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ORIGINAL PAPER

# An integrated multi-ship crane allocation in Beirut Port container terminal

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## Abstract

This paper investigates the integration between the quay and yard sides for multiple berthing ships with transshipment containers. This paper is motivated by the experience of an operator at Beirut Port. An integer linear programming model is formulated to minimize the total number of cranes used in both quay and yard sides for all berthing ships with transshipment containers unloading during a finite and discretized time horizon. The number of containers to be unloaded is determined in each time period, by each quay crane, at each ship bay location, along with the designated storage location at the yard side. The number of yard cranes needed at each storage yard block is also determined over the time horizon. Major capacity, time, and spatial constraints related to transshipment operations are taken into consideration. One insight from our numerical results is that restricting resources at the yard side will lead to an increase in required cranes at the quay side, and vice versa, which confirm results in earlier literature on single ship. However, we argue, via several counter examples, that single-ship solutions are not easily adaptable to multi-ship situations, which justifies the purpose of integrated formulations such as ours.

**Keywords** Berthing ships · Beirut Port · Crane scheduling · Integer programming · Transshipment

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## 1 Introduction

Beirut Container Terminal Consortium (BCTC), the container terminal operator at Beirut Port, handled more than 1.3 million twenty-foot equivalent units (TEUs) in year 2017 with a growth of 38% compared to year 2008, where BCTC handled 0.945 million TEUs (BCTC 2018). Figure 1 illustrates Beirut Port container throughput from year 2008 to year 2017. Even with the worldwide financial crisis that occurred in summer 2008, Beirut container terminal throughput increased significantly, as illustrated in Fig. 1. Worldwide, the container throughput was estimated to be 752 million TEUs in 2017 with a growth of 54.4% from year 2006, where it was estimated to be 487 million TEU, as mentioned by the United Nations Conference for Trade and Development (UNCTAD) reports (UNCTAD 2008, 2016, 2018).

With such figures, operators of ports at Beirut, and elsewhere, opt to sustain their container throughput growth by optimizing the use of their resources (Kaysi and Nehme 2016). Indeed, the increase in container volume coupled with an increase in ship size, led to a decrease of efficiency in ports worldwide. For example, the average port productivity loss in 2017 compared with 2016 is estimated at 3%, where productivity is defined as the number of container moves per hour of time spent by vessels in port (Mooney 2018).

Transshipment occurs when containers are transferred from one ship to another after a temporary storage at the yard (e.g. Stahlbock and Voß 2008). In 2017, 25.8% of the worldwide container throughput was composed of transshipped containers (UNCTAD 2008). This reflects the growth of transshipment for maritime containers worldwide, especially in port of Beirut, where about 30% of the container throughput is composed of transshipped containers.

At a container terminal, containers are divided into three categories: imported, exported, and transshipped. Normally, a container terminal yard is composed of two main areas: the quay side area and the yard side area. The loading and unloading of containers to and from vessels occur at the quay side. When the vessel berths at the quay side, the assigned quay cranes (QCs) are used to unload the transshipped

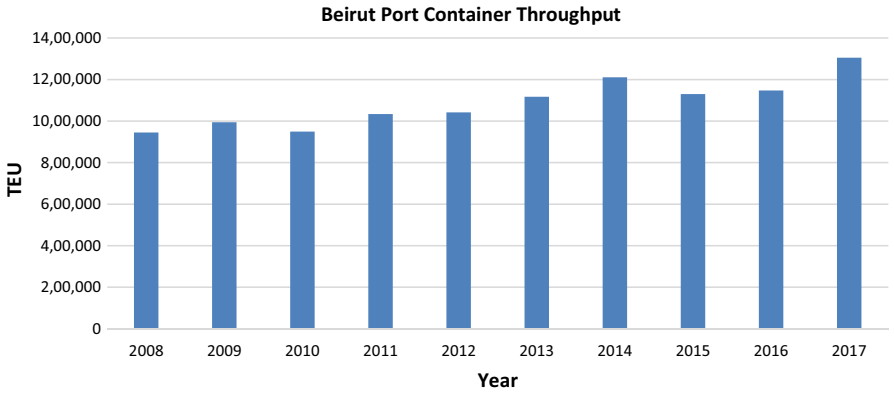


**Fig. 1** Beirut Port container throughput from 2008 to 2017

containers onto internal trucks (ITs) that move the containers to assigned blocks in the yard. Specified yard cranes (YCs) then unload the transshipped containers in the storage yard. Subsequently, these containers are discharged from the yard side area, via the YCs and the ITs, to be loaded into outbound vessels by the QCs. In this paper, we analyze the unloading sequence of operations in the transshipment process. The loading process can be handled in a similar manner.

With such complex operations, the need to optimize resource allocation is essential to order to minimize operations cost inside the transshipment container terminal and to integrate different transshipment operations during loading and unloading of containers from the quay side to the yard side (Nehme and Awad 2010; Van de Voorde 2005).

This research investigates the integrated scheduling of quay and yard sides for multiple berthing ships with transshipment containers assuming an ample availability of internal trucks. It is motivated by our experience consulting an operator at Beirut Port container terminal. Our analysis methodology is based on formulating and solving an integer linear program that aims at minimizing the crane utilization (at both quay and yard sides) subject to constraints on crane capacity, time, and space in both the discharge and storage areas. As such, this paper extends the work (Kaysi et al. 2012) that considers a similar objective and methodology, albeit for a single birthing ship. The multi-ship case considered in this paper adds considerable complexity to the model formulation. In addition, it is a common practice to have transshipment operations spanning multiple berthing ships concurrently. Our paper provides useful decision tools and managerial insights that assist in optimizing such multi-ship transshipment operations in Beirut Port and beyond.

The paper is structured as follows. Section 2 presents a brief review of the relevant literature. Section 3 presents our mathematical formulation in terms of the objective function and the relevant constraints. Section 4 presents a numerical study. Section 5 draws useful managerial insights and observations from the results in Sect. 4. Finally, Sect. 6 summarizes the paper and suggests areas for future research.

## 2 Literature review

This section presents an overview of the literature related to resource allocation at container terrminals, mainly related to integrated planning of resources. (Stahlbock and Voß 2008) present a comprehensive literature review on operations research at container terminals. The authors emphasize the scarcity of studies reflecting integrative views on container terminal logistics.

Most of the research on container port operations is concerned with scheduling and capacity allocation of the three key resources, QCs, ITs and YCs, which are utilized in the loading and unloading of containers as described in Sect. 1. Most of the literature presents models to improve the efficiency of one of these three resources in isolation. A substantive literature targets planning QCs assuming exogenous availability of ITs and YCs, such as Al-Dhaheri and Diabat (2015), Bierwirth and Meisel (2010, 2015), Choo et al. (2010), Daganzo (1989), Fu and Diabat (2015), Giallombardo et al. (2010), Kim and Park (2004), Lee et al. (2008),

Liang et al. (2017), Meisel (2011), Murty et al. (2005), Peterkofsky and Daganzo (1990), Türkoğullari et al. (2014), and Zeng et al. (2015). Likewise, an extensive amount of work exists on isolated YC operations, such as, Cao et al. (2010), Chen and Langevin (2011), Cordeau et al. (2007), Li et al. (2009), Ng and Mak (2005), Gharehgozli et al. (2015), He et al. (2015a), Kozan and Preston (2006), Lin (2000), and Lee et al. (2006). A common theme among this vast QC and YC related works is the assumption of deterministic resource availability and the adoption of mathematical programming methodology, especially mixed integer programming (MIP) and machine scheduling. As we argue in Sect. 3.1, we believe that this is tied to a predictable berthing schedule of ships at most ports. This vast literature provides justification for our deterministic MIP model.

Relatively, limited work addresses the coordination between resources (QC, IT, and YC) planning at container terminal. Wang et al. (2017) presents a survey of this literature along with an insightful classification scheme. We adopt the classification scheme of Wang et al. (2017) and expand on it with further relevant works. This classification scheme is based on whether decisions variables are included (Y/N/given) on scheduling (and resource allocation) of (1) ITs, (2) QCs, and (3) YCs. Other aspects of the classification that we adopt from Wang et al. (2017) are (4) whether a decision variable is included (Y/N/given) on locating containers in the yard, (5) whether both loading and unloading operations are simultaneously considered (Y/loading/unloading/unloading or loading), and (6) the key aspects of the solution methodology. Table 1 presents an updated classification of the container terminal integrative operational literature based on this scheme, which clarifies the positioning of our paper in the recent literature.

It is clear from the classification scheme in Table 1 that by including decisions integrating both quay and yard crane operations and the location of containers in the yard, our paper has only two counterparts in its decision facets league (Gambardella et al. 2001; Kaysi et al. 2012). Gambardella et al. (2001) present two separate submodels for (1) resource allocation (number of QCs and YCs) and (2) scheduling of QCs and YCs. Our paper integrates these two sets of decisions into one model, which should lead to superior globally-optimal solutions. Compared to Kaysi et al. (2012), we offer an expansion in the scope of the model from a single ship to multiple ships, which provides an integrative aspect that boosts productivity further.

## 3 Model and assumptions

Our model has a focus on transshipment operations related to container unloading from multiple berthing ships (via QCs), transferring to a yard (by ITs), and, finally, unloading by YCs. The transshipment loading operation follows a reverse flow and can be handled in a similar fashion.

Consider $V$ berthing ships with transshipment containers, with different bays (locations) for storing containers at the ship. The number of bays in ship $v$ is $B_v$. A container is classified into one of different flags (types). Different flags are defined based on container attributes such as (1) weight class, (2) size (20′ or 40′ length), and (3) port of destination. The number of total flags is $F$. The number of containers

**Table 1** Literature classification and positioning of the paper

| Literature | IT planning (1) | QC planning (2) | YC planning (3) | Yard location (4) | Loading and unloading (5) | Methodology (6) |
|---|---|---|---|---|---|---|
| Assadipour et al. (2014) | N | Y | Y | N | Unloading | MIP + GA |
| Bish (2003) | Y | Y | N | Y | Y | Two sub problems + heuristics |
| Bish et al. (2001) | Y | Given | N | Y | Unloading | Two sub problems + heuristics |
| Cao et al. (2008) | Y | Given | Y | Y | Unloading | MIP + GA |
| Cao et al. (2010) | Y | Given | Y | Given | Loading | MIP + benders decomposition |
| Chen et al. (2007) | Y | Given | Y | N | Y | MIP + tabu |
| Chen et al. (2013) | Y | Y | Y | N | Y | Constraint programming |
| Gambardella et al. (2001) | Given | Y | Y | Y | Y | Two sub problems + graph + TS |
| Han et al. (2008) | Y | Given | N | Y | Y | MIP + workload balancing |
| He et al. (2015b) | Y | Y | Y | N | Loading | MIP + simulation + GA/PSO |
| Homayouni et al. (2014) | Y | Y | Y | N | Y | GA |
| Kaveshgar and Huynh (2015) | Y | Y | N | N | Unloading | MIP + GA |
| Kaysi et al. (2012) | N | Y | Y | Y | Unloading | MIP |
| Lau and Zhao (2008) | Y | Y | Y | N | Y | MIP + GA |
| Lee et al. (2009) | Y | Given | N | Y | Y | MIP + insertion algorithm |
| Lee et al. (2010) | Y | Given | Y | N | Y | MIP + MCF/GA |
| Lu & Le (2014) | Y | Given | Y | N | Unloading or loading | MIP + PSO |
| Luo and Wu (2015) | Y | Given | Y | Y | Y | MIP + GA |
| Tang et al. (2014) | Y | Y | N | N | Unloading | MIP + PSO |
| Wang et al. (2017) | Y | Given | Y | Y | Y | MIP + tree structure search |
| Zhen et al. (2019) | Y | Y | N | N | Unloading | MIP + PSO |
| This paper | N | Y | Y | Y | Unloading | MIP |

from flag $f$, stored in bay $b$ of ship $v$ is $N_{vbf}$, $f=1, \ldots, F$, $b=1, \ldots, B_v$. A container is unloaded from ship $v$ via a QC and loaded on an internal truck. The number of internal trucks is assumed to be large enough to handle the operational workload, which is justified in this case since the cost of internal trucks is relatively low compared to the cost of cranes.

Time is discretized into small intervals, 1, 2, …, $T$, where each bay can accommodate only one quay crane per time period. A quay crane can hold a maximum of $C_Q$ containers per time period. The number of quay cranes at time $t$, $t \in \{0, 1, \ldots, T\}$, $Q_t$, available to unload all ships, is assumed to be known a priori. In practice, the port operator can determine $Q_t$ by splitting the available QCs according to anticipated loads of different container operations (i.e., loading and unloading related to import, export and transshipment). The truck moves the container to a designated yard storage location, denoted as a sub-block. The number of sub-blocks is $S$. Once the truck reaches the yard area, the container is stored at the appropriate sub-block via an appropriate yard crane. A yard crane can hold a maximum of $C_Y$ containers per time period. An adequate number of yard cranes, $YC_t$, is available in every period to store all the containers unloaded from ships. Similar to $Q_t$, the number of cranes available for transshipment, $YC_t$, can be estimated from a prior analysis of the anticipated load from different operations. The ability to determine the available number of cranes, $Q_t$ and $YC_t$, assume a predictable schedule of berthing over a short horizon. We argue that this is true for Beirut Port in particular, and at other ports, globally, in Sect. 3.1.

A binary variable $I_{fs}$ is defined, where $I_{fs}=1$ if flag $f$ is allowed to be stored in sub-block $s$, $f=1, \ldots, F$, $s=1, \ldots, S$ and $I_{fs}=0$, otherwise. Due to spatial and maneuver constraints inside the sub-block, there is a limitation on the number of yard cranes serving each sub-block in a time period. The maximum number of yard cranes allowed to serve sub-block $s$ at time $t$, is $K_{st}$. Since the yard area space is limited, a maximum of $C_{fs}$ containers of flag $f$ are allowed to be stored in sub-block $s$. Sharing the same block is possible between different ships.

The mathematical model is presented in Sects. 3.2–3.6 after a justification of the assumption that berth times are predictable in Sect. 3.1, which allows a deterministic allocation of resources on both the quay and yard sides. A discussion of the model complexity is presented in Sect. 3.7.

### 3.1 Predictable birth times

The crane operations described in the paper take place after the ship arrival and berthing at the port. Typically, a ship arrives at the port, then waits to be berthed, and subsequently, the ship is berthed and unloaded. While there could be uncertainty in the arrival time, the berth time is typically predictable after the ship arrival. The snapshot in Fig. 2 on Beirut port ship arrivals confirms this. While there is disparity between expected arrival time (ETA) and actual arrival time (ATA), the time of berthing (TB) seems to be predictable with ETB and ATB being the same.

We could not find detailed data on waiting time to berth at Beirut Port except for limited observations such as those in Fig. 2. The global average on this waiting

MV: Mother Vessel
RORO: Roll-on/Roll-off
LOA: Vessel Length (m)
D20: Discharge 20 Foot Containers
D40: Discharge 40 Foot Containers
LFCL: Load Full Containers
LMTY: Load Empty Containers
ETA: Estimated Time of Arrival
ATA: Actual Time of Arrival at Pilot Station
ETB: Estimated Time of Berthing
ATB: Actual Time of Berthing
ETD: Estimated Time of Departure
ATS: Actual Time of Sailing

BCTC BEIRUT CONTAINER TERMINAL CONSORTIUM An IPM Company

**Vessel Schedule**

| ETA | Vessel Name | Status | Type | Moves | Quay | ATA | ETB | ATB | ETD | ATS |
|---|---|---|---|---|---|---|---|---|---|---|
| 30/06/19 00:01 | ENIGMA | Berthing | | 32 | Q13 | 29/06/19 23:30 | 02/07/19 08:00 | 02/07/19 08:00 | TBA | TBA |
| 02/07/19 18:00 | MSC JEMIMA | **Operating** | | 866 | Q16W | 02/07/19 17:20 | 02/07/19 18:20 | 02/07/19 18:20 | 03/07/19 14:00 | TBA |
| 02/07/19 20:30 | SEALAND MICHIGAN | **Operating** | MV | 1202 | Q16E | 02/07/19 20:30 | 03/07/19 07:38 | 03/07/19 07:38 | 04/07/19 03:00 | TBA |
| 03/07/19 00:45 | MSC RHIANNON | Arrived | | 642 | | 03/07/19 01:15 | TBA | TBA | TBA | TBA |
| 03/07/19 01:00 | PACAYA | Arrived | | 615 | | 02/07/19 22:00 | TBA | TBA | TBA | TBA |
| 03/07/19 06:00 | CARTAGENA TRADER | Berthing | | 1037 | Q16W | 03/07/19 10:00 | 03/07/19 12:00 | 03/07/19 12:00 | TBA | TBA |
| 03/07/19 12:00 | CMA CGM ARISTOTE | At Sea | | 270 | | TBA | TBA | TBA | TBA | TBA |
| 03/07/19 19:00 | ALEXANDRA A | At Sea | | 707 | | TBA | TBA | TBA | TBA | TBA |

**Fig. 2** Snapshot on arrival and berth times at Beirut Port. *Source*: BCTC website, www.bctc-lb.com/vesselschedule.aspx

time is around 3 h with the Middle East being on the high-end (Mooney 2018). This indicates that the berthing time at Beirut Port is typically long enough to allow allocation of resources with high certainty, as assumed in this paper. The deterministic assumption on resource availability in crane scheduling is also common in the literature, as discussed in Sect. 2.

### 3.2 Indices

In this model the indices are

- $v$, ship label, $v = 1, \ldots, V$.
- $b$, bay number for ship $v$, $b = 1, \ldots, B_v$.
- $s$, sub-block area number, $s = 1, \ldots, S$.
- $f$, flag type, $f = 1, \ldots, F$.
- $t$, time period, $t = 1, \ldots, T$.

### 3.3 Parameters

In this model the parameters are

- $Q_t$, the number of available quay cranes at time $t$ for all ships.
- $C_Q$, the maximum number of containers a quay crane can hold in one period of time.
- $C_Y$, the maximum number of containers a yard crane can hold in one period of time.
- $YC_t$, the total number of available yard crane at time $t$.
- $K_{st}$, number of allowed YC for every sub-block $s$ at time $t$.

- $N_{vbf}$, the number of containers to be unloaded from bay $b$ of ship $v$ and of flag type $f$.
- $$I_{fs} = \begin{cases} 1, & \text{if flag f is assigned to sub-block } s \\ 0, & \text{otherwise} \end{cases}$$
- $C_{fs}$, the number of containers of flag type $f$ allowed to be discharged in sub-block $s$.

### 3.4 Decision variables

In this model, the decision variables are

- $y_{vbt}$, the number of quay cranes allocated to ship $v$, bay $b$ at time $t$ ($y_{vbt}$ is binary).
- $z_{st}$, the number of yard cranes allocated to sub-block $s$ in time period $t$ ($z_{st}$ is integer).
- $x_{vbfts}$, the number of containers of flag type $f$ unloaded from ship $v$, bay $b$ to sub block $s$ in time $t$, integer (auxiliary decision variable).

### 3.5 Objective function

The model objective is to determine the number of quay cranes needed for every ship at every time period, concurrently with the number of yard cranes needed at every time period, from a set of available cranes, in a way that minimizes the crane usage cost. The formulated model has the objective function given in (1).

$$Minimize \quad w \sum_{v=1}^{V} \sum_{b=1}^{B_v} \sum_{t=1}^{T} y_{vbt} + (1-w) \sum_{s=1}^{S} \sum_{t=1}^{T} z_{st} \tag{1}$$

The objective in (1) is to minimize the total number of all cranes used in the quay-side and the yard-side areas during the unloading of berthing ships. A weight $w$ is assigned, which varies between 0 and 1, to signify the relative cost of the yard crane compared to quay crane.

### 3.6 Constraints

Several constraints are applied for the multi-ship model such as crane capacities on both quay and yard sides, time, and spatial capacities for both the discharge and storage areas. These constraints are as follows.

The total number of quay cranes, at every time period, at all bays, for all ships shall not exceed the number of available quay cranes,

$$\sum_{v=1}^{V} \sum_{b=1}^{B_v} y_{vbt} \leq Q_t, \quad \forall t. \tag{2}$$

The number of containers unloaded is restricted by the capacity of quay cranes allocated for every bay of every ship at every time period,

$$\frac{\sum_{f=1}^{F}\sum_{t=1}^{S} x_{vbfts}}{C_Q} \leq y_{vbt} \quad \forall v, \quad \forall b, \quad \forall t. \tag{3}$$

All transshipment containers, for a given ship, are unloaded by the end of the time horizon, $T$,

$$\sum_{t=1}^{T}\sum_{s=1}^{S} x_{vbfts} = N_{vbf} \quad \forall v, \quad \forall b, \quad \forall f. \tag{4}$$

The number of yard cranes used, at every time period, at any sub-block, shall not exceed the number of allowed yard cranes, $K_{st}$,

$$z_{st} \leq K_{st} \quad \forall s, \quad \forall t. \tag{5}$$

The total number of yard cranes used, at every time period, for all sub-blocks, shall not exceed the number of available yard cranes,

$$\sum_{s=1}^{S} z_{st} \leq YC_t \quad \forall t. \tag{6}$$

The total number of containers discharged from all ships shall not exceed the capacity of the yard cranes available for every sub-block, at every time period,

$$\frac{\sum_{v=1}^{V}\sum_{f=1}^{F}\sum_{b=1}^{B_v} x_{vbfts}}{C_Y} \leq z_{st} \quad \forall s, \quad \forall t. \tag{7}$$

Containers of flag type $f$ are restricted to be stored in sub-block $s$, so that $I_{fs} = 1$,

$$x_{vbfts} \leq I_{fs}.M \quad \forall v, \quad \forall b, \quad \forall f, \quad \forall t, \quad \forall s, \tag{8}$$

where $M$ is defined to be a large constant number. For numerical implementation, the parameter $M$ can be defined to be equal to the total number of containers on the ship.

The total number of containers discharged for all ships of a flag type $f$, in every sub-block, shall properly fit within the spatially allocated area of sub-block $s$,

$$\sum_{v=1}^{V}\sum_{b=1}^{B_v}\sum_{t=1}^{T} x_{vbfts} \leq C_{fs} \quad \forall f, \quad \forall s. \tag{9}$$

Figure 3 summarizes our model as a mixed integer program (MIP).

**Multi Ship Model**

Minimize $w\sum_{v=1}^{V}\sum_{b=1}^{B_v}\sum_{t=1}^{T} y_{vbt} + (1-w)\sum_{s=1}^{S}\sum_{t=1}^{T} z_{st}$ Equation (1)

Subject to

$\sum_{v=1}^{V}\sum_{b=1}^{B_v} y_{vbt} \le Q_t \ , \forall t$ Equation (2)

$\frac{\sum_{f=1}^{F}\sum_{t=1}^{S} x_{vbfts}}{C_Q} \le y_{vbt} \quad \forall v, \forall b, \forall t$ Equation (3)

$\sum_{t=1}^{T}\sum_{s=1}^{S} x_{vbfts} = N_{vbf} \ \forall v, \forall b, \forall f$ Equation (4)

$z_{st} \le K_{st} \ \ \forall s, \forall t$ Equation (5)

$\sum_{s=1}^{S} z_{st} \le YC_t \ \ \forall t$ Equation (6)

$\frac{\sum_{v=1}^{V}\sum_{f=1}^{F}\sum_{b=1}^{B_v} x_{vbfts}}{C_Y} \le z_{st} \quad \forall s, \forall t$ Equation (7)

$x_{vbfts} \le I_{fs}.M \quad \forall v, \forall b, \forall f, \forall t, , \forall s$ Equation (8)

$\sum_{v=1}^{V}\sum_{b=1}^{B_v}\sum_{t=1}^{T} x_{vbfts} \le C_{fs} \quad \forall f, \forall s$ Equation (9)

$x_{vbfts}$ , $z_{st}$ integer, $y_{vbt}$ binary $\forall v, \forall b, \forall f, \forall t$

**Fig. 3** MIP model

### 3.7 Problem complexity

The problem at hand is complex and does not lend itself to mathematical analysis easily. For example, a simplified, single-ship, single-flag, single-bay, single-sub-block, version of our problem is equivalent to a multi-dimensional knapsack, which is a NP hard problem (e.g. Fréville 2004, Wolsey 1998) with no obvious structural results. "Appendix 1" present the details of this case. In addition, a family of problems, which is related is the fixed-charge transportation problem, where a fixed cost is charged every time a shipment is sent on top of to the classical variable cost.

In our transshipment setting, there are no variable costs for unloading containers from ship to yard. However, there is a fixed cost (of *w* for utilizing a QC), which is shared among multiple routes as containers from several bays might be handled by one quay crane. However, our problem seems to be more complicated. For example,

the constraints on the integrality of the quantity transported ($x_{vbfts}$) variables could not be relaxed in our case unlike the fixed-charge transportation problem (e.g. Balinski 1961; Buson et al. 2014).

## 4 Numerical results

We numerically analyze the model presented in Sect. 3. In Sect. 4.1, we analyze a small-scale instance, and then in Sect. 4.2, we consider a large-scale problem of realistic size. It is worth noting that the numerical scenarios are solved using GUROBI via AMPL compiler. Insights from the numerical analysis are presented in Sect. 5.

We limit the numerical study to two berthing ships on purpose due to the capacity at Beirut Port. The largest berth at Beirut Port is Quay 16 with a berth length of 600 m which is dedicated to handle large container ships. With large ship lengths in the 100–300 m range, it is reasonable to assume that Quay 16 is not likely to accommodate more than two ships.

### 4.1 Small-scale problems

Consider two berthing ships ($V=2$), with two bays ($B=2$) each, in a yard with two sub-blocks ($S=2$), with containers of two flags ($F=2$), and over a time horizon of three time intervals ($T=3$). In addition,

- The cost of quay crane is four times the cost of yard crane; i.e., $w=0.8$,
- The quay crane capacity is $C_Q=20$ containers/unit time, and the yard crane capacity is $C_Y=15$ containers/unit time.
- The number of quay cranes available at every time period for all ships is 6, i.e., $\mathbf{Q}=(3\ 3\ 3)$ and the number of yard cranes available at every time period for all ships is 3, i.e., $\mathbf{YC}=(3\ 3\ 3)$.
- The number of containers of flag $f$ to be unloaded from ship $i$ bay $b$, $N_{vbf}$, $v=1, 2$, is 10 for all $b$ and $f$, i.e., $N_v = \begin{bmatrix} 10 & 10 \\ 10 & 10 \end{bmatrix}$.
- The allocation of flags to yard sub-blocks is unrestricted, $I_{fs}=1$ for all $f$ and $s$, i.e., $I = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$.
- The maximum allowed YC per sub-block $s$ at time period $t$ is $K_{st}=2$, i.e., $K = \begin{bmatrix} 2 & 2 & 2 \\ 2 & 2 & 2 \end{bmatrix}$. The sub-block capacity for all flags is $C_{fs}=80$, i.e., $C = \begin{bmatrix} 80 & 80 \\ 80 & 80 \end{bmatrix}$.

The optimal solution is as follows.

- The number of quay crane used per time period per vessel is $y_{111}=1$, $y_{122}=1$, $y_{211}=1$, $y_{222}=1$ and $y_{1bt}=0$, otherwise.
- The number of yard cranes used per time period per sub-block is $z_{11}=2$, $z_{21}=1$, $z_{12}=2$, $z_{22}=1$, and $z_{\mathrm{st}}=0$, otherwise.

- Containers are unloaded from the two vessels as per the schedule $x_{11111}=10$, $x_{11211}=10$, $x_{12121}=10$, $x_{12221}=10$, $x_{21111}=10$, $x_{21212}=10$, $x_{22121}=10$, $x_{22222}=10$, and $x_{vbfts}=0$, otherwise.

This solution can be explained as follows. In period 1, one quay crane is used for each ship, working at full capacity. The containers unloaded from ship 1, bay 1 of flag 1 (10 containers), the containers unloaded from ship 1, bay 1 of flag 2 (10 containers), and the containers unloaded from ship 2, bay 1 of flag 1 (10 containers) are all stored in sub-block 1, which requires two YCs working at full capacity. On the other hand, the containers unloaded from ship 2, bay 1 of flag 2 (10 containers) are stored in sub-block 2, which requires one YC working at two-third capacity. The same process repeats in period 2.

Several variations, of the base case, with their respective solutions are presented in Table 2. The "change" column indicates the variation from the base case while holding other parameters at their base values. To present the solution in a compact form, the total number of quay cranes and yard cranes utilized in every time period is presented as such $\mathbf{y_1}=(y_{11}\ y_{12}\ y_{13})$ for ship 1, $\mathbf{y_2}=(y_{21}\ y_{22}\ y_{23})$ for ship 2, and $\mathbf{z}=(z_1\ z_2\ z_3)$, where $y_{1t}=\sum_{b=1}^{B_1} y_{1bt}$, $y_{2t}=\sum_{b=1}^{B_2} y_{2bt}$ and $z_t=\sum_{s=1}^{S} z_{st}$.

Table 2 also reports benchmark results considering that one of the two (identical) ships considered here is served in isolation without the existence of the other ship. These are obtained by solving the problem using the single-ship model in Kaysi et al. (2012). In Sect. 5, these single-ship solutions will be used to demonstrate the value of multi-ship integration.

### 4.2 Large scale problems

The model is applied on selected large-scale problems motivated by the experience in Beirut container terminal. Consider two ships ($V=2$), with eight bays each

**Table 2** Small instances results

| Case | Change from base case | Description | Two ship berthing | | | One ships in isolation | |
|---|---|---|---|---|---|---|---|
| | | | $y_1$ | $y_2$ | z | $y$ | z |
| 1 | None | Base case | (1 1 0) | (1 1 0) | (3 3 0) | (2 0 0) | (3 0 0) |
| 2 | $\mathbf{YC}=(2\ 2\ 2)$ | Decrease number of yard cranes | (2 0 1) | (0 1 1) | (2 2 2) | (1 1 0) | (2 2 0) |
| 3 | $\mathbf{Q}=(3\ 1\ 1)$ | Decrease number of quay cranes | (2 0 0) | (0 1 1) | (3 2 2) | (2 0 0) | (3 0 0) |
| 4 | $I=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$ | Restrict flag allocation | (2 0 1) | (0 1 1) | (2 2 2) | (1 1 0) | (2 2 0) |
| 5 | $I=\begin{bmatrix}1 & 0\\ 1 & 0\end{bmatrix}$ | Use only one sub-block for all flags | (1 2 0) | (1 0 1) | (2 2 2) | (1 1 0) | (2 2 0) |
| 6 | $C=\begin{bmatrix}40 & 0\\ 40 & 0\end{bmatrix}$ | Use only one sub-block and decrease sub-block capacity | (1 2 0) | (1 0 1) | (2 2 2) | (1 1 0) | (2 2 0) |

($B=8$), four flags ($F=4$), in a yard with four sub-blocks ($S=4$), over a time horizon eight time intervals ($T=8$). In addition, (1) the cost of QC is four times the cost of YC; i.e., $w=0.8$, (2) the quay crane capacity is $C_Q=20$ containers/unit time and the yard crane capacity is $C_Y=15$ containers/unit time, (3) the number of quay cranes available at every time period for all ships is 10, i.e., $Q_t=10$, $t=1, 2, \ldots, 8$, and the number of yard cranes available at every time period for all ships is 20, i.e., $YC_t=20$, $t=1, 2, \ldots, 8$, (4) the number of containers of flag $f$ to be unloaded from ship $v$, bay $b$ is 10 for both ships and all bays and flags, $N_{vbf}=10$, $v=1, 2$, $b=1, 2, \ldots, 8$, and $f=1, 2, 3, 4$, (5) the allocation of flags to sub-blocks is unrestricted, i.e., $I_{fs}=1, f=1, 2, 3, 4, s=1, 2, 3, 4$, (6) the maximum allowed yard cranes per sub-block is 5 for all sub-blocks and time periods, $K_{st}=5$, $s=1, 2, 3, 4$, $t=1, 2, \ldots, 8$, and (7) the sub-block capacity for all flags is 500, $C_{fs}=500, f=1, 2, 3, 4, s=1, 2, 3, 4$.

Table 3 shows the optimal solution for this large-scale problem. To simplify the presentation, the total numbers of QCs and YCs utilized, $\mathbf{\Psi_v} = \sum_{t=1}^{T} \sum_{b=1}^{B_1} y_{1bt}$, $v=1, 2$, and $\mathbf{Z} = \sum_{t=1}^{T} \sum_{s=1}^{S} z_{st}$. The "change" column reports results for variations from the base case while holding other parameters at their base values.

## 5 Analysis results and insights

In this section, we present our insights based on the numerical results reported in the previous section. In Sect. 5.1, we confirm the insights deduced in Kaysi et al. (2012) for the single ship model, and then in Sect. 5.2 we draw insights related to multiple ships berthing at the same time.

### 5.1 Confirmation of insights from the single-ship model

Table 1 confirms the insights deduced in Kaysi et al. (2012) for the single-ship model. Specifically,

**Table 3** Large instances results

| Case | Change from base case | Description | Two ships berthing | | |
|---|---|---|---|---|---|
| | | | $\Psi_1$ | $\Psi_2$ | Z |
| 1 | None | Base case | 16 | 16 | 43 |
| 2 | $\mathbf{YC}=(10\ 10\ 10\ 10\ 3\ 0\ 0\ 0)$ | Decrease number of yard cranes | 18 | 16 | 43 |
| 3 | $\mathbf{Q}=(5\ 5\ 5\ 5\ 5\ 5\ 5\ 5)$ | Decrease number of quay cranes | 16 | 16 | 44 |
| 4 | $I=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ | Restrict flag allocation | 16 | 16 | 44 |
| 5 | $C=\begin{bmatrix} 160 & 0 & 0 & 0 \\ 0 & 160 & 0 & 0 \\ 0 & 0 & 160 & 0 \\ 0 & 0 & 0 & 160 \end{bmatrix}$ | Decrease sub-block capacity | 16 | 16 | 44 |

The limitation of the available cranes over time at either the quay side or the yard side will affect allocation and scheduling of cranes on the other side.

In case 2 of Table 2, the restriction of yard YCs leads to more usage of quay QCs, with respect to the base case (case 1). In case 3 of Table 2, the restriction of QCs leads to more usage of YCs.

Restricting flag allocation to sub-blocks in a multi ship scenario leads to using more resources on the quay side.

This insight is confirmed in cases 4 and 5 of Table 2 where restricting flags allocation on the yard led to an increase in the required number of QCs, with respect to the base case.

Restricting storage capacities in sub-blocks in a multi ship scenario leads to using more resources on the quay side.

This insight is confirmed in case 6 of Table 2 where restricting sub-block capacity on the yard led to an increase in the number of QCs, with respect to the base case.

### 5.2 Insights from the multi-ship model

The main insight from the multi-ship aspect of the problem is on the value that multi-ship integration brings to the efficiency of resources utilization. Specifically, we show that for most of the instances in Table 2, one cannot easily obtain feasible multi-ship solutions based on single-ship solutions. That is, the single-ship model presented in the earlier literature cannot be adapted easily to situations with multiple berthing ships.

A simple heuristic that one can use in multi-ship settings is to apply single-ship solutions sequentially. In the two-ship setting of Sect. 4.1, one would solve a single-ship problem and utilize the solution to assign and schedule cranes to the first ship. Then, the level of available resources ($Q_t$ and $YC_t$) would be decreased based on the first ship solution. To demonstrate, in the base case of Sect. 4.1 (case 1 Table 2), the single-ship solution assigns two QCs and three YCs in period 1. The first stage of the single-ship heuristic (SSH) is to use this solution to assign and schedule resources on ship 1, leading to QC and YC assignments on this ship given by $\mathbf{y^I} = (2\ 0\ 0)$ and $\mathbf{z^I} = (3\ 0\ 0)$. Then, in the second stage of SSH, the level of available resources for ship 2 is decreased to $\mathbf{Q'} = (1\ 3\ 3)$ and $\mathbf{YC'} = (0\ 3\ 3)$. SSH solves another single-ship problem with these updated resource levels. It is clear that the solution in this case would be to assign two QCs and three YCs to ship 2 in period 2. That is, to adopt a resource assignment to ship 2, given by $\mathbf{y^{II}} = (0\ 2\ 0)$ and $\mathbf{z^{II}} = (0\ 3\ 0)$. This heuristic solution is of the same quality as the optimal solution in Table 2, as it requires four QCs and six YCs, in total.

With more restrictions on resources for other cases in Table 2, SSH does not always perform as competitively as it did on case 1.

- In case 2 of Table 2, SSH would start by assigning one QC and two YCs to ship 1 in periods 1 and 2, i.e., $\mathbf{y^I} = (1\ 1\ 0)$ and $\mathbf{z^I} = (2\ 2\ 0)$, leaving the following

resources for ship 2, $\mathbf{Q'}=(2\ 2\ 3)$ and $\mathbf{YC'}=(0\ 0\ 2)$. This leads to an infeasible solution in the second stage of SSH, as the number of available YCs, with a capacity of 15 container/YC/period, is not enough to handle the total number of containers (40 in this case).

- In case 3 of Table 2, the first stage of SSH yields an assignment of cranes on ship 1 given by $\mathbf{y^I}=(2\ 0\ 0)$ and $\mathbf{z^I}=(3\ 0\ 0)$ leaving resources for ship 2 given by $\mathbf{Q'}=(1\ 1\ 1)$ and $\mathbf{YC'}=(0\ 3\ 3)$. It is not hard to see that the SSH Stage 2 solution is to assign resources to ship 2 given by $\mathbf{y^{II}}=(0\ 1\ 1)$ and $\mathbf{z^{II}}=(0\ 2\ 2)$. With a total of four QCs and seven YCs utilized, this solution is of the same quality as the optimal solution shown in Table 2.
- In cases 4, 5 and 6, the single-ship solutions are identical, leading to crane assignment to ship 1, in the first stage of SSH, given by $\mathbf{y^I}=(1\ 1\ 0)$ and $\mathbf{z^I}=(2\ 2\ 0)$, and remaining resources for ship 2, in the second stage of SSH, given by $\mathbf{Q'}=(2\ 2\ 3)$ and $\mathbf{YC'}=(1\ 1\ 3)$, respectively. Here, since there is not enough YC capacity in periods 1 and 2, and not more than two YC can be used in period 3 (due to the restriction on the number of YCs assigned to a sub-block, $K_{st}=2$), the second stage SSH solution is infeasible.

To recap, the inability of SSH to produce feasible solutions in cases 2, 4, 5, and 6 demonstrates the value of utilizing our integrated two-ship model. That is, single-ship solutions, like those given by SSH, cannot be always adapted to multi-ship situations.

## 6 Summary and future research

In this paper, the resource (quay and yard cranes) allocation and scheduling, from an operational perspective, during the container transshipment process, is studied. This is motivated by the experience of an operator at Beirut container terminal. The integration between the scheduling of quay and yard sides for multiple berthing ships with transshipment containers is investigated, where the unloading of containers from several vessels berthing at the same time is considered. Our methodology is based on formulating and solving a MIP model.

We validate that the insights drawn for a related single ship model (Kaysi et al. 2012) are also applicable for the multi-ship model, mainly that restricting resources at one side (e.g. quay) leads to more resources at the other side (e.g. yard). We, however, demonstrate via counter examples, that single-ship solutions such as those in Kaysi et al. (2012) cannot be easily adapted to provide feasible solutions for multiple ship situations. This implies that integrated formulations like ours are needed in real-life situations where multiple ships may berth concurrently.

For future research, developing a more efficient solution methodology for our MIP model is recommended. This will help especially in situations involving large vessels. With simple heuristics based on single-ship "decomposition" that are apparently not suited for this purpose, metaheuristics such as genetic algorithms and tabu search may be plausible, as demonstrated in the related literature. Considering the availability of

internal trucks on the transshipment process is also a worthwhile direction for further research. Finally, integrating transshipment with other concurrent activities such as import and export may also worth further investigation especially at busy ports, such as Beirut container terminal. This may require an expanded model with simultaneous loading and unloading of containers on the same vessel.

## Appendix 1. Proof that the problem is NP hard

We show that the problem is NP hard by proving that it reduces to the multi-dimensional knapsack problem in a special case. Then, we discuss the number of integer decision variables needed in the solution. Consider a special case of the problem in Sect. 3 with one ship having one bay, a yard having one sub-block, and no restriction on the number of available cranes and storage capacity. That is, $V=1$, $B_1=1$, $F=1$, $S=1$, $QC_t$, $YC_t$, $K_{st}$, and $C_{fs} \rightarrow \infty$. In this special case, denote the total number of containers by $N$, the number of quay and yard cranes utilized in period $t$ by $y_t$ and $z_t$, and the number of unloaded containers in period $t$ by $x_t$. The model in Sect. 3 simplifies to,

$$\text{Minimize} \quad w \sum_{t=1}^{T} y_t + (1-w) \sum_{t=1}^{T} z_t$$

Subject to

$$\frac{x_t}{C_Q} \leq y_t, \quad \forall t$$

$$\sum_{t=1}^{T} x_t = N$$

$$\frac{x_t}{C_Y} \leq z_t, \quad \forall t$$

$$x_t,\ z_t \text{ integer},\ y_t,\ \text{binary}.$$

Replacing the value of $x_t$ from the second constraint, $x_t = N - \sum_{i \in Y | \{t\}} x_i$, where $Y = \{1, 2, \ldots, T\}$ in the first and third constraints, the problem becomes equivalent to

$$\text{Minimize} \quad w \sum_{i \in Y} y_i + (1-w) \sum_{i \in Y} z_i$$

Subject to

$$C_Q y_t + \sum_{i \in Y | \{t\}} x_i \geq N, \quad \forall t$$

$$\sum_{i \in Y} x_i = N$$

$$C_Y z_t + \sum_{i \in Y | \{t\}} x_i \geq N, \quad \forall t$$

$$x_t,\ z_t \text{ integer},\ y_t,\ \text{binary}.$$

This model is equivalent to a multi-dimensional knapsack problem with decision variables, $x_t$, $y_i$, and $z_i$. Since the knapsack problem is NP hard as discussed by Wolsey (1998), we conclude that our transshipment ILP model is NP hard problem.

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