Optimization of operations in container terminals: hierarchical vs integrated approaches

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Abstract

Over the last years, international sea freight container transportation has grown dramatically and container terminals play nowadays a key role within the global shipping network. Terminal's operations have received increasing interest in the scientific literature and operations research techniques are more and more used to improve efficiency and productivity.

In this work we provide an overview of container terminal's operations and associated decision problems. We review state-of-the-art optimization approaches in terminal's management and we discuss what are in our opinion the current research trends. In particular, we focus on the following streams: the integrated optimization of interdependent decision problems, the analysis of issues related to traffic congestion in the yard and the tactical planning of operations.

The discussion is based on the Tactical Berth Allocation Problem (TBAP), an integrated decision problem that deals with the simultaneous optimization of berth allocation and quay crane assignment. Yard housekeeping costs are also taken into account in the objective function. We use the TBAP as a case study to illustrate the benefits of an integrated optimization approach. A comparative analysis with the traditional hierarchical solution approach is provided. Computational results based on real-world data provided by the MCT (port of Gioia Tauro, Italy) show that the additional computational effort required by the integrated optimization approach allows for more efficient solutions.

Keywords

container terminals, berth allocation, quay crane assignment, integrated optimization

1 Introduction

Global container trade has steadily increased over the last two decades much faster than international trade. The average annual rate in this period has been estimated to be about 10% (UNCTAD, 2009; ISL, 2010); however, due to the financial crisis, the growth of container traffic has slowed down with a drop of 9% in 2008 (Figure 1). This trend is confirmed by Table 1, that reports the throughput of top container terminals in the World and in Europe on a TEU (Twenty feet Equivalent Unit) ranking basis. The dominance of Asia in international shipping is impressive and has grown up to 50% of the total cargo traffic in 2008.

	Million TEUs				**TEU % Growth**		
Worldwide	**1999**	**2007**	**2008**	**2009**	**07-08**	**08-09**	**99-09 (annual)**
1 Singapore (Singapore)	15.9	27.9	29.9	25.9	7.2%	-13.4%	5.0%
2 Shangai (China)	4.2	26.1	28.0	24.9	7.3%	-11.1%	19.5%
3 Hong Kong (China)	16.2	23.9	24.5	21.1	2.5%	-13.9%	2.7%
Europe							
1 Rotterdam (Netherlands)	6.2	10.7	10.8	9.7	0.9%	-10.2%	4.5%
2 Antwerp (Belgium)	3.6	8.1	8.7	7.3	7.4%	-16.1%	7.3%
3 Hamburg (Germany)	3.8	9.9	9.7	7.0	-2.0%	-27.8%	6.5%

Table 1: *Top container ports by TEU-ranking (UNCTAD, 2009; ISL, 2010).*

The multi-modality feature of container transport is an important factor, among others, that contributed to its growth: in particular, any container has a standardized load unit that is suitable also for truck and train transportation. In this framework, container terminals are crucial connections between different transportation modes and cargo handling represents a critical point in the transportation chain. Therefore, improvements in port productivity and efficiency are nowadays more and more needed and an effective operational system can significantly help to make the best use of port infrastructure and resources. Not surprisingly, the optimization of container terminal operations has received increasing interest in the scientific literature over the last years.

In the remainder of this paper we provide a brief description of operations and decision problems in container terminals (section 2) and we identify the current research trends in the literature (section 3). In section 4 we compare a hierarchical solution approach to an integrated solution approach. The discussion is based on two highly interdependent problems: the berth allocation and the quay crane assignment. A case study illustrates the benefits of integrated optimization over the traditional hierarchical approach. Computational results are provided and discussed in section 5.

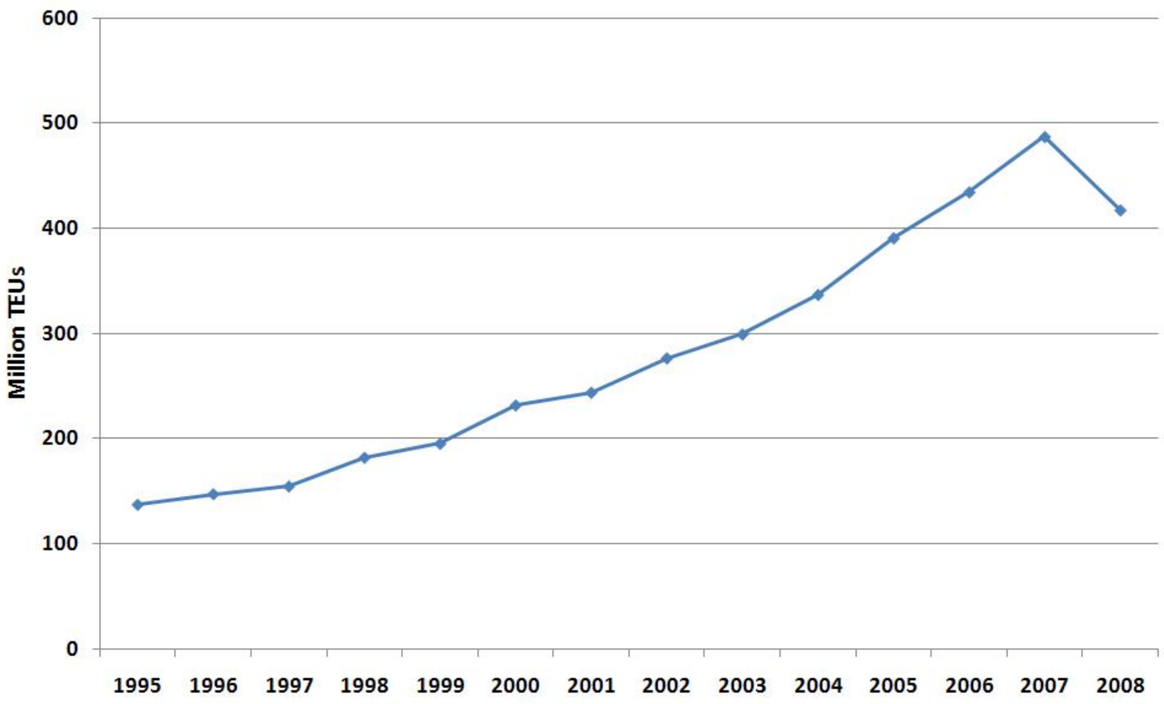

Figure 1: *World container port traffic between 1995 and 2008 (UNCTAD, 2009).*

2 Container terminal operations and decision problems

A container terminal is the zone of the port where vessels dock on a berth and containers are loaded, unloaded and stored in a buffer area called yard. In import-export terminals the flow of containers continues inland and containers are picked-up and delivered by trucks and trains in a area called gate, whereas in transshipment terminals containers are exchanged between ships commonly referred to as mother vessels and feeders, according to a hub-and-spoke system. Figure 2 illustrates the main subsystems and operations in a container terminal.

A container terminal can be ideally divided into two areas, the quayside and the landside (Figure 3). The quayside is made up of berthing positions along the quay and quay cranes (QC) that load/unload containers from vessels calling at the berth. Containers are commonly transferred

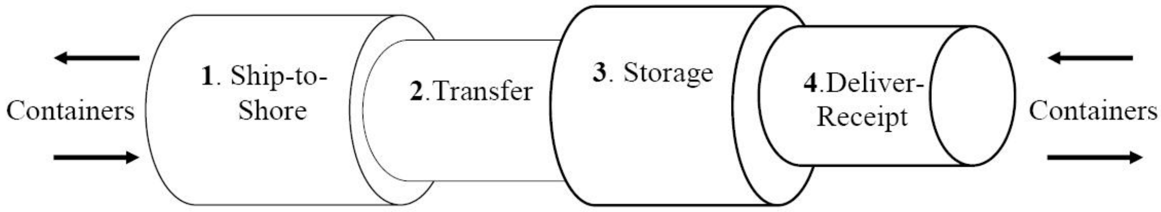

Figure 2: *The main subsystems in a container terminal (Henesey, 2006).*

to the yard by automatic guided vehicles (AVG), straddle carriers (SC) or internal trucks. The transportation equipment is also used to move containers from the yard to the gate and, in some cases, to relocate containers within the storage area. The yard serves as a buffer for loading, unloading and transshipping containers and it is typically divided into blocks: each container block is served by one or more yard cranes (YC), such as rubber-tired or rail-mounted gantry cranes (RTG/RMG).

Although congestion issues are often disregarded, operations are usually slowed down because of overloaded areas in the yard and congestion spreads rapidly to the whole system. While in import/export terminals traffic congestion and bottlenecks affect both the transfer zone and the gate, in transshipment hubs all the operations are concentrated between the quay and the yard and, in particular, congestion issues raise when mother vessels and feeders are performing simultaneously loading and unloading operations.

Container terminal operations and decision problems can be grouped in four main classes.

Berth allocation and scheduling. The berth allocation problem consists of assigning and scheduling ships to berths (discrete case) or to quay locations (continuous case) over a given time horizon. Constraints usually taken into account includes the ship's length, the berth's depth, time windows on the arrival and departure times of vessels, priority ranking, favorite berthing areas. The typical time horizon is up to one week for operational berth allocation and up to one month for tactical berth allocation.

Quay crane allocation and scheduling. The quay crane allocation problem aims to efficiently assign quay cranes to vessels that have to be operated over a given time horizon. The allocated resources must be sufficient to complete the workload within the given time window, although many configurations are possible. The loss of productivity due to crane interference must also be taken into account. Furthermore, quay cranes usually represent one of the most scarce resources in the terminal, as they are highly expensive. The quay crane scheduling problem is more operational: planners must assign specific quay cranes to specific tasks (set of containers) and produce a detailed schedule of the loading and unloading moves for each quay crane. Issues related to interference among cranes, precedence and operational constraints, such as no overlapping, must also be taken into account.

Transfer Operations. Containers are usually transferred from the quayside to the yard, from the yard to the gate and viceversa by internal trucks, straddle carriers and AGVs. The transfer originates decision problems such as vehicle routing and dispatching strategies. Typical objectives aim to minimize the vehicle fleet size, the total distance traveled to complete the tasks, the fleet operating costs or the total operations delay. Some optimization strategies can also include deadlock prevention and real-time conflict avoidance for automated guided vehicles.

Storage and stacking. The management of yard operations involves several decision problems.

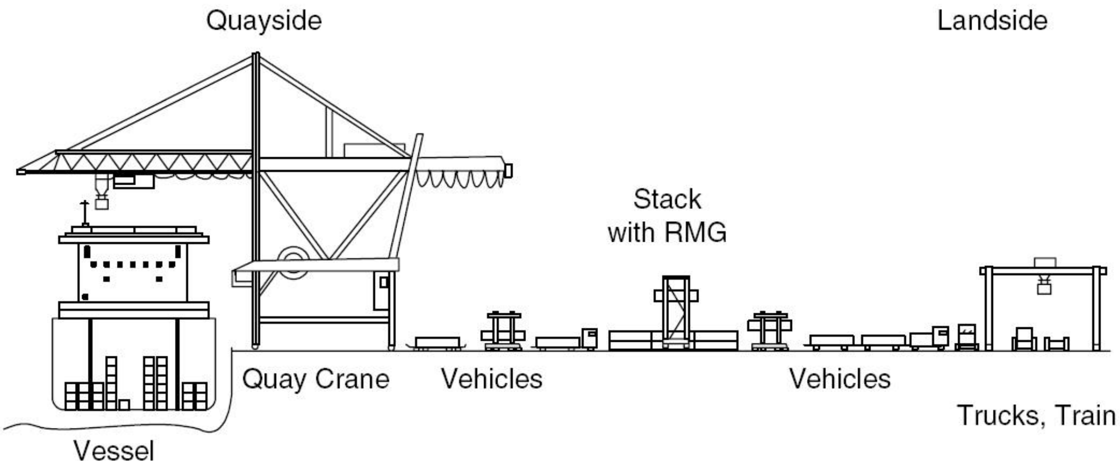

Figure 3: *Schematic representation of a container terminal (Steenken et al., 2004).*

The yard allocation problem refers to the design of storage policies at the block level according to the specific features of the container (size, weight, destination, import/export etc.). At the operational level, the plan becomes more detailed and a specific position in the block (identified by the row, bay and tier) is assigned to each container. Another interesting problem is the yard crane deployment, that concerns the allocation of cranes to blocks, their routing and the scheduling of the tasks based on the container loading sequence. Finally, advanced methods for container stacking are investigated, such as the design of re-marshalling policies for export containers. The container retrieval process is optimized via relocation and rehandling strategies performed in advance, in order to speed up the loading operations; this policy is also referred to as housekeeping.

3 Current challenges in container terminal optimization

Container terminal operations and their optimization have received increasing interest in the operations research (OR) community over the last years, as confirmed by recent surveys (Steenken *et al.*, 2004; Stahlbock and Voss, 2008). Additional references are Vis and de Koster (2003), Kim (2005), Murty *et al.* (2005), Günther and Kim (2005) and Crainic and Kim (2007).

At first, researchers focused on very specific problems and there exists many contributions dedicated to sophisticated models for single operational problems at container terminals, such as *berth allocation* (Lim, 1998; Imai *et al.*, 2001; Kim and Moon, 2003; Imai *et al.*, 2005; Cordeau *et al.*, 2005; Monaco and Sammarra, 2007; Dai *et al.*, 2008), *quay crane scheduling* (Daganzo, 1989; Lim *et al.*, 2004; Kim and Park, 2004; Moccia *et al.*, 2006; Sammarra *et al.*, 2007; Lee *et al.*, 2008), *transfer operations* (Kozan, 2000; Liu *et al.*, 2004; Cheng *et al.*, 2005;

Vis *et al.*, 2005; Lee *et al.*, 2007) and *yard operations* (Kim and Bae, 1998; Kim *et al.*, 2000, 2003; Ng and Mak, 2005; Ng, 2005; Kang *et al.*, 2006; Lee *et al.*, 2006; Yang and Kim, 2006). Thanks to the expertise acquired from previous work, some authors developed an accurate insight and enriched of details the models to provide more reliable solutions.

More recently, we have identified new research trends and in this section we describe what are, in our opinion, the current challenges in container terminal optimization. We believe that an increase of the knowledge on the following issues would lead to an enrichment of the decisional tools offered to key actors of container terminals.

Integration of operations. A promising research trend is represented by the integrated optimization of decision problems that are highly interdependent, yet usually solved hierarchically by terminal's planners. Indeed research is moving towards this direction: in particular, authors with experience on single optimization problems try to combine the problems and the solution methods into a unique approach.

On the quayside, the simultaneous optimization of berth allocation and quay crane scheduling represents a challenging problem for the integration of operations. The integrated planning was firstly introduced by Park and Kim (2003) and further investigated by Meisel and Bierwirth (2006) and Imai *et al.* (2008). Giallombardo *et al.* (2010) propose an integrated model that also takes into account the yard housekeeping costs generated by the berth template. A recent survey (Bierwirth and Meisel, 2010) review the contributions on this topic and classify the existing models by space (continuous vs discrete berthing positions), time (static vs dynamic arrivals), integration concept (monolithic vs bi-level approach, feedback loops) and performance measures (completion time, utilization rate or throughput).

On the landside, transfer and storage planning are two important problems affecting the efficiency of the operations. The integration of yard truck scheduling and storage allocation was introduced by Bish *et al.* (2001) and a solution approach was proposed by Bish (2003). Recently, Lee *et al.* (2009) contributed by taking into account at the same time loading and discharging requests, so that the empty moves of yard trucks can be reduced.

Tactical decision level. While most papers in the literature study operational problems, only a few contributions on tactical planning are available. In the current practice, many tactical problems are still solved by rules of thumb by terminal planners: it is therefore likely that improvements in terms of efficiency and productivity can be reached by using more quantitative solution approaches. Furthermore, taking into account operational constraints (in terms of rules, common policies and best practices) in the definition of the tactical problems would allow to introduce the concept of robustness in the tactical planning.

The papers of Moorthy and Teo (2006) and Cordeau *et al.* (2007) study tactical problems arising in transshipment container terminals. Moorthy and Teo (2006) address the design of a berth template, a tactical planning problem that arises in transshipment hubs and that concerns the allocation of favorite berthing locations (home berths) to services periodically calling at the terminal. The authors propose two procedures able to build good and robust templates and evaluate their performance via simulation. Cordeau *et al.* (2007) introduce the service allocation problem, a yard-related decision problem that occurs at the tactical planning level. The authors provide a berth and yard template able to minimize the container rehandling operations inside the yard.

Congestion and traffic. Congestion issues in container terminals are becoming more and more relevant, especially because of the volume increase in container traffic. A few papers have tackled this aspect in the very recent past.

Lau and Lee (2007) analyze the quayside traffic condition of a very busy container port in Hong Kong using simulation. The study provides some insight on the effects of deployment strategies for trucks on traffic congestion and quay crane utilization. In particular, a traffic reduction also reduces the performance of quay cranes. Han *et al.* (2008) focus on transshipment hubs, where loading and unloading operations are highly concentrated and yard activity is heavy. The authors propose a storage strategy able to minimize traffic congestion using a high-low workload balancing protocol.

4 Hierarchical vs Integrated solution approaches

In this section we provide a comparative analysis of hierarchical vs integrated solution approaches. The analysis is performed on a case study that focus on two highly interdependent decision problems: the Berth Allocation Problem (BAP) and the Quay Crane Assignment Problem (QCAP).

The BAP and the QCAP are usually solved hierarchically by the terminal planners: firstly, vessels are assigned to berths and scheduled over a time horizon accordingly to their time windows and to their expected handling time; secondly, quay cranes are assigned to vessel accordingly to the berth allocation plan, taking into account the vessel's workload and the quay crane capacity of the terminal.

The two problems are indeed strictly correlated, since the number of quay cranes assigned to a ship affects its expected handling time, and thus has impact on the scheduling in the berth allocation plan. It makes therefore sense to use an integrated approach and solve the BAP and the QCAP simultaneously, aiming to gain efficiency and to make a more effective use of resources.

In particular, for what concerns the integrated optimization model, we refer to the Tactical Berth

Allocation Problem (TBAP) introduced by Giallombardo *et al.* (2010). This formulation arises in the context of transshipment container terminals and takes into account the housekeeping costs generated by the berth template as a proxy of yard congestion.

In section 4.1 we briefly describe the hierarchical approach while the integrated optimization scheme is outlined in section 4.2.

4.1 Hierarchical approach: BAP + QCAP

In the hierarchical approach, the berth allocation and the quay crane assignment are solved sequentially. The main assumption concerns the handling time of vessels, that is assumed to be known in advance. In practice, the expected handling time is provided by terminal planners, that base their estimations on quantitative data such as vessel's workload, average QC productivity, availability of transfer equipment, vessel's priority, as well as on their experience. In particular, some extra time can also be included in the estimation in order to guarantee more robustness and flexibility to the schedule.

The expected handling time of vessels is the necessary input of the whole hierarchical optimization process, that consists of the following two sequential steps:

1. **Berth Allocation Problem (BAP)**
   In this step, every vessel is assigned to a berth. For every berth, vessels are scheduled over the time horizon according to their time windows and expected handling times. The objective function aims to minimize the yard housekeeping costs generated by the resulting berth template.

2. **Quay Crane Assignment Problem (QCAP)**
   In this step, a quay crane profile (representing the number of quay cranes operating on the vessel during the working shifts associated to the allocated handling time) is assigned to every vessel. The main constraint is represented by the total quay crane capacity of the terminal, that is limited and must not be exceeded, especially when two or more vessels are serviced simultaneously. The berth allocation plan and scheduling determined at step 1 is therefore a necessary input. The objective function aims to maximize the monetary value associated to the quay crane profiles assigned to vessels.

The hierarchical approach is based on two separated models for the BAP and the QCAP. For this study, we used the models provided by Vacca *et al.* (2010a) and we refer the reader to the paper for more details on the two formulations. In particular, the objective functions of the two models are consistent with the global objective of the integrated TBAP model, in order to allow for comparison between the two approaches.

4.2 Integrated approach: TBAP

The Tactical Berth Allocation Problem (TBAP) with Quay Crane Assignment (Giallombardo *et al.*, 2010) is a model for the integrated optimization of berth allocation and quay crane assignment. The objective is, on the one hand, to maximize the monetary value associated to the quay cranes assigned to the vessels and, on the other hand, to minimize the housekeeping costs generated by the berth allocation plan. The authors provides a detailed description of the problem, as well as two mixed integer programming models and a heuristic solution algorithm. Computational experiments are performed on realistic instances provided by the port of Gioia Tauro, Italy.

The TBAP model is very interesting since it tackles somehow all the current challenges identified in section 3:

- integrated optimization of two decision problems usually solved hierarchically: berth allocation and quay crane assignment;
- tactical planning: the model takes into account the terminal point of view in the context of negotiation with shipping lines;
- congestion issues: yard housekeeping costs generated by the berth assignment are taken into account by a quadratic term in the objective function.

We remark that in the integrated problem formulation the handling time of the vessel becomes a decision variable that depends on the number of assigned quay cranes.

For more details on the integrated TBAP model we refer the reader to the paper by Giallombardo *et al.* (2010).

5 Comparative analysis

We implemented a branch-and-price algorithm for solving the integrated TBAP (Vacca *et al.*, 2010b), further adapted to solve the BAP model in the hierarchical approach. The QCAP model has been solved using a general-purpose MIP solver. The dataset is provided by Giallombardo *et al.* (2010).

5.1 Handling time estimation

As mentioned, the hierarchical approach requires an estimation of the handling time, usually provided by the terminal's planners.

Among the available TBAP data, we are given the set of feasible quay crane assignment profiles defined for every vessel and known in advance; in particular, we know the duration in terms of working shifts of every feasible QC profile.

In order to start the entire hierarchical optimization process, we produce two different estimations for the handling time, both motivated by the practice:

Scenario A for every vessel, the handling time is given by the longest feasible quay crane assignment profile;

Scenario B for mother vessels, the handling time is given by the shortest feasible quay crane assignment profile whereas for feeders, the handling time is given by the longest feasible quay crane assignment profile.

Scenario A is very conservative and somehow represents the worst-case scenario, when all vessels are serviced at the lowest rate. However, this handling time estimation may be useful to produce robust schedules.

Scenario B can be considered more realistic, since mother vessels typically have higher priority than feeders. In particular, we expect the terminal to operate as fast as possible mother vessels in order to minimize their stay at the port.

We remark that both scenarios are realistic and reasonable in practice.

5.2 Computational results

Table 2 compares the optimal solutions for the hierarchical approach under scenarios A and B to the integrated TBAP approach. We considered instances with 10 vessels and 3 berths over a time horizon of one week. The name of the instance $inst$ indicates the traffic volume, high (H) or low (L), and the number of feasible quay crane assignment profiles for each vessel (10, 20 or 30). For all solutions we report the value of the objective function (obj), the number of used berths (K) and the computational time in seconds ($t(s)$). Columns '$\%(A)$', '$\%(B)$' indicate the improvement of the integrated solution with respect to the hierarchical approach under scenarios A, B respectively. We remark that the global objective functions refer to a maximization problem.

As expected, the integrated TBAP provides better solutions, although it seems that these specific instances do not allow for a significant gain in terms of objective function. The average improvement is 0.68$\%$ over scenario A and 0.36$\%$ over scenario B. The computational effort varies a lot among instances, from seconds (class H2) up to hours (class L2). Surprisingly, the hierarchical approach finds good quality solutions and much faster (about 1 minute of computational time on average).

	BAP+QCAP Scen.A			BAP+QCAP Scen.B			Integrated TBAP				
$inst$	obj	K	$t(s)$	obj	K	$t(s)$	obj	K	$t(s)$	$\%(A)$	$\%(B)$
H1_10	**787167**	2	15	**789478**	2	26	**790735**	2	114	0.45%	0.16%
H1_20	**787117**	2	16	**789754**	2	16	**791011**	2	995	0.49%	0.16%
H1_30	**787151**	2	16	**789788**	2	16	**791045**	2	557	0.49%	0.16%
H2_10	**730702**	2	3	**733276**	2	2	**733276**	2	12	0.35%	0.00%
H2_20	**730418**	2	6	**732659**	2	6	**735646**	2	29	0.72%	0.41%
H2_30	**730454**	2	4	**732695**	2	6	**735682**	2	25	0.72%	0.41%
L1_10	**513661**	2	85	**515017**	2	308	**515902**	2	4054	0.44%	0.17%
L1_20	**513696**	2	21	**515052**	2	171	**518049**	2	761	0.85%	0.58%
L1_30	**513731**	2	21	**515087**	2	173	**518084**	2	470	0.85%	0.58%
L2_10	**559683**	2	30	**561705**	2	24	**564831**	2	4697	0.92%	0.56%
L2_20	**559719**	2	14	**561741**	2	26	**564867**	2	1573	0.92%	0.56%
L2_30	**559755**	2	14	**561777**	2	27	**564903**	2	2680	0.92%	0.56%

Table 2: *Optimal solutions for 10 vessels over a time horizon of one week.*

Since the results seems to indicate that the tested instances are not very tight, we performed additional tests by defining more congested instances. Such instances were obtained by reducing the time horizon from one week to four days.

Results for instances with a time horizon of four days are illustrated in Table 3. As soon as instances become more congested, the hierarchical approach clearly shows its drawbacks: first of all, the hierarchical approach is not always able to provide a feasible solution. In particular, the quay crane assignment may not be feasible for a given berth allocation plan, due to the QC capacity constraint. On the contrary, the integrated approach always finds the optimal solution of the problem in a reasonable time (about 4 minutes on average).

The gain in terms of objective function is still modest: for the cases where a hierarchical solution is found, the average improvement is 0.82% over scenario A and 0.52% over scenario B. However, it is interesting to notice that the integrated solution makes use, in some cases, of one berth less than the solution provided by the hierarchical approach. Therefore, the gain in terms of resources is significant.

Analyzing the results, we can conclude that the increased computational effort required for the integrated solution approach is worth it, especially for congested instances (that are those closer to reality). In particular, the integrated TBAP provides a more efficient use of terminal's resources.

	BAP+QCAP Scen.A			**BAP+QCAP Scen.B**			**Integrated TBAP**				
$inst$	obj	K	$t(s)$	obj	K	$t(s)$	obj	K	$t(s)$	$\%(A)$	$\%(B)$
H1_10	**x**			**x**			**777398**	3	59	$+\infty$	$+\infty$
H1_20	**776331**	3	11	**x**			**779674**	3	150	0.43%	$+\infty$
H1_30	**776365**	3	12	**x**			**782300**	3	93	0.76%	$+\infty$
H2_10	**x**			**x**			**722431**	3	45	$+\infty$	$+\infty$
H2_20	**719927**	3	7	**722674**	3	8	**724345**	3	55	0.61%	0.23%
H2_30	**719998**	3	5	**722674**	3	8	**725585**	3	53	0.78%	0.40%
L1_10	**507528**	3	5	**x**			**512533**	2	17	0.99%	$+\infty$
L1_20	**507365**	3	4	**508505**	3	8	**512533**	2	107	1.02%	0.79%
L1_30	**507400**	3	4	**508540**	3	8	**512991**	2	1725	1.10%	0.88%
L2_10	**553971**	3	6	**556179**	3	11	**558750**	2	69	0.86%	0.46%
L2_20	**554380**	3	6	**556272**	3	9	**558786**	2	197	0.79%	0.45%
L2_30	**554380**	3	6	**556280**	3	10	**558822**	2	86	0.80%	0.46%

Table 3: *Computational results for 10 vessels over a time horizon of four days.*

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