ASSIGNMENT AND DEPLOYMENT OF QUAY CRANES AT A MARITIME CONTAINER TERMINAL

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ABSTRACT

The complex logistic process of vessel berthing followed by container discharge/loading, at maritime container terminals (MCTs), is focused in this paper. Discrete-event simulation models are well capable of representing the entire process in a stochastic, dynamic environment. Hence, simulation results to be an effective planning and control tool for decision making and evaluation. The assignment of quay cranes to berthed vessels and their deployment along the berth represent crucial decisions that could be well supported by integer programming (IP) models. Usually, these models are used as standalone tools. Starting from a discrete-event simulator for the berth planning, previously developed for a real maritime container terminal, we propose two IP models that can be embodied within the simulator to verify whether or not the weekly plan of the berth schedule produced by the simulator itself is feasible with respect to the available quay cranes. If not, the manager would be asked to repeat the berth planning step by rerunning simulation. The goodness of the proposed IP formulations is established by a numerical comparison against a test case taken from literature.

Keywords: scheduling problem, quay cranes, maritime container terminals, discrete-event simulation,

1. INTRODUCTION

A maritime container terminal is a complex set of physical and human resources organized around a set of logistic processes. In a pure transhipment terminal, logistic processes are defined around the pure “store and forward” function of the terminal. This asks for the respect of high standards in the quality of service provided to shipping companies, otherwise, the terminal could lose some of these companies to competition. Thus the internal organization should be carefully optimized. Vice versa, in a different terminal devoted to an import/export function, possibly connected to a dry port (Roso 2007), the logistic operations and infrastructures for optimally supporting inland/outland transportation by different modal choices should also be carefully considered (Parola and Schomachen 2005) to improve the reasons of competitiveness.

Here we focus on a real terminal of pure transhipment: the container terminal in Gioia Tauro, Italy, which is situated along the major maritime routes from the far-east port sources in Asia to the ports of Northern Europe and other western destinations. Our preliminary consideration when addressing the modelling efforts referred to this system, is that the major operational activities and resources should be managed by considering that they belong to multiple, interacting logistic processes (e.g. vessel arrival and vessel discharge/loading processes) where some limited resources should be adequately shared. This fact is critical for a cost-effective management of the system and the choice of the modelling approach for performance evaluation and system optimization. Terminal competitiveness can be improved by optimizing the internal organization through the introduction of decision support systems in resource allocation and scheduling of logistic resources and operations (Vis and de Koster 2003, Steenken et al. 2004), with the objective of decreasing the operating costs and service times.

Several papers focus on IP models for specific processes in port logistics (Park and Kim 2003, Ambrosino et al. 2004, Legato and Monaco 2004, Cordeau et al. 2005). Besides, other papers based on simulation, such as (Yun and Choi 1999, Legato and Mazza 2001, Bielli et al. 2006, Canonaco et al. 2008) point out the opportunity of evaluating starvation and congestion phenomena occurring at those major resources on which both the terminal productivity and response time strongly depend.

Recently, a simulator (Canonaco et al. 2007) has been developed and tuned for the container terminal located at the port of Gioia Tauro. The tool was mainly requested to perform a scenario analysis meant to highlight the possibility that the entrance channel to the port could become the terminal bottleneck, as the channel itself became progressively more shared by different flows of maritime traffic entering the port of Gioia Tauro. Currently, the same tool is being refined to support the formulation of the so called weekly plan under the programmed flow of containership arrivals, provided that the statistical analysis of delays upon arrivals is continuously updated taking into account all the sources of uncertainty of the arrival process. In this context, the estimation of the vessel processing time (at berth) for discharge/loading operations is recognized as the second key point upon which the effectiveness of the whole planning process depends. The current release of the simulator asks the user to provide the so called "crane intensity", i.e. the average number of cranes that work, simultaneously, on the same vessel, as it is fixed by formal agreement with the shipping company to which the same vessel belongs. Hence, a decisional problem arises for the cranes manager because he should dynamically deploy the right number of rail mounted quay cranes along the berth and assign these cranes to the vessels that succeed at the various berthing points, day by day, according to the weekly plan. The major constraints consist in respecting the vessels' due-time of departure and shifting the cranes (on rail) along the quay-side. The objective to pursue is that of employing the minimum number of quay cranes, while maximizing crane productivity.

In the language of Operations Research the above decisional problem may be referred as *the quay crane deployment problem* (QCDP) (Legato et al. 2008). It is a complex assignment-scheduling problem that we tackle by two separated IP-based formulations. The first is focused on the assignment phase and produces the optimal number of cranes that must be assigned to each berthed vessel on the basis of a one-hour time-slot, under the guarantee that due-times of departure are respected. In the second IP formulation, the cumulative number of cranes returned by the first model is deployed over all the vessels previously berthed, each in their own position, in order to establish which cranes should service any given vessel on berth and minimize the number of crane shifts between adjacent vessels.

The paper is organized as follows. In the next section some necessary details on the logistic processes of interest are given. Afterwards, the focus is on the QCDP and on the mathematical models applied within the two-phase approach. Finally, some computational results are presented.

2. LOGISTICS AND DECISION PROBLEMS

The container terminal at the port of Gioia Tauro is a logistic platform of pure transshipment characterized by a relatively large roadstead where incoming containerships have to stop and wait for a pilot boat, before they are allowed to seize the entrance channel for some minutes (10 to 15) and reach their assigned berth position. Berthing positions are all sequenced on the unique available quay, which amounts to 3,300 meters and bears different levels of water depth. A significant number of rail-mounted gantry cranes (RMGCs) are available along the quay, to allow for a significant degree of parallelism under a high discharge/loading rate of service offered to berthed vessels. A fleet of several dozens of straddle carriers (SCs) are available to transfer containers between the berth and the yard and pick-up/deliver containers from/to selected storage positions reached within a very regular layout based on "blocks". Each yard block is divided into approximately 16 lines of 32 slots organized on 3 tiers, therefore the average block capacity is about 1500 TEUs.

Containership entrance at the terminal is planned on the basis of its expected time of arrival (ETA), but it depends on the following requirements: *i) formal conditions* (e.g., contractual agreements between the vessel's shipping line and the port of call for the use of port facilities), that ask for a priority policy when managing the port entrance queue; *ii) operational settings* (i.e., pilot/tug availability, berth space assignment). If requirements are met, the vessel is maneuvered into its berth slot by one or two pilot tugs; otherwise it must wait in the roadstead. This is the arrival of the so-called vessel process. Vessels are of two types: mother vessels and feeders. The first one is a large container ship (whose capacity ranges between 3,000 and 14,000 TEUs) that covers transoceanic routes (hub-to-hub connections). Feeders are smaller ships that cover short and middle routes. They are widely used to connect the spokes to the transshipment hub (and vice versa).

Once a vessel is berthed, operations for container discharge/loading can be initiated only if mechanical (and human) resources are allocated; if not, the ship waits in its berth position until resource assignment takes place. Discharge/loading operations are performed by RMGCs placed along the berth: one or multiple cranes move containers between the ship and the quay area. The maximum number of quay cranes that may be assigned to each vessel is restricted by *i)* the total number of cranes in the quay and *ii)* the maximum number of cranes allowed for each vessel, due to physical (i.e. the length of the vessel) and logical constraints (i.e. interference between cranes). Considering the span of the cranes (approximately 30 m) and the horizontal space necessary to stack and transfer the incoming/outgoing containers of a vessel, the maximum number of cranes allowed for the longest vessel is usually 5 (this number is proportionally decreased for shorter vessels). When multiple cranes are assigned to the same ship, crane interference has to be avoided and a complex scheduling problem is required to manage the relationships (precedence and mutual exclusion) existing among the holds of the same vessel. Considering that the service rate of an RMGC is *28 TEUs/hour*, the performance of the discharge/loading process highly depends on the availability of this type of crane and the related turnover speed. Therefore, the best deployment of these resources affects the overall completion time of each vessel.

2.1. The Quay Crane Deployment Problem

An IP formulation of the *quay crane deployment problem* together the *berth allocation problem* (BAP) has been successfully discussed by Park and Kim (op cit). In real life, the QCDP arises as follows.

The planning office of the terminal operating company constructs a weekly "berth schedule", which contains the berthing position and time window for each incoming vessel (this being the solution to the so-called *berth scheduling problem*). A time window shows the expected time of berthing and un-berthing for a single vessel; time windows are constructed using the ETA (Expected Time of Arrival) and PTD (Promised Time of Departure) of each vessel (a penalty cost must be sustained if the departure of a vessel occurs later than its previously committed PTD). Figure 1 shows an example of a berth schedule, where the berth time and space are partitioned into 22 x 24 grid squares (24 one-hour time-slots).

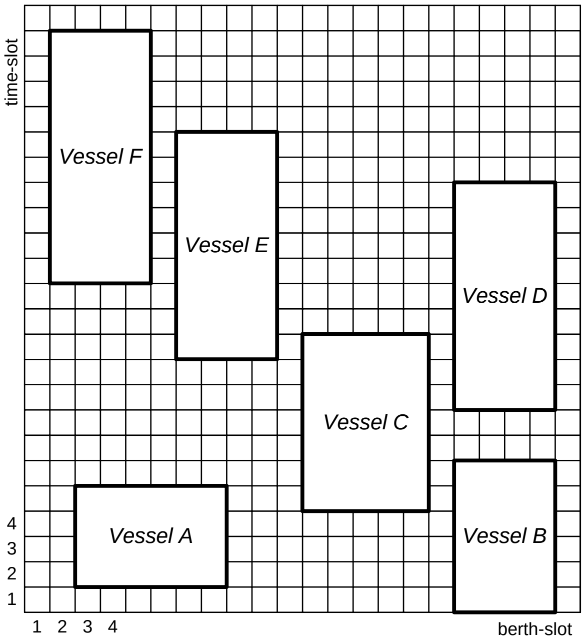

Figure 1: An Example of Berth Schedule Presented by Park and Kim

The berth schedule is used to assign the RMG quay cranes to the incoming vessels on a daily basis. The double goal is to *i)* minimize the number of quay cranes to be employed and *ii)* maximize their utilization, under the constraint of completing the discharge/loading operations, for each vessel, within the related expected time of un-berthing,

The QCDP is solved under the following assumptions.

1. Each vessel has a time window; the lower bound of the time window is the vessel's expected time of berthing, while the upper bound is the vessel's expected time of un-berthing.
2. Each vessel has a total number of TEUs to be handled within its time window: this number is related to the container discharge/loading moves required by the vessel.
3. Each vessel has a maximum and minimum number of cranes that can and must be assigned when operations starts. The maximum number of cranes that can be simultaneously assigned to a vessel is limited by vessel length. Vice versa, the minimum number of cranes to be assigned (usually for mother vessels) depends on the contract terms between the terminal operating company and the vessel's shipping company. By default, when operations start on a vessel, mostly all of the time-slots related to that vessel receive one crane.
4. Quay cranes are RMGCs, so non-crossing constraints must be guaranteed. Furthermore, cranes are never unavailable.

The solution approach we propose here to the QCDP follows a previous promising research study by Legato, Gullì and Trunfio (2008). It is decomposed into two phases, as shown in Figure 2.

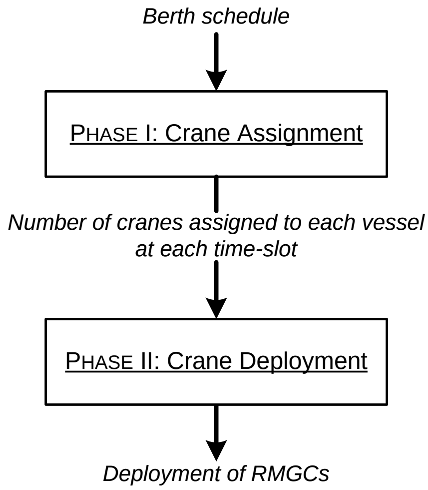

Figure 2: The Schema of the Two-Phase Approach to the QCDP

In the first phase (*crane assignment phase*), we solve an IP mathematical model using CPLEX (ILOG 1999) to identify the optimal number of cranes that must be assigned to each vessel at each time-slot. Thus, the model is able to identify exactly when the discharge/loading operations start and end within the vessel's time-window. In literature, this problem is known as the *quay crane assignment problem* (QCAP) and it is usually studied together with the BAP as in (Meisel and Bierwirth 2006).

In the second phase, another IP model is used to deploy the cranes along the quay, with the aim of matching the previously identified vessel-crane assignment in order to *i)* respect the non-crossing constraints, and *ii)* minimize the number of crane shifts from one vessel to another.

With respect to the two phases, the first IP model is the well-known QCAP, while the second is called the *quay crane deployment problem*; neverthless, one could give a mathematical model which combines both of the previous IP models and still refers to a QCDP.

2.2. IP Model for the Crane Assignment Phase

The following notations will be used for the formulation of the QCAP:

T	:	the set of time-slots, with $\lvert T\rvert = N$
Ω	:	the set of vessels
C	:	the set of quay cranes, with $\lvert C\rvert = M$
s_c	:	the service rate for crane *c*, expressed in TEUs per time-slot
m_i	:	the number of moves for vessel *i*
etb_i	:	the berthing time for vessel *i*, i.e. the time-slot starting from which vessel *i* is ready for the first lift, where: $1 \le etb_i \le N - etu_i + 1$
etu_i	:	the un-berthing time of vessel *i*; thus it is the last time-slot during which vessel *i* is available for operations, where: $etb_i \le etu_i \le N$
min_i	:	the minimum number of cranes that must be assigned to vessel *i* when operation starts
max_i	:	the maximum number of cranes that can be assigned to vessel *i*.

We introduce the following decisional variables:

V	:	the maximum number of cranes used to performs vessel operations
θ_{it}^{c}	:	1, if crane *c* works on vessel *i* at time-slot *t*, 0 otherwise
ϕ_{it}	:	1, if vessel *i* is processed at time-slot *t*, 0 otherwise
γ_{it}	:	1, if operations for vessel *i* start at time-slot *t*, 0 otherwise.
η_{it}	:	1, if operations for vessel *i* have not been completed at time-slot *t*, 0 otherwise
ρ_{it}	:	is the difference between the number of cranes assigned at time-slot *t* and those assigned at the previous time-slot (*t-1*).

The QCAP can be formulated as follows:

$$min \quad N \cdot V + \sum_{i\in\Omega}\sum_{t=etb_i}^{etu_i}\phi_{it} + \sum_{i\in\Omega}\sum_{t=etb_i+1}^{etu_i}\lvert\rho_{it}\rvert \qquad (1)$$

s.to

$$\gamma_{it} \le \gamma_{i(t+1)} \qquad \forall i\in\Omega, t=etb_i,\ldots,etu_i \qquad (2)$$

$$\eta_{it} \ge \eta_{i(t+1)} \qquad \forall i\in\Omega, t=etb_i,\ldots,etu_i \qquad (3)$$

$$\gamma_{it} + \eta_{it} = \phi_{it} + 1 \qquad \forall i\in\Omega, t=etb_i,\ldots,etu_i \qquad (4)$$

$$\sum_{c\in C}\sum_{t=etb_i}^{etu_i-1} s_c\theta_{it}^{c} = m_i \qquad \forall i\in\Omega \qquad (5)$$

$$\sum_{c\in C}\sum_{t=1}^{etb_i-1}\theta_{it}^{c} = 0 \qquad \forall i\in\Omega \qquad (6)$$

$$\sum_{c\in C}\sum_{t=etu_i+1}^{n}\theta_{it}^{c} = 0 \qquad \forall i\in\Omega \qquad (7)$$

$$\sum_{i\in\Omega}\theta_{it}^{c} \le 1 \qquad \forall c\in C, t\in T \qquad (8)$$

$$\sum_{c\in C}\theta_{it}^{c} \le \max_i \phi_{it} \qquad \forall i\in\Omega, t=etb_i,\ldots,etu_i \qquad (9)$$

$$\sum_{c\in C}\theta_{it}^{c} \ge \min_i \phi_{it} \qquad \forall i\in\Omega, t=etb_i,\ldots,etu_i \qquad (10)$$

$$\sum_{c\in C}\theta_{it}^{c} - \sum_{c\in C}\theta_{i(t-1)}^{c} = \rho_{it} \qquad \forall i\in\Omega, t=etb_i+1,\ldots,etu \qquad (11)$$

$$\sum_{c\in C}\sum_{i\in\Omega}\theta_{it}^{c} \le V \qquad \forall t\in T \qquad (12)$$

$$V \ge 0, \in \mathrm{N} \qquad (13)$$

$$\rho_{it} \in \mathrm{N} \qquad \forall i\in\Omega, t\in T \qquad (14)$$

$$\theta_{it}^{c} \in \{0,1\} \qquad \forall i\in\Omega, t\in T, c\in C \qquad (15)$$

$$\phi_{it}, \gamma_{it}, \eta_{it} \in \{0,1\} \qquad \forall i\in\Omega, t\in T \qquad (16)$$

The objective function of the previous mathematical model aims to the minimization of *i)* the number of quay cranes employed in the planning horizon, *ii)* the overall number of time-slots required to perform vessel discharge/loading operations, and *iii)* the crane back and forth movements (implicitly accounted for by the $\lvert\rho\rvert$ factor, to be linearized as usual). Clearly, function (1) appears as the sum of inhomogeneous terms and must be suitably adjusted for numerical experiments.

Constraints (2)-(4) ensure that for every vessel, once discharge/loading operations start, the operations must be performed without interruption until they are completed (the vessel operations cannot be preempted). Constraints (5) specify that for each vessel, the discharge/loading operations must be executed and completed within the vessel time-window. Constraints (6) and (7) ensure that no cranes can be assigned to a vessel before its *etb* and after its *etu*. Constraints (8) guarantee that every crane can be assigned to only one vessel at each time-slot. Constraints (9) and (10) ensure that the number of cranes assigned to a vessel during its operations time is between a *minimum* (i.e., due to contractual agreement) and a *maximum* (i.e., due to the vessel length). Constraints (11) evaluate the value of variables ρ_{it}. Constraints (12) guarantee that, for each time-slot *t*, the number of assigned cranes result not greater than the number of available cranes. Constraints (13)-(16) are the basic constraints on the decision variables.

The IP model defined above is a refinement of the QCAP developed by Legato, Gullì and Trunfio (op cit).

2.3. IP Model for the Crane Deployment Phase

As stated before, the solution of the QCAP provides the number of cranes that must be assigned in order to complete the operations in time. This data is used in the following to deploy, for each time-slot, the RMG quay cranes. The deployment follows the criteria of non-crossing cranes and crane shifting reduction between vessels during different time-slots.

In the following we introduce the notations that will be used for the formulation of the quay crane deployment problem (QCDP):

T	:	the set of time-slots, with |T| = N
Ω	:	the set of vessels
C	:	the set of quay cranes, with |C| = M
ac_t	:	the number of cranes assigned to the vessels berthed at time-slot *t*
ac_{it}	:	the number of cranes assigned to vessel *i* at time-slot *t*
cb_{it}	:	the number of cranes assigned to the vessels berthed at time-slot *t* before (from the left-side of the berth) vessel *i*
ca_{it}	:	the number of cranes assigned to the vessels berthed at time-slot *t* after (from the left-side of the berth) vessel *i*
w_i	:	the time-window of vessel *i*; this time-window is computed from the first time-slot in which discharge/loading operations start to the time-slot in which operations end.

Moreover, the following decisional variables are introduced:

ϕ_{it}^c	:	1, if crane *c* is assigned to vessel *i* at time-slot *t*, 0 otherwise
γ_{it}^c	:	1, if crane *c* is after (or is itself) the left-most crane assigned to vessel *i* at time-slot *t*
η_{it}^c	:	1, if crane *c* is before (or is itself) the right-most crane assigned to vessel *i* at time-slot *t*
f_{it}	:	is the left-most crane assigned to vessel *i* at time-slot *t*
l_{it}	:	is the right-most crane assigned to vessel *i* at time-slot *t*
sf_i	:	it is the sum over time of all the left-most crane indexes of vessel *i*
sl_i	:	it is the sum over time of all the right-most crane indexes of vessel *i*.

The QCDP can be formulated as follows:

$$min \quad \sum_{t\in T}\sum_{i\in\Omega}\left(M - ac_t\right)\cdot\left(\left|\frac{sf_i}{w_i} - f_{it}\right| + \left|\frac{sl_i}{w_i} - l_{it}\right|\right) \quad (17)$$

s.to

$$\sum_{c\in C}\phi_{it}^c = ac_{it} \qquad \forall i\in\Omega, t\in T \quad (18)$$

$$\gamma_{it}^c \le \gamma_{it}^{c+1} \qquad \forall i\in\Omega, t\in T, \; c = 1,\dots,M-1 \quad (19)$$

$$\eta_{it}^c \ge \eta_{it}^{c+1} \qquad \forall i\in\Omega, t\in T, \; c = 1,\dots,M-1 \quad (20)$$

$$\gamma_{it}^c + \eta_{it}^c = \phi_{it}^c + 1 \qquad \forall i\in\Omega, t\in T, \; c\in C \quad (21)$$

$$\sum_{c\in C}\gamma_{it}^c \le M - cb_{it} \qquad \forall i\in\Omega, t\in T \quad (22)$$

$$\sum_{c\in C}\eta_{it}^c \le M - ca_{it} \qquad \forall i\in\Omega, t\in T \quad (23)$$

$$\sum_{c\in C}\gamma_{it}^c + f_{it} = M + 1 \qquad \forall i\in\Omega, t\in T \quad (24)$$

$$\sum_{c\in C}\eta_{it}^c - l_{it} = 0 \qquad \forall i\in\Omega, t\in T \quad (25)$$

$$\sum_{t\in T} f_{it} - sf_i = \left(M + 1\right)\cdot w_i \qquad \forall i\in\Omega \quad (26)$$

$$\sum_{t\in T} l_{it} - sl_i = 0 \qquad \forall i\in\Omega \quad (27)$$

$$\phi_{it}^c, \gamma_{it}^c, \eta_{it}^c \in \{0,1\} \qquad \forall i\in\Omega, t\in T, \; c\in C \quad (28)$$

$$f_{it}, l_{it}, sf_j, sl_j \ge 0, \in \mathrm{N} \qquad \forall i\in\Omega, t\in T \quad (29)$$

In this IP mathematical model, we aim to identify the RMG quay cranes that must process the berthed vessels at each time-slot, with the goal of minimizing the number of cranes shifting from one vessel to another (i.e., if possible, the model tries to assign to each vessel always the same quay cranes,).

Constraints (18) specify that exactly the desired number of quay cranes is assigned to every vessel at each time-slot. Constraints (19)-(21) ensure that RMG quay cranes are assigned with respect to non-crossing constraints.

Constraints (22) force the assignment of quay cranes to vessel *i* at time-slot *t*, once the preceding vessels along the berth have received the expected amount of quay cranes. Likewise, constraints (23) ensure that crane assignment to vessel *i* at time-slot *t* is done coherently with the assignment of the considered cranes to the vessels that follows along the berth.

Constraints (24) identify the first crane from the left-side of the quay (i.e., the *left-most crane*) that must perform discharge/loading operations on vessel *i* at time-slot *t*; otherwise, constraints (25) assign the last crane from the left-side of the quay (i.e., the *right-most crane*) that must perform discharge/loading operations on the same vessel and at the same time-slot. Likewise, constraints (26) and (27) extend constraints (24) and (25), respectively, over all the time-slots that constitute the vessel time-window.

Constraints (28)-(29) are the basic constraints on the decision variables.

3. NUMERICAL EXPERIMENTS

Numerical results obtained by the exact solution of the two IP formulations proposed in previous section are compared against the results reported by Park and Kim (2003).

In Figure 3 we repeat the optimal assignment reported in the paper by Park and Kim based on the berth schedule previously shown in Figure 1. For each vessel, ringed numbers depict the quay cranes assigned to each vessel. As it is possible to see, the QCDP solved by Park and Kim makes use of 9 cranes to complete all the operations in time.

In this case study, the minimum number of cranes that must be assigned to the vessels during operations is one, while the maximum number of cranes that can be assigned to a specific vessel is equal to the number of occupied berth-slots (each corresponding to 50 meters).

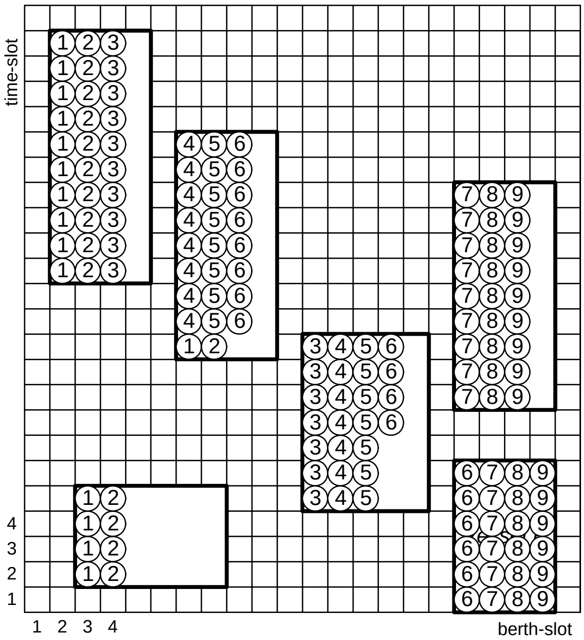

Figure 3: The Optimal Deployment Found by the Park and Kim Methodology

The first step of our approach produces the assignment depicted in Figure 4. In this berth schedule, the optimal value of ac_{it}, for each couple of vessel *i* and time-slot *t,* is reported within each corresponding rectangle.

As it is easy to recognize, our mathematical model fills-in a berth schedule while minimizing the overall number of cranes that must be used to process all of the vessels. In fact, the first phase of our approach produced an assignment of 7 quay cranes against the 9 quay cranes found by Park and Kim. Moreover, in our solution, once operations start, no operation discontinuity can occur for any vessel: this is a primary contractual agreement requested to the terminal operating company by shipping companies, along with the minimum number of cranes to be assigned and the respect of the bounds on operation completion time.

As a result of the second phase of our methodology, we propose the quay crane deployment shown in figure 5.

The improvement obtained with the approach proposed in this paper is not only due to the minimization of the activated cranes. In fact, in three cases *i)* we obtained a reduction of the vessel overall completion time and *ii)* we improved the average crane utilization (*0.69 vs. 0.87*).

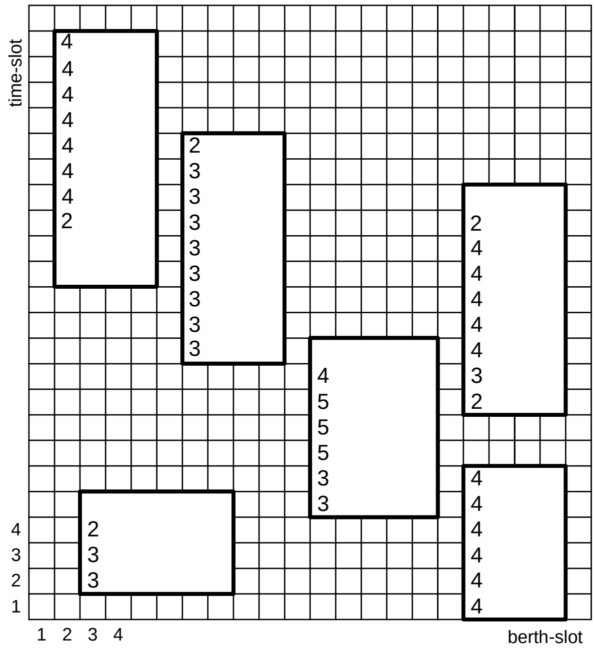

Figure 4: The First Phase Output of our Methodology

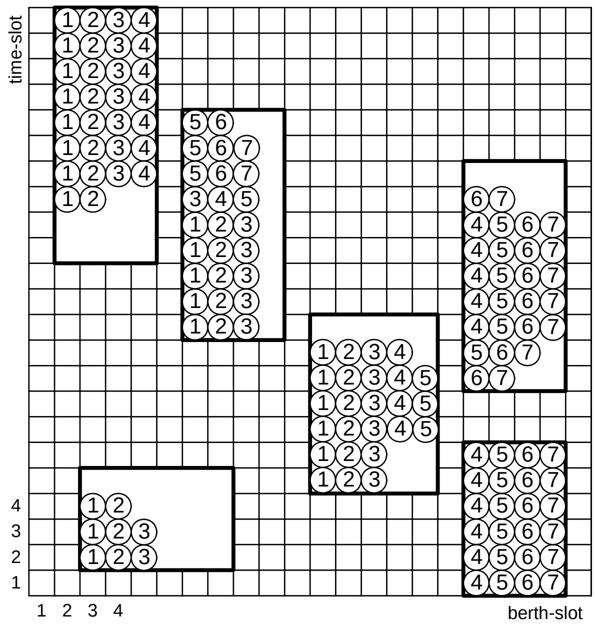

Figure 5: The Final Output by our Methodology

4. CONCLUSION

We have reported on the possibility of improving the benefit of using a simulator when managing the logistic process of vessel berthing and discharge/loading at a maritime container terminal. Combining discrete-event simulation with integer programming models results in a very powerful tool, where the solution of assignment and scheduling problems plays a crucial role. We have proposed a practical solution to the problem of guaranteeing the respect of the planned time windows (berthing–unberthing) but also pursuing the objective of minimizing quay crane idle time. The novelty is that we avoid handling a unique, unmanageable formulation and, furthermore, that for practical applications in real life, we may use a berth schedule produced by a simulator, i.e. in a more realistic modelling environment where operation delays and unpredictable events may occur. Thus we may integrate the IP models with their respective solution algorithms in a new release of the available discrete-event simulator to support run-time crane assignment using a berth schedule. A metaheuristics based approach will be clearly pursued to develop solution algorithms for real instances; this will also enable simulation based optimization features within the above discrete-event simulator.

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