The matrix of distances $[d_{kw}]$ is a 13x13 matrix which takes into account the costs estimated by the terminal to move containers between two berthing positions. Several matrices of flows $[f_{ij}]$ are generated accordingly to the distributions of containers reported on the historical data. As usual, we distinguish between feeders and mother vessels: the traffic volume is mostly influenced by the proportion between these two classes, since mother vessels present a number of loading/unloading containers in average higher than feeders. In these preliminary tests, we do not consider time windows for the ships' arrival and berths are assumed to be available for the whole time horizon, which we set to one week. A working day is divided in 4 shifts of 6 hours each, for a total of 168 time steps of 1 hour or 56 time steps of 3 hours, depending on the chosen granularity.

The sets of feasible profiles have been synthetically generated in accordance with operational rules and good practices in use at the MCT terminal. As illustrated in Table 1, we fix a set of parameters for each ship class to which a profile must comply with in order to be feasible: namely, the minimum and the maximum number of QCs to be assigned to each vessel per shift as well as the minimum and the maximum handling time (HT) allowed for each class. We consider a crane productivity of 24 containers per hours and we therefore obtain, per each class, a minimum and a maximum number of containers (column "volume" in the table): vessels' traffic volumes must comply with these ranges, according to the class they belong to. Furthermore, for all classes, a variation of at most 1 QC is allowed between a shift and the subsequent; profiles can start either at the beginning of the shift or in the middle of the shift.

Class	min QC	max QC	min HT	max HT	volume (min,max)
Mother	3	5	3	6	(1296, 4320)
Feeder	1	3	2	4	(288, 1728)

Table 1: Parameters for the profile set's generation.

Once the whole feasible set has been generated for each class, profiles are assigned to vessels accordingly to the QC hours they need to be operated. At this point, a monetary value is associated to the couple (vessel,profile) with respect to the number of containers to be handled. This value is then adjusted by taking into account the profile's length and the utilized resources with respect to the average case.

To validate our model, we derived 24 instances organized in 3 classes: E (easy), M (medium) and D (difficult). Class E contains 9 instances in which we consider 10 ships and 3 berths with a maximum of 8 quay cranes available. Class M contains 9 instances in which we consider 20 ships and 5 berths with a maximum of 13 quay cranes available. Class D contains 6 instances in which we consider 30 ships and 5 berths with a maximum of 13 quay cranes available. For each class, we generate different traffic volumes in scenarios A, B, C, where scenario A presents a higher number of mother vessels while scenarios B and C presents the same number of mother vessels and feeders. Each scenario is tested with a set of $\bar{p} = 10, 20, 30$ feasible profiles for each ship. We remark that, by construction, instances of size $\bar{p} = 10$ are included in instances of size $\bar{p} = 20$, which are included in instances of size $\bar{p} = 30$. Thus, any feasible solution for $\bar{p} = 10$ is also feasible for $\bar{p} = 20, 30$ and so on. Time horizon is set to one week for all instances: each scenario in class E is tested with different granularity of time (56 and 168 time steps) whereas classes M and D are only tested with respect to 56 time steps.

5.2 Computational results

The MIQP and MILP formulations have been tested with CPLEX 10.2 and computational results are shown in Table 2 and Table 3. MIQP and MILP formulations are compared to a third model, called MTV (Maximization of Total Value), which represents an upper bound for the TBAP with quadratic costs. MTV is a mixed integer linear program and can be formulated as:

$$MTV = \{\max \sum_{i \in N} \sum_{p \in P_i} v_i^p \lambda_i^p \ : \ (2) - (24)\}.$$

CPLEX MIP solver parameters, such as “mip emphasis” and “heuristic frequency”, have been set to different values, in order to speed up either the feasibility (by identifying at least a feasible solution) or the optimality (by finding better bounds); however, the best results have been obtained with default values.

Time limit for instances of class E has been set to 1 hour, while time limit for instance of class M and D has been set to 2 hours.

As expected, CPLEX is able to solve at optimality all instances of class E, while it hardly finds a feasible solution for instances of classes M and D within the time limits (in this case, column "gap" is set to ∞).

With respect to class E, both MILP and MIQP formulations provide optimal or near-optimal solutions for all the instances. With respect to 56 time steps, MILP optimally solves 8 instances out of 9, while MIQP finds the optimum only for 4 instances. However, we observe that MILP formulation performs poorly when the same instance is solved with the finest granularity (168 time steps): in this case, MILP cannot find any feasible solution within the time limit for any instance of the class, whereas MIQP confirms the results (4 instances optimally solved and 5 near-optimally solved), with a behaviour which seems to be independent from the granularity of time steps.

With respect to class M, no feasible solution is found within the time limit by neither MILP nor MIQP for all the 9 instances except one (scenario C with $\bar{p} = 10$ profiles, gap of 7.55% provided by the MILP formulation), whereas the MTV formulation optimally solves 5 instances out of 9. It means that the quadratic yard-related costs in the objective function, even if linearized, add complexity to the problem, as expected. Concerning the upper bounds provided by these formulations, MILP bounds are better than those provided by MTV at optimum, while MIQP bounds are not competitive with those of the linear formulations. Furthermore, analyzing the MTV results, we can observe that the increasing number of feasible profiles per vessel (parameter $\bar{p}$) makes the instances more difficult to be solved, which is reasonable.

With respect to class D, no feasible solution is found by any formulation within the time limit. Again, the best upper bounds are those provided MILP, whereas MIQP bounds seem to be by far the poorest.

With respect to the upper bounds provided by MTV and MILP when any feasible solution is found, we remark that the final upper bound provided after 2 hours of computations is the same bound computed at the root node: this usually means that the problem is characterized by several symmetric solutions.

These preliminary results show that the problem is difficult to solve as-it-is already on small instances. CPLEX or any other commercial solver are not a viable way to solve TBAP with quadratic costs, especially on bigger instances like those we expect to have in a tactical problem which often involves months as time horizon. Our next step will therefore consist in devising reformulations and/or ad-hoc solution techniques (possibly heuristics) able to tackle the problem with instances of real dimension.

				MTV FORMULATION				MILP FORMULATION				MIQP FORMULATION			
Size	Sc	$\bar{p}$	H	OBJ	GAP (%)	UB	CPU (sec)	OBJ	GAP (%)	UB	CPU (sec)	OBJ	GAP (%)	UB	CPU (sec)
10x3	A	10	56	732283	0	-	8.98	645995	0	-	99.07	643871	0.33	645995	3600
10x3	A	10	168	732283	0	-	8.46	-	∞	645995	3600	643871	0.33	645995	3600
10x3	A	20	56	732317	0	-	9.15	646029	0	-	2.78	642263	0.59	646029	3600
10x3	A	20	168	732317	0	-	8.13	-	∞	646029	3600	642263	0.59	646029	3600
10x3	A	30	56	732317	0	-	22.07	641402	0.72	646029	3600	646029	0	-	1018.26
10x3	A	30	168	732317	0	-	21.66	-	∞	646029	3600	646029	0	-	843.07
10x3	B	10	56	440201	0	-	5.15	387855	0	-	6.71	387855	0	-	1008.69
10x3	B	10	168	440201	0	-	5.29	-	∞	387855	3600	387855	0	-	1961.1
10x3	B	20	56	440201	0	-	642.38	387855	0	-	25.92	386252	0.42	387855	3600
10x3	B	20	168	440201	0	-	589.04	-	∞	387855	3600	386252	0.42	387855	3600
10x3	B	30	56	440201	0	-	140.61	387855	0	-	1457.3	386252	0.42	387855	3600
10x3	B	30	168	440201	0	-	116.59	-	∞	387855	3600	386252	0.42	387855	3600
10x3	C	10	56	692745	0	-	1.32	611219	0	-	16.34	608650	0.42	611219	3600
10x3	C	10	168	692745	0	-	1.51	-	∞	611219	3600	608650	0.42	611219	3600
10x3	C	20	56	692813	0	-	0.52	611287	0	-	36.97	611287	0	-	1018.43
10x3	C	20	168	692813	0	-	0.54	-	∞	611287	3600	611287	0	-	1065.08
10x3	C	30	56	692813	0	-	0.78	611287	0	-	2.08	611287	0	-	3384.06
10x3	C	30	168	692813	0	-	0.87	-	∞	611287	3600	611287	0	-	1875.38

Table 2: Computational results for instances of class E.

				MTV FORMULATION				MILP FORMULATION				MIQP FORMULATION			
Size	Sc	$\bar{p}$	H	OBJ	GAP (%)	UB	CPU (sec)	OBJ	GAP (%)	UB	CPU (sec)	OBJ	GAP (%)	UB	CPU (sec)
20x5	A	10	56	1272086	0	-	9.9	-	∞	1122068	7200	-	∞	1409782	7200
20x5	A	20	56	-	∞	1272825	7200	-	∞	1122807	7200	-	∞	1444628	7200
20x5	A	30	56	-	∞	1272825	7200	-	∞	1122807	7200	-	∞	1498501	7200
20x5	B	10	56	956102	0	-	61.77	-	∞	843126	7200	-	∞	1088668	7200
20x5	B	20	56	956136	0	-	300.44	-	∞	843160	7200	-	∞	1117253	7200
20x5	B	30	56	-	∞	956136	7200	-	∞	843160	7200	-	∞	1158170	7200
20x5	C	10	56	1547165	0	-	6.31	1269372	7.55	1365148	7200	-	∞	1664112	7200
20x5	C	20	56	1547634	0	-	120.6	-	∞	1365697	7200	-	∞	1699890	7200
20x5	C	30	56	-	∞	1547714	7200	-	∞	1365697	7200	-	∞	1744295	7200
30x5	A	10	56	-	∞	2929259	7200	-	∞	2585442	7200	-	∞	3251301	7200
30x5	A	20	56	-	∞	2931183	7200	-	∞	2587366	7200	-	∞	3338800	7200
30x5	A	30	56	-	∞	2931183	7200	-	∞	2587366	7200	-	∞	3424546	7200
30x5	B	10	56	-	∞	2104195	7200	-	∞	1856658	7200	-	∞	2355458	7200
30x5	B	20	56	-	∞	2105156	7200	-	∞	1857619	7200	-	∞	2413565	7200
30x5	B	30	56	-	∞	2105156	7200	-	∞	1857619	7200	-	∞	2476674	7200

Table 3: Computational results for instances of class M and D.

6 CONCLUSIONS AND FUTURE WORK

We have studied the integration, at the tactical level, of the berth allocation problem with the assignment of quay cranes from the point of view of a container terminal, in the context of a negotiation process with shipping lines. We have characterized this new decision problem and illustrated the concept of QCs assignment profiles. Two mixed integer programming formulations have been presented, respectively, with a quadratic and a linearized objective function, and tested on instances based on real data.

Computational results confirm that the problem is hardly solvable already on small instances via exact methods, hence further work is definitely needed to tackle the computational complexity of TBAP via ad-hoc techniques. As usual in such cases, we will particularly focus on two different classes of approaches. On the one hand, we will consider the problem from the primal viewpoint, by devising new heuristic methods with the aim of finding good feasible solutions of TBAP in a reasonable amount of time. On the other, from the dual viewpoint, we will focus on obtaining good upper bounds on the optimal solution. As for the former, along the lines of previous works, our focus will be on the class of genetic algorithms. As for the latter, decomposition methods seem to be the most promising way to face the problem. In fact, we are considering a reformulation based on Dantzig-Wolfe decomposition and column generation, and an incremental approach based on Lagrangian dual, in order to exploit the structure of TBAP and its relation with the BAP formulation, aiming at saving computational time by solving subproblems via inexact or truncated methods.

Finally, with respect to the application, we remark that the main contribution is represented by the simultaneous control of the terminal on critical resources such as berths and quay cranes, in addition to the added value given by the integration, in a more direct way, of different terminal's costs. However, while transshipment-related housekeeping costs have been sufficiently studied to provide some quantitative results, the value associated to different QCs assignment profiles and to different ship classes need to be analyzed more in depth. Further research could therefore include more sophisticated economical measures for the profile's value.

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References

Cordeau, J. F., Gaudioso, M., Laporte, G. and Moccia, L. (2006). A memetic heuristic for the generalized quadratic assignment problem, *INFORMS Journal on Computing* **18**(4): 433–443.

Cordeau, J. F., Gaudioso, M., Laporte, G. and Moccia, L. (2007). The service allocation problem at the Gioia Tauro maritime terminal, *European Journal of Operational Research* **176**: 1167–1184.

Cordeau, J. F., Laporte, G., Legato, P. and Moccia, L. (2005). Models and tabu search heuristics for the berth-allocation problem, *Transportation Science* **39**: 526–538.

Dai, J., Lin, W., Moorthy, R. and Teo, C. P. (2007). Berth allocation planning optimization in container terminals, *in* C. S. Tang, C. P. Teo and K. K. Wei (eds), *Supply Chain Analysis*, Vol. 119 of *International Series in Operations Research & Management Science*, Springer, pp. 69–104.

Hahn, P., Kim, B. J., Guignard, M., Smith, J. and Zhu, Y. R. (2008). An algorithm for the generalized quadratic assignment problem, *Computational Optimization and Applications* **40**(3): 351–372.

Imai, A., Chen, H. C., Nishimura, E. and Papadimitriou, S. (2008). The simultaneous berth and quay crane allocation problem, *Transportation Research Part E* **44**: 900–920.

Imai, A., Nagaiwa, K. and Chan, W. T. (1997). Efficient planning of berth allocation for container terminals in Asia, *Journal of Advanced Transportation* **31**: 75–94.

Imai, A., Nishimura, E., Hattori, M. and Papadimitriou, S. (2007). Berth allocation at indented berths for mega-containerships, *European Journal of Operational Research* **179**: 579–593.

Imai, A., Nishimura, E. and Papadimitriou, S. (2001). The dynamic berth allocation problem for a container port, *Transportation Research* **35B**: 401–417.

Imai, A., Nishimura, E. and Papadimitriou, S. (2003). Berth allocation with service priority, *Transportation Research Part B* **37**: 437–457.

Imai, A., Sun, X., Nishimura, E. and Papadimitriou, S. (2005). Berth allocation in a container port: using a continuous location space approach, *Transportation Research Part B* **39**: 199–221.

Kim, K. H. and Park, Y. M. (2004). A crane scheduling method for port container terminals, *European Journal of Operational Research* **156**: 752–768.

Lim, A. (1998). The berth planning problem, *Operations Research Letters* **22**: 105–110.

Meisel, F. and Bierwirth, C. (2006). Integration of berth allocation and crane assignment to improve the resource utilization at a seaport container terminal, *Operations Research Proceedings 2005*, Springer, pp. 105–110.

Meisel, F. and Bierwirth, C. (2008). Heuristics for the integration of crane productivity in the berth allocation problem, *Transportation Research Part E* p. doi:10.1016/j.tre.2008.03.001.

Moccia, L., Cordeau, J. F., Gaudioso, M. and Laporte, G. (2006). A branch-and-cut algorithm for the quay crane scheduling problem in a container terminal, *Naval Research Logistics* **53**: 45–59.

Monaco, M. F. and Sammarra, M. (2007). The berth allocation problem: a strong formulation solved by a lagrangean approach, *Transportation Science* **41**: 265–280.

Moorthy, R. and Teo, C. P. (2006). Berth management in container terminal: the template design problem, *OR Spectrum* **28**: 495–518.

Nishimura, E., Imai, A. and Papadimitriou, S. (2001). Berth allocation planning in the public berth system by genetic algorithms, *European Journal of Operational Research* **131**: 282–292.

Park, Y. M. and Kim, K. H. (2003). A scheduling method for berth and quay cranes, *OR Spectrum* **25**: 1–23.

Stahlbock, R. and Voss, S. (2008). Operations research at container terminals: a literature update, *OR Spectrum* **30**: 1–52.

Steenken, D., Voss, S. and Stahlbock, R. (2004). Container terminal operation and operations research - a classification and literature review, *OR Spectrum* **26**: 3–49.

UNCTAD (2007). Review of maritime transport, *Technical report*, United Nations, New York and Geneva.

Vis, I. F. A. and de Koster, R. (2003). Transshipment of containers at a container terminal: An overview, *European Journal of Operational Research* **147**: 1–16.

Wang, F. and Lim, A. (2007). A stochastic beam search for the berth allocation problem, *Decision Support Systems* **42**: 2186–2196.