An integrated model for berth and yard planning in container terminals with multi-continuous berth layout

H.L. Ma

Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

Email: helen.hl.ma@polyu.edu.hk

S.H. Chung

Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

Email: mfnick@polyu.edu.hk

H.K. Chan

Nottingham University Business School China, University of Nottingham Ningbo China, China

Email: Hingkai.Chan@nottingham.edu.cn

L. Cui

Business School, Dalian University of Technology

Email: cuili@dlut.edu.cn

1. INTRODUCTION

Quay discontinuities or sharp curves, as shown in Fig. 1, naturally exist in many container terminals in reality, for examples, the Medcenter Container Terminal and the BLG Italia terminal located at the Port of Gioia Tauro (Cordeau et al. 2005; 2007; 2011), the Brani Terminal at the Port of Singapore (Lee et al. 2012), the Port of Izmir Alsancak Container Terminal (Esmer et al. 2013), etc. To deal with quay discontinuities, in general, there are 2 types of approaches known as, i) discrete approach, and ii) hybrid approach (Cordeau et al 2005; Moorthy and Teo 2006; Cheong et al. 2010; Turkogullari et al. 2014; Fu and Diabat 2015). In discrete approach, only one vessel can be assigned to one berth at a time, while in the hybrid approach, a berth is divided into a number of small segments. Accordingly, a vessel can be assigned to a number of consecutive segments to maximize the berth space utilization (Bierwirth and Meisel 2010). The discrete model takes an advantage of ease of scheduling, but leads to lower berth utilization, while the hybrid model can achieve a better space utilization. However, determining the length of the segment is critical because a short segment increased computational complexity, while a long one reduces utilization.

In recent years, continuous berth layout modeling approach is more prevalent. This approach allows vessels to berth on any arbitrary position within the quay. As a result, it enhances quay space utilization and increases berth allocation flexibility. It is especially beneficial to those busy transshipment hubs, which usually involve many transshipment activities, meanwhile it has inbound/outbound activities (Imai et al. 2005; Rashidi and Tsang 2013). Optimizations of transshipment activities have attracted much attention in the last few years (Zhen et al 2011, Lee et al. 2012, Lee et al, 2013, Tao and Lee 2015, Zhen et al. 2016). In the literature, although there are many papers applying continuous berth layout approach (Ganji et al. 2010; Lee et al. 2010; Park and Kim 2002), they only consider one long quay without discontinuities. Thus, to fill this research gap, we propose a multi-continuous berth modeling approach as shown in Fig. 1.

In this paper, we studied a new integrated Berth Allocation Problems (BAP), Quay Crane Assignment (QCA), and Yard Storage Allocation (YSA) model with the existing of quay discontinuity. We proposed a virtual partition modeling approach to develop a new Mixed Integer Linear Programming (MILP) model and a new Guided Neighborhood Search (GNS) heuristic to increase the computational efficiency. Our objective is to minimize the total servicing cost induced by the deviation of vessels from the expected turnaround time intervals, and the total operating cost induced by the transshipment of the containers between the quay side and the yard storage sub-block. The rest of the paper is structured in the following sections. Section 2 gives a review on the relevant literature. Section 3 presents the problem formulations, and describes the framework and the mechanism of the proposed GNS. Numerical experiments and results are presented in Section 4. Section 5 concludes the paper.

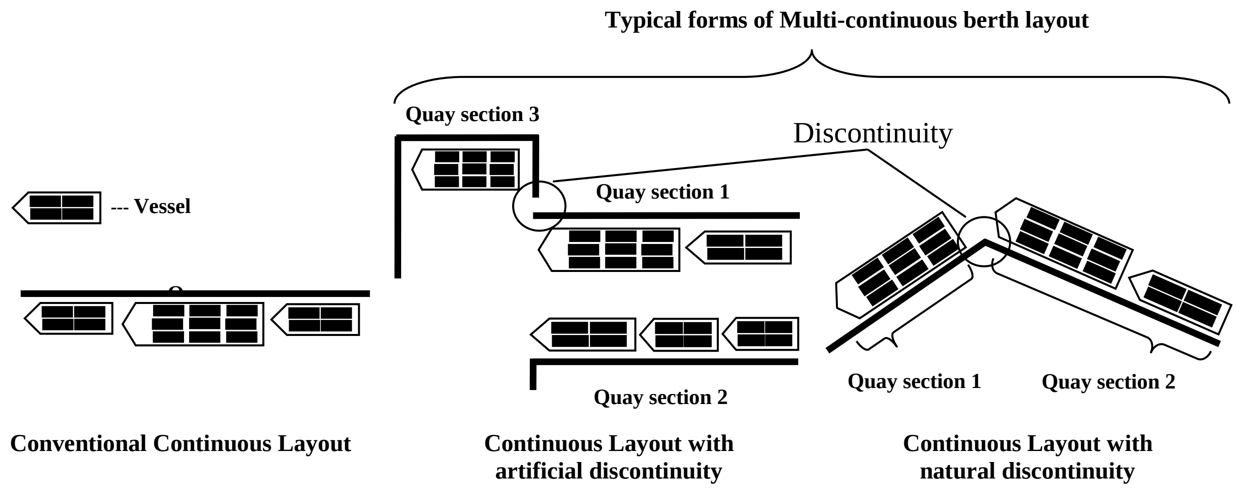


Fig. 1 Multi-continuous berth layout

2. LITERATURE REVIEW

BAP decides where and when vessels are to be moored (Ursavas 2015). Generally, the decisions will be made at two levels, known as operational level and tactical level. The Operational Berth Allocation Problem (OBAP) is exercised in a short planning horizon covering a few days by taking real time operational constraints into consideration, while the Tactical Berth Allocation Problem (TBAP) is exercised in a relatively longer planning horizon covering may be a month to support decisions made by terminal managers in their negotiations with shipping lines. It also serves as a reference for OBAP (Cordeau et al. 2005).

In the past, OBAP were considered as the main focus in the literature. Various modeling approaches can be found such as discrete berth layout modeling approach (Cordeau et al. 2005; Golias et al. 2014), hybrid berth layout modeling approach (Cordeau et al. 2005; Turkogullari et al. 2014), and continuous berth layout modeling approach (Cheong et al. 2010; Wang and Lim 2007; Lee and Chen 2009; Meisel and Bierwirth 2009; Yang et al. 2012). A comprehensive review can be referred to (Bierwirth and Meisel, 2010). Among different modeling approaches, the continuous modeling approach is more prevalent as it enhances the berth space utilization (Giallombardo et al. 2010). However, it cannot handle quay with discontinuities.

To deal with quay discontinuities, many papers applied hybrid berth layout. For example, Cordeau et al. (2005) studied the Gioia Tauro terminal, where discontinuities exist in the middle of the quay. They divided the quay into a number of segments, and large vessels were allowed to occupy two or more consecutive segments at a time. They proposed two formulations to model the problem in the discrete scenario, and developed a heuristic algorithm for the hybrid scenario. Cheong et al. (2010) also studied a similar layout. They divided the entire quay into a number of discrete segments. However, among each segment, they applied continuous modeling rather than discrete to maximize the berth space utilization. They optimized the allocation of vessels into each segment and determined the corresponding servicing priority and berthing location. They mentioned this layout is closer to real-world settings, and proposed a meta-heuristic approach named multi-objective evolutionary algorithm. Our paper applies the similar concept, which is dividing the quay into segments and then treats each segment by continuous modeling approach. However, instead of apply meta-heuristic, we proposed MILP. In addition, we considered QCA and YSA because they are also significantly affecting the performance of a terminal especially in transshipment hub terminals (Guan et al. 2013, Ramírez-Nafarrate et al. 2016, Zhen et al. 2016).

In recent years, TBAP has attracted much more attention (Moorthy and Teo 2006; Cordeau et al. 2007, Giallombardo et al. 2010; Zhen et al. 2011). TBAP usually combines various resources planning including BA, QCA and YSA into a single large scale optimization problem. TBAP is crucial to terminal managers because it helps them evaluate the overall capacity in receiving new orders from shipping companies. In this stream, Moorthy and Teo (2006) firstly introduced the concept of the berth and yard templates in transshipment hubs. They also addressed the problem of quay discontinuities and applied hybrid berth layout modeling approach by dividing the quay into a number of linear sections which were further subdivided into berths. They developed a sequence pair approach to pack the vessels in berths with a fixed handling time, and proposed a standard annealing scheme to search the space of all sequence pairs, aiming to minimize to the total expected delays and connectivity cost between the berthing positions.

Cordeau et al. (2005) studied the tactical service allocation problem in a terminal located at the Port of Gioia Tauro utilizing a housekeeping strategy, which dedicated specific positions of the yard and the quay to a shipping company. The problem was formulated in a generalized quadratic assignment model, aiming to minimize the re-handling operations of containers inside the yard, and an evolutionary heuristics was developed. As an extended work of Cordeau et al. (2005), Cordeau et al. (2007) further created an additional constraint to avoid service requiring two berth spaces being allocated to a pair of berths showing discontinuity. Giallombardo et al. (2010) later on extended the work of Cordeau et al. (2007) to further consider the usage of QCs. They modeled the quay by using discrete berth layout instead of hybrid, and introduced the concept of QC-profile. For each vessel, a set of feasible QC-profile is generated, and each QC-profile consists of a number of working shifts occupied by a vessel and a number of QCs assigned to the vessel on each shift. They aimed to maximize the total value of the selected QC-profiles and minimize the housekeeping costs generated by transshipment flows between vessels simultaneously. A heuristics, combining a tabu serach and mathematical programming techniques, was proposed to solve the problem.

Zhen et al. (2011) undertook a comprehensive study, which covered both the berth and yard template to decide where and when the vessel was to be moored, how many QCs and which sub-blocks should be assigned to the vessel at a tactical level in a transshipment hub. To solve the integrated tactical berth and yard template planning, they formulated a MILP for the BAP and QCA (hereafter named as $\mathcal{M}\_\mathcal{B}_{\mathrm{n}}$), and a MILP for the YSA (hereafter named as $\mathcal{M}\_\mathcal{Y}$). They also proposed a local refinement approach (hereafter named as $\mathcal{M}\_\mathcal{BY}_{\varphi\delta}$) to refine solution by an iterative process. Comparing to Cordeau et al. (2007) and Giallombardo et al. (2010), Turkogullari et al. (2014) further considered travelling time in the TBAP. They modeled the transportation of containers to and from their storage sub-block (location) in the yard, and determined the best sub-block for storage by a heuristics approach. They considered the terminal as the conventional continuous berth layout and also took into account the periodic nature of the schedule and container types, while the total QC capacity devoted to each vessel was given. Apart from these, there are some more papers, for examples, Lee et al. (2012) considered multi-terminal operations, Robenek et al. (2014) studied bulk ports, and Lee and Jin (2013) focused on proactive management strategy by designing the schedule of feeders from the perspective of container terminals. However, there is a lack of paper studying on continuous modeling approach for quay with discontinuities. Therefore, we propose a virtual partition modeling approach to fulfill the research gap.

3. METHODOLOGY

The optimization methodology is developed based on the work done by Zhen et al. (2011) studying integrated BAP, QCA, and YSA model but without quay discontinuities. Our main contribution to the literature is to propose a virtual partition modeling approach in berth allocation and a new GNS heuristics to change the priority list of the vessels for large-scale problems. The methodology is outline as in Fig. 2. First of all, in Step 1, vessels will be prioritized either according to their importance weighting or their slack time as commonly used in literature. Next, a segment of vessels in the list will be selected at a time to determine the optimal BAP and QCA regardless of the YSA at the moment. In our model, as traditional MILP formulation will lead to infeasible solution as shown in Fig. 3. In order to handle the problem of quay discontinuity, we will introduce a virtual partition modeling approach as shown in Appendix 1. The idea of virtual partitions is to divide the quay into a set of quay sections C where no discontinuity or curve exists in each section $c \in C$. Then it will be used to develop the constraints to divide a continuous quay in the traditional MILP formulation into a number of continuous berths as detail in Appendix 1. Then, based on the result obtained in Step 2, YSA can then be optimized. After that, local refinement will be carried out until no better solution can be obtained by solving the integrated BAP, QCA, and YSA (details in Section 3.1). Then it will move to the next segment in the vessel list and restart the processes until all the vessels are optimized. Lastly, the whole vessel sequence list will be changed and the process will start over again by using the proposed GNS heuristics (details in Section 3.2). The detail formulation of Steps 2 and 3 are shown as in Appendix 1.

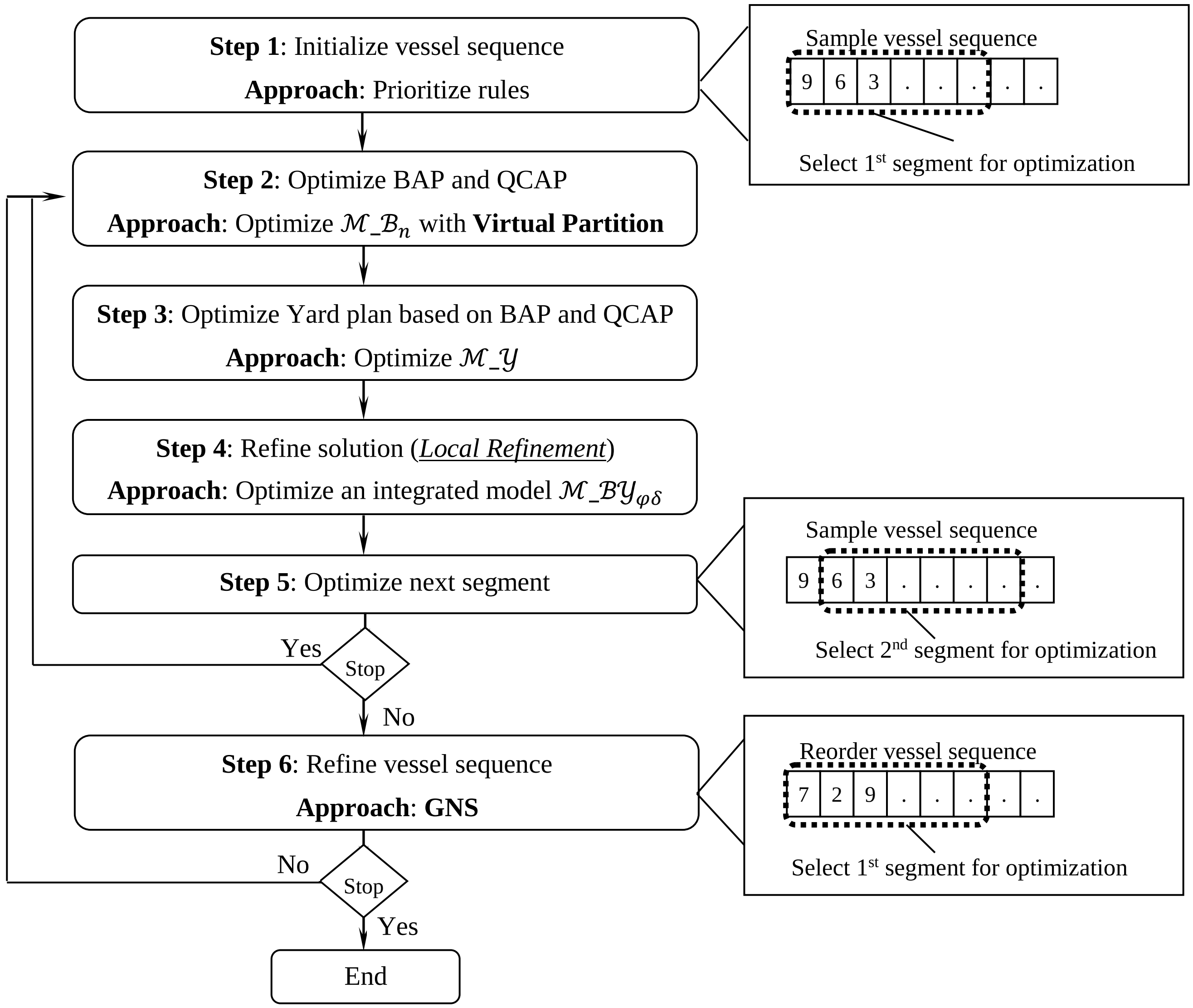


Fig. 2 Outline of the proposed methodology

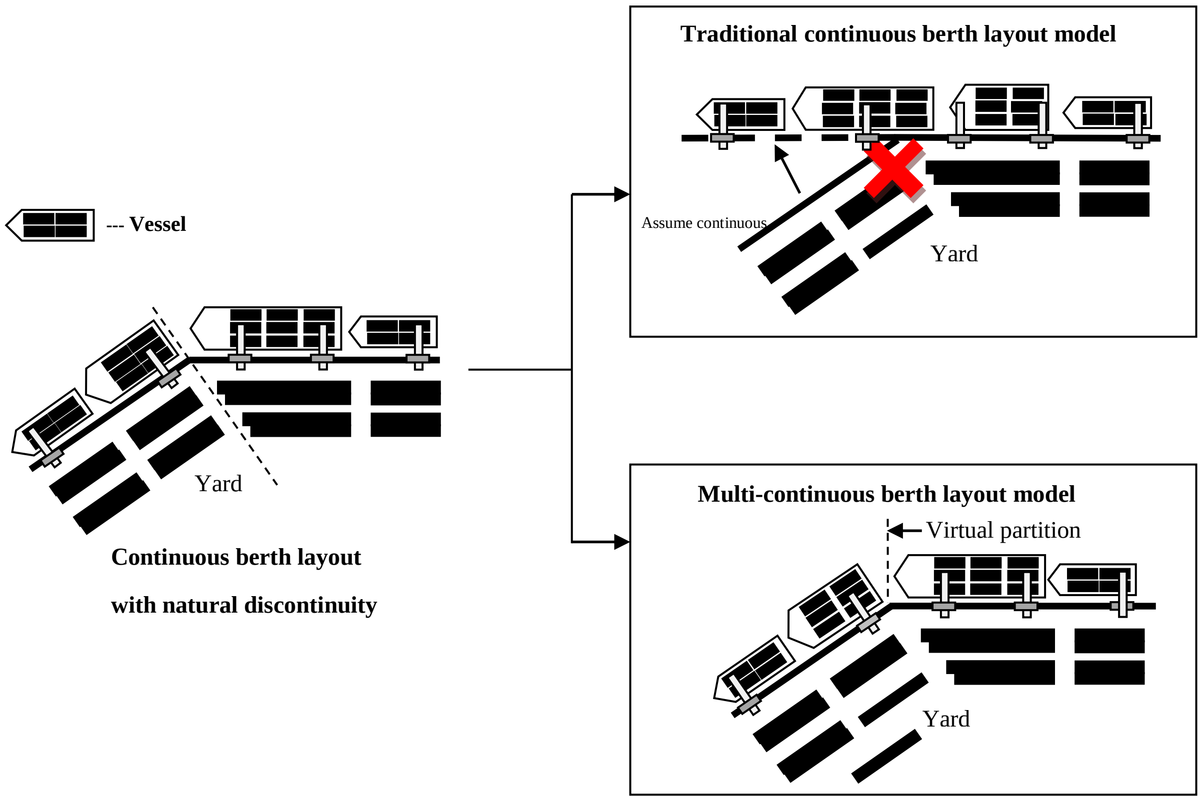


Fig. 3 Different modeling approaches on continuous berth layout with natural discontinuity

3.2 Local Refinement

In Step 4, the idea of local refinement is to iteratively refine the solution by alternatively fixing the decision variables involved in $\mathcal{M}\_\mathcal{B}_{\mathrm{n}}$ and $\mathcal{M}\_\mathcal{Y}$. First of all, the berth-related decisions will be refined by fixing the yard-related decision ($\varphi_{i,k}$). Then, the improved berth-related decisions ($\omega_{i,b}$ and $\theta_{i,t}$) will be fixed to refine the yard-related decision, where $\omega_{i,b} \in [0, 1]$ set to 1 if $\beta_{i\in V}$ is in berth segment $b \in B$, and 0 otherwise, and $\theta_{i,t} \in [0, 1]$ set to 1 if vessel $i \in V$ is loading in time step t, and 0 otherwise. The iteration will stop until no better solution is obtained. It is noted that for large scale problems, a proportion α of the $\delta^T_{i,j}$ and $\delta^B_{i,j}$ parameters is suggested to be fixed in $\mathcal{M}\_\mathcal{Y}$. As a result, the final solution is obtained by integrating $\mathcal{M}\_\mathcal{B}_{\mathrm{n}}$, and $\mathcal{M}\_\mathcal{Y}$.

Once the solution is obtained for this segment, it will move on to the next segment until the end of the vessel in the list as in Step 5. The logic flow is outline below, in which depth of search (*DS*) defines the number of iterations ($N - DS$) conducted, and the length of the segment is $DS + 1$.

The logic flow of the **iterative local refinement approach** is outlined as follows:

1: Input: Vessel Priority Sequence (σ)

2: *bool* = True;

3: For n = 1 to *N*-*DS* // *N* is the number of vessels, while depth of search (*DS*) = 10

4: Do{

5: Solve $\mathcal{M}\_\mathcal{B}_{\mathrm{n}}$;

6: Input variables: $\omega_{i,b}$ and $\theta_{i,t}$

7: Solve $\mathcal{M}\_\mathcal{Y}$;

8: Fixed variable: $\varphi_{i,k}$ and α of $\delta_{i,j}^{T}$ and $\delta_{i,j}^{B}$

9: Solve α-$\mathcal{M}\_\mathcal{BY}_{\varphi\delta}$; //Local Refinement, set *bool* = False if no improvement achieved

10: }While (*bool*)

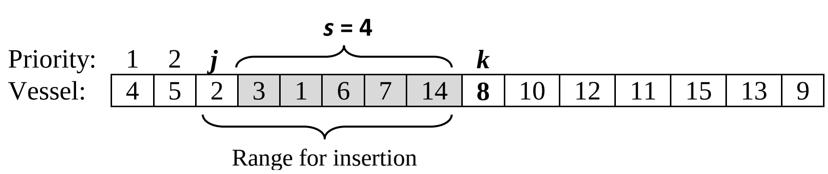
3.3 Guided Neighborhood Search (GNS)

In literature, Zhen et al. (2011) proposed an approach named Critical-Shaking Neighborhood Search (CSNS) to change the vessel priority sequence. It randomly changes the priority of the critical elements, which are the vessels with a high objective value. However, we note that this randomness maybe ineffective, and may result in a very long and unstable computational time. Therefore, in Step 6, we propose a new heuristics named GNS to make it more efficient and stable.

GNS is introduced to change the vessel priority sequence. Given a priority sequence of vessels and the corresponding objective cost of each vessel (V_i), we define a critical level ℓ as a portion ∂ of the highest vessel objective cost (Lim and Xu 2006). Any vessels with objective cost above ℓ are identified as the critical elements for changing the priority. Since some of the vessels with the highest V_i may have no room for improvement, especially for those who have already had high priority, the critical elements search will start from the vessel with priority (*DS*+2), because the first (*DS*+1) vessels have already been solved simultaneously in the 1st iteration. Before changing the priority of the critical elements, we suggest there are two-way movements, including forward movement and backward movement. Forward movement aims to promote one's priority, while backward movement lightens one's priority. It is noted that the critical elements are used to compete the resources, such as berthing location, berthing time, yard storage space, etc., with some other vessels that are regarded as its potential competitors. Therefore, it is suggested the critical elements to be moved or inserted into a new position in the vessel priority sequence in order to be considered with its potential competitor in the same iteration. For example in Fig. 4, if DS = 4, for the Case 1, Vessel 8 with the priority k is selected as the one of the critical elements. Vessel 2 with the priority j, which is higher than k, is the potential competitor. In this case, forward movement is suggested for Vessel 8 for higher priority, and it is randomly inserted into the priority between (j-1) and (j+DS+1) in order to involve both vessels in the same iteration. Similarly, for case 2, if backward movement is suggested, Vessel 1 with priority k should be inserted randomly between the priorities (j+1) and (j-DS+1).

To decide which type of movement should be used for the critical element, the reason accounting for the high cost should be tracked back first. Since the objective cost is comprised of the berth part and the yard part, we compare the costs caused by each part and determine which part contributes the most. If the cost mainly comes from the berth part, check whether the cost is related to the deviation caused by earliness or tardiness. We suggest a backward movement if the deviation involves only earliness, otherwise a forward movement is suggested. If the cost mainly comes from the yard part, a forward movement is suggested.

Case 1: Forward movement



Case 2: Backward movement

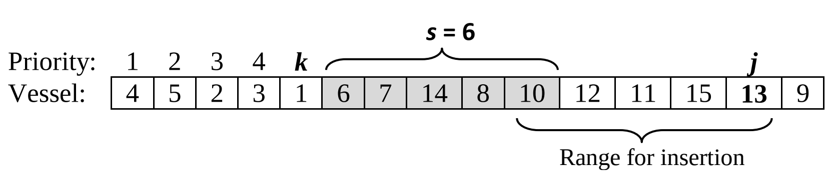


Fig. 4 Forward and backward movement of the vessel priority

To identify the position for the insertion of the critical element, the corresponding potential competitors should be firstly identified. We divide the planning horizon into a number of time intervals based on the average vessel handling time, i.e. 4 time steps as a time interval. Then, assign the vessels to the interval when they berth. Since it is critical to allocate resources, i.e. berth space, QCs, to the vessels with the same or the adjacent time intervals, as they most likely are competing with each other, these critical vessels should be considered in the same iteration.

Case 1: For those whose high cost is mainly come from the berth part, if the deviation involves only earliness, or both earliness and tardiness, it means the vessel may not berth at its desired berthing time. Therefore, we define those working at the same or the adjacent time intervals as potential competitors.

Case 2: If the deviation involves only tardiness, it may be because of insufficient QC resources assigned to the vessel. Similarly, the vessels working at the same or adjacent time intervals can then be regarded as potential competitors as they compete with each other for the QC resource.

Case 3: It may be because of the assigned quay section, which does not have sufficient QC resources. In this case, the potential competitors should be those assigned to the section with sufficient QC resources while working at the same or the adjacent time intervals.

Case 4: For those whose high cost mainly comes from the yard part, the yard cost is affected mainly by the transshipment volume and transportation distance. Those vessels berthed in the same locations compete the nearest yard storage sub-block with each other. Moreover, the transshipment volume has not been considered in the priority rules. Therefore, we suggest that the vessels that have higher priority, while berthing in the same location with fewer transportation volume can be regarded as potential competitors.

Case 5: Lastly, we also suggest that the vessels should be considered with their transshipment partners in the same iteration.

The overall procedures of GNS are shown as follows:

Generate initial sequence σ_0 for the *N* vessels according to the priority rule

Let σ_0 be σ and σ_0 be the optimal sequence σ_{opt};

Let the maximum check ($L_{max} = 3$) be L;

Do{

  Input: σ

  Algorithm 1: Iterative Heuristic algorithm;

  Select a number of *NC* critical elements whose $V_i \geq \ell$;

  for ($n = 1$ to $n = NC$){

    Forward movement / backward movement;

    Identify the potential competitor for each critical element;

    Change the priority of the critical elements within the suggested range;}

  A new σ' generated. If σ' has already been generated before, generates a new one;

  Input: σ'

  Algorithm 1: Iterative Heuristic algorithm;

  If (σ' is better than σ_{opt})

  then{

    $\sigma_{opt} \leftarrow \sigma'$;

    $L \leftarrow L_{max}$;

    $\sigma \leftarrow \sigma'$;}

  else{

    $L = L-1$;}

} While ($L > 0$)

4. Numerical Experiments

In this section, the generation of the test instances and parameter settings is described, and numerical experiments are provided to verify the solution quality of the proposed GNS and to demonstrate the significance of the multi-continuous berth layout model. The proposed approach was programmed in JAVA language and solved by using CPLEX on a PC with a CPU of 1.33GHz and 8GB RAM.

4.1 Generation of test instance and parameter setting

Generation of the test instances is based on information provided in Zhen et al. (2011), in which each day is divided into six time steps, and a planning horizon covers one week with a total of 42 time steps. The test instances are classified into six problem scales as shown in table 1. Since the study considers quay discontinuities, the quay was divided into 2 quay sections in problem scales 15 to 30, and 3 quay sections in problem scales 40 to 60. QC capacity in each section is also given in table 1. The vessels served by the terminal can be classified into three groups: (i) Feeder, (ii) Medium, and (iii) Jumbo, according to the technical specifications shown in table 2. This information is also used for generating the QC-profiles. We assume a QC can handle about 30 containers per hour. This assumption meets the common requirement of the industry. The vessels can arrive randomly along the planning horizon. The feasible time windows $[a_i^M, b_i^M]$, and the expected time window $[a_i^e, b_i^e]$ can be the same or at a maximum five times its average handling time. It is assumed that the average loading and unloading container tasks are half to half for each vessel, and all containers are of 40-ft size, i.e. two TEUs. The number of containers transshipped from vessel i to vessel j (c_{ij}), can be randomly generated without violating the total number of loading and unloading containers of the vessel. The number of subblocks reserved for vessel i (r_i), is generated according to its container volume. Moreover, some assumptions on yard configuration are also made, as in other yard studies. We assume each block of the storage yard consists of 5 subblocks, and we use a subblock as a basic unit for yard template planning. The capacity and the length of a subblock are about 240 TEUs and 50 m. The width of the passing lanes in the yard is set at 30 m. To ensure the same order of magnitude of berth-side and yard-side cost, ω^Y is set as 5×10^{-6}.

Table 1 - Test instances classes

Number of Vessels	Number of sub-blocks	Total quay length (m)	No of quay sections	Quay section length (m) [Number of QCs available in each section]		
				Section 1	Section 2	Section 3
15	80	500	1	500 [5QCs]	--	--
20	120	700	2	300 [4QCs]	400 [3QCs]	--
30	160	1100	2	500 [6QCs]	600 [5QCs]	--
40	240	1500	3	500 [6QCs]	600 [5QCs]	400 [4QCs]
50	300	1800	3	500 [6QCs]	800 [5QCs]	500 [7QCs]
60	360	2000	3	500 [6QCs]	800 [6QCs]	700 [8QCs]

Table 2 - Test instances classes

Class	Vessel length (m)	QC Capacity	Handling time (time steps)	Average handling time (time steps)	workload (QC × time step)	Earliness and Tardiness Weightings (ω_i^{Be}& ω_i^{Bt})	Total number of unloading and loading containers (TEU)	The number of subblocks reserved for vessel
Feeder	100-200	1-3	2-4	3	2-5	2-6	240-600	2-3
Medium	200-300	2-4	3-5	4	6-14	6-10	720-1680	2-4
Jumbo	300-400	3-6	4-6	5	15-20	10-14	1800-2400	8-10

4.2 Testify the solution quality of the proposed GNS approach

To verify the solution quality of the proposed GNS approach, we compare it with the CSNS approach proposed by Zhen et al. (2011). As suggested by Zhen et al. (2011), *DS* is set as 10 for all instances, and for the large scale instances, the parameter α is applied and set as 0.2 for 40 vessels, 0.3 for 50 vessels, and 0.4 for 60 vessels in both the CSNS and GNS approaches. The results obtained from the experiment are presented in table 3. For the small scale problems, no obvious improvement in objective value can be seen from the results. However, for large scale problems, the difficulty increases with the scale, and the searching mechanism of the algorithm becomes more significant to the solution quality. By improving the procedure of changing the vessel priority sequence, the proposed GNS approach can finally achieve a maximum improvement of 7% in the objective value. Moreover, a maximum 45% reduction in computational time can be found. The results show that the proposed GNS can obtain better results, more effectively, especially in large scale problems. We also note that the enhanced searching mechanism in the GNS approach can reduce the number of checking trials from 5 to 3 before terminating the approach if no improvement can be achieved. Since the computational time for each trial is long, such reduction can significantly reduce the computational time in both small and large scale problems.

Table 3 – Results of comparing GNS with CSNS

Small Scale Problem								Large Scale Problem							
Instances	CSNS		The proposed GNS					Instances	CSNS		The proposed GNS				
	Obj	Time (min)	Obj	Improvement (%)	Time (min)	Improvement (%)			Obj	Time (min)	Obj	Improvement (%)	Time (min)	Improvement (%)	
15-1	368	18	368	0.00	12	33.33		**40-1**	715	116	699	2.30	87	25.00	
15-2	326	7	326	0.00	5	28.57		**40-2**	723	147	709	1.89	67	54.42	
15-3	360	16	360	0.00	10	37.50		**40-3**	712	183	694	2.46	146	20.22	
15-4	355	14	355	0.00	10	28.57		**40-4**	809	212	798	1.37	141	33.49	
15-5	393	26	393	0.00	18	30.77		**40-5**	726	134	713	1.84	96	28.36	
15-6	342	13	342	0.00	8	38.46		**40-6**	776	129	749	3.45	90	30.23	
15-7	328	11	328	0.00	7	36.36		**40-7**	723	102	705	2.55	74	27.45	
15-8	395	17	395	0.00	11	35.29		**40-8**	814	155	800	1.74	121	21.94	
15-9	367	15	367	0.00	10	33.33		**40-9**	745	134	727	2.48	101	24.63	
15-10	369	16	369	0.00	12	25.00		**40-10**	787	162	763	3.1	135	16.67	
20-1	454	45	454	0.00	32	28.89		**50-1**	1076	289	937	4.12	224	22.49	
20-2	437	28	437	0.00	17	39.29		**50-2**	1119	224	1060	5.31	162	27.68	
20-3	474	62	471	0.63	34	45.16		**50-3**	1247	279	919	4.26	186	33.33	
20-4	420	69	420	0.00	51	26.09		**50-4**	903	191	875	3.05	114	40.31	
20-5	416	55	414	0.48	34	38.18		**50-5**	947	164	902	4.71	91	44.51	
20-6	482	66	482	0.00	44	33.33		**50-6**	1238	266	968	5.08	193	27.44	
20-7	451	48	448	0.67	28	41.67		**50-7**	1110	272	1074	3.21	197	27.57	
20-8	422	34	420	0.47	21	38.24		**50-8**	946	161	901	4.79	120	25.47	
20-9	451	57	446	1.11	38	33.33		**50-9**	1043	187	1010	3.21	149	20.32	
20-10	417	54	414	0.72	42	22.22		**50-10**	951	195	907	4.67	106	45.64	
30-1	658	159	652	0.91	119	25.16		**60-1**	1364	285	1263	7.4	200	29.82	
30-2	593	124	589	0.67	83	33.06		**60-2**	1527	294	1431	6.3	229	22.11	
30-3	646	204	631	2.32	130	36.27		**60-3**	1308	371	1228	6.12	216	41.78	
30-4	600	140	599	0.17	86	38.57		**60-4**	1342	344	1240	7.57	258	25.00	
30-5	627	93	624	0.48	56	39.78		**60-5**	1460	410	1369	6.22	261	36.34	
30-6	635	172	628	1.10	109	36.63		**60-6**	1453	267	1371	5.61	205	23.22	
30-7	580	89	573	1.21	60	32.58		**60-7**	1517	397	1420	6.37	265	33.25	
30-8	661	167	660	0.15	106	36.53		**60-8**	1336	210	1253	6.22	134	36.19	
30-9	604	108	594	1.66	72	33.33		**60-9**	1305	322	1212	7.11	193	40.06	
30-10	628	169	620	1.27	127	24.85		**60-10**	1387	277	1312	5.43	215	22.38	

4.3 Significance of the multi-continuous berth layout model

This paper addresses a very realistic quay layout characteristic - quay discontinuity, and proposes using a multi-continuous modeling approach to deal with that. To demonstrate the significance of the proposed model, we compare the proposed modeling approach with the traditional used modeling approach. However, since traditional modeling approach cannot be applied directly in a terminal with quay discontinuity, we adopt a practical approach that vessels are assigned to one of the quay sections based on the ascending order of the vessel arrival time, and then we do the optimization on each section by using the traditional continuous modeling approach. We designed and conducted experiments to simulate the practical approach and compared it with the proposed GNS approach, which considers the multi-continuous berth layout model. Experimental results are summarized in table 4. Both the practical approach and the proposed GNS approach can obtain feasible solutions, while the results show that the percentage time gap between the two approaches is quite large with a maximum of 450%. It is because vessels are already been assigned to the quay section, and the problem scales of each section become smaller. Since these approaches are for decision making at the tactical level, the computational time required is still acceptable. However, it is also significant that the proposed GNS approach can improve the performance by about 8 to 12 % for small scale problems, and 27 to 44 % for large scale problems.

5. CONCLUSIONS

This paper proposes a multi-continuous berth layout modeling approach which additionally considers quay discontinuities in the conventional continuous berth layout model. We formulate a mixed integer linear programming model for the new berth layout, which is based upon the existing integrated berth and yard template model proposed by Zhen et al. (2011). The proposed model can be applied in real-world container terminals with discontinuities on the quay, while enhancing the utilization of each quay section. The objective of the integrated model is to minimize the service cost caused by the deviation from expected turnaround time intervals of vessels, and the operation cost caused by the transshipment of the containers from the quay space to the yard storage sub-block. Moreover, a guided neighborhood search (GNS) is proposed for a more effective search of the optimization algorithm. A number of computational experiments are conducted, and the results show that the proposed algorithm can obtain a better solution when compared with the existing critical shaking neighborhood search (CSNS) approach in terms of solution quality and time. To demonstrate the significance of the proposed layout model, we also compared it with the practical approach. Although the computational time required by the proposed approach is longer than that of the practical approach, it is still acceptable for tactical planning. More important, the results showed great improvement in the objective value obtained by using the proposed model. Lastly, it is noted that the current virtual partition modeling approach is developed based on the set partitioning solution approach. It is suggested that more research effort can be spend on the development of the solution approach to achieve an even higher computational efficiency.

Acknowledgement

This research was partially supported by the Ningbo Soft Science Programme, the Ningbo Science and Technology Bureau (Grant No. 2016A10037), and by the International Academy of Marine Economy and Technologies and Ningbo Science and Technology Bureau (Grant No. 2014A35006).

Table 3 – Results of comparing GNS with the practical approach

Instances	Practical Approach		The proposed GNS approach			
	Obj	Time (min)	Obj	Improvement (%)	Time (min)	Time Gap (%)
20-1	498	11	454	8.84	32.00	190.91
20-2	461	6	437	5.21	17.00	183.33
20-3	510	8	471	7.60	34.00	325.00
20-4	451	20	420	6.79	51.00	155.00
20-5	435	7	414	4.91	34.00	385.71
20-6	522	8	482	7.59	44.00	450.00
20-7	477	13	448	6.08	28.00	115.38
20-8	453	11	420	7.24	21.00	90.91
20-9	473	14	446	5.77	38.00	171.43
20-10	444	18	414	6.83	42.00	133.33
30-1	705	40	652	7.52	119.00	197.50
30-2	633	31	589	6.95	83.00	167.74
30-3	706	36	631	10.62	130.00	261.11
30-4	659	27	599	9.10	86.00	218.52
30-5	681	24	624	8.37	56.00	133.33
30-6	702	40	628	10.54	109.00	172.50
30-7	647	22	573	11.44	60.00	172.73
30-8	731	38	660	9.71	106.00	178.95
30-9	646	31	594	8.05	72.00	132.26
30-10	708	48	620	12.43	127.00	164.58
40-1	855	54	699	18.25	87.00	61.11
40-2	964	33	709	26.45	66.82	102.48
40-3	894	42	694	22.37	146.40	248.57
40-4	995	39	798	19.80	141.33	262.39
40-5	872	47	713	18.23	95.71	103.65
40-6	950	45	749	21.16	90.30	100.67
40-7	890	30	705	20.79	74.18	147.27
40-8	1078	59	800	25.79	120.56	104.33
40-9	924	49	727	21.32	100.50	105.10
40-10	1001	67	763	23.78	135.00	101.49
50-1	1316	84	937	28.80	224.00	166.67
50-2	1528	102	1060	30.64	162.00	58.82
50-3	1365	68	919	32.67	186.00	173.53
50-4	1206	72	875	27.44	114.00	58.33
50-5	1352	88	902	33.28	91.00	3.41
50-6	1433	76	968	32.45	193.00	153.95
50-7	1496	84	1074	28.21	197.00	134.52
50-8	1303	86	901	30.84	120.00	39.53
50-9	1415	97	1010	28.64	149.00	53.61
50-10	1257	64	907	27.82	106.00	65.63
60-1	2112	122	1263	40.20	199.50	63.52
60-2	2332	96	1431	38.64	228.67	138.19
60-3	1955	88	1228	37.19	216.42	145.93
60-4	1959	132	1240	36.70	258.00	95.45
60-5	2353	103	1369	41.82	260.91	153.31
60-6	2104	126	1371	34.84	205.38	63.00
60-7	2561	163	1420	44.55	264.67	62.37
60-8	1750	84	1253	28.40	133.64	59.09
60-9	1736	87	1212	30.18	193.20	122.07
60-10	2109	141	1312	37.79	215.44	52.80

Time Gap % = (Time(GNS) – Time(practical))/ Time(practical)

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Appendix 1 – MILP formulation by using virtual partition modeling approach

This appendix introduces the detail MILP formulation for the models mentioned in Steps 2 and 3 in Fig. 2.

Notations being used in the paper:

Input Data

V	set of vessels, $V = \{1,2,3,\dots I\}$
B	set of berth segments, $B = \{1,2,3,\dots B\}$
C	set of quay sections, $C = \{1,2,3,\dots C\}$
P_i	set of the QC-profiles for vessel, $i \in V$
T	set of time steps under consideration, $T = \{1, 2,\dots H + E\}$
s	length of a berth segment in meter
H	number of time steps in a planning horizon
E	maximum handling time of all vessels, $E = max_{\forall i \in V}\{h_{i,p} \| p \in P_i\}$
$[a_i^M, b_i^M]$	feasible turnaround time interval for vessel i, $i \in V$, $a_i^M, b_i^M \in T$
$[a_i^e, b_i^e]$	expected turnaround time interval for vessel i, $i \in V$, $a_i^e, b_i^e \in T$
SL_c	starting point of section $c \in C$
EL_c	ending point of section $c \in C$
μ_i	length of vessel i, $i \in V$ in meter
Q_{tc}	number of available QCs in time step t, $t \in \{1, 2,\dots H\}$, $c \in C$
$h_{i,p}$	handling time (time steps) of vessel i by using QC-profile p, $i \in V$, $p \in P_i$
$q_{i,p,m}$	number of QCs utilized in the m^{th} time step if vessel i is served by QC-profile p, $i \in V$, $m \in \{1,\dots h_{i,p}\}$, $p \in P_i$
c_{ij}	number of containers transshipped from vessel i to j, $i \neq j \in V$
$\omega_i^{Be}, \omega_i^{Bt}$	the weights for vessel i assigned to the earliness and tardiness beyond the vessel's expected turnaround time interval, $i \in V$
ω^Y	the weight assigned to the transportation distance of containers in yard, $i \in V$
M	a sufficiently large positive number

Variables

$\delta_{i,j}^T$	$\in [0, 1]$	set to 1 if the handling of vessel i ends earlier than the handling of vessel j starts, and 0 otherwise, $i \neq j \in V$
$\delta_{i,j}^B$	$\in [0, 1]$	set to 1 if vessel i is moored below vessel j along the berth axis and 0 otherwise, $i \neq j \in V$
$\eta_{i,p,t,c}$	$\in [0, 1]$	set to 1 if vessel i is assigned to quay section c, and is served by QC-profile p and begins handling in time step t, and 0 otherwise, $i \in V$, $p \in P_i$, $t \in T$, $c \in C$
$\zeta_{i,b}$	$\in [0, 1]$	set to 1 if vessel i occupies berth segment b, and 0 otherwise. In addition, two auxiliary variables, $\zeta_{i,b}^U$, $\zeta_{i,b}^L \in [0, 1]$, are defined for $\zeta_{i,b}$, such that if $\zeta_{i,b}^U = \zeta_{i,b}^L = 1$, then $\zeta_{i,b} = 1$, $i \in V$, $b \in B$
ε_i	$\in \{1, \dots H\}$	the starting time step of handling for vessel i, $i \in V$
σ_i	$\in T$	the ending time step of handling for vessel i, $i \in V$
o_b, d_b	$\in T$	start and end time steps for berth segment b, $b \in B$
ρ_{tc}	≥ 0	the number of used QCs at time step t, $t \in T$, $c \in C$
$\lambda_{i,j}^U$	≥ 0	the average of unloading route length between the berth position of vessel i and all the sub-blocks reserved for vessel j, $i \neq j \in V$
λ_j^L	≥ 0	the average of loading route length between the berth position of vessel j and all the sub-blocks reserved for vessel j, $j \in V$

Decision variables

β_i	$\in$ [0, L]	continuous variable, berthing position according to the middle point of vessel *i*, $i \in V$
$\pi_{i,t}$	$\in$ [0, 1]	set to 1 if vessel *i* begins handling in time step *t*, and 0 otherwise, $i \in V$, $t \in T$
$\gamma_{i,p}$	$\in$ [0, 1]	set to 1 if vessel *i* is served by QC-profile *p* and zero otherwise, $i \in V$, $p \in P_i$
y_{ic}	$\in$ [0, 1]	set to 1 if vessel *i* is assigned to quay section *c* and zero otherwise, $i \in V$, $c \in C$

Objective function

$$\sum_{i\in V}(\omega_i^{Be}\cdot(a_i^e-\varepsilon_i)^+ + \omega_i^{Bt}\cdot(\sigma_i-b_i^e)^+) + \omega^Y\sum_{i\epsilon V}\sum_{j\epsilon V,j\neq i}c_{ij}\cdot(\lambda_{i,j}^U+\lambda_j^L) \tag{1}$$
$$\sum_{i\in V}(\omega_i^{Be}\cdot\tau_i^{a+} + \omega_i^{Be}\cdot\tau_i^{a-} + \omega_i^{Bt}\cdot\tau_i^{b+} + \omega_i^{Bt}\cdot\tau_i^{b-}) + \omega^Y\sum_{i\epsilon V}\sum_{j\epsilon V,j\neq i}c_{ij}\cdot(\lambda_{i,j}^U+\lambda_j^L) \tag{2}$$

Objective function (1) aims to minimize the service cost induced by the deviation from the vessels expected turnaround time intervals, and the operation cost induced by the transshipment of the containers from the quay space to the yard storage block. The nonlinear objective function (1) is linearized to a linear objective function (2) by adding four positive integer variables $\tau_i^{a+}, \tau_i^{a-}, \tau_i^{b+}, \tau_i^{b-}$, and constraints (3) – (5):

$$a_i^e + \varepsilon_i = \tau_i^{a+} - \tau_i^{a-} \qquad ,\forall i \in V \tag{3}$$
$$\sigma_i - b_i^e = \tau_i^{b+} - \tau_i^{b-} \qquad ,\forall i \in V \tag{4}$$
$$\tau_i^{a+}, \tau_i^{a-}, \tau_i^{b+}, \tau_i^{b-} \geq 0 \qquad ,\forall i \in V \tag{5}$$

Constraints

The model is subject to two types of constraints, i) modified berth template model constraints ($\mathcal{M}\_\mathcal{B}_\mathrm{n}$), and ii) yard template model constraint ($\mathcal{M}\_\mathcal{Y}$). The others two constraints are explained as the follows.

Modified berth template model constraints ($\mathcal{M}\_\mathcal{B}_n$):

The idea of virtual partitions modeling approach is to divide the quay into a set of quay sections *C* where no discontinuity or curve exists in each section $c \in C$. A decision variable y_{ic} is introduced, and constraint (6) ensures each vessel $i \in V$ to be assigned to one quay section.

$$\sum_{i\in V}\sum_{c\in C} y_{ic} = 1 \qquad \forall i \in V, \forall c \in C \qquad (6)$$

A set of vessels (*V*) is to be berthed within a planning horizon of (*H*) time step. To model the handling time of vessel *i* ($h_{i,p}$), Zhen et al. (2011) adopted the concept of QC-profile by Giallombardo et al. (2010). A set of possible feasible QC-profiles (P_i) are generated for vessel $i \in V$. The selected QC-profile indicates the number of time steps required for handling which is the vessel handling time, and the number of QCs assigned to the vessel in each time step. The QC-profile allows variation of the number of QCs between two adjacent time steps, and takes into account the maximum and the minimum number of QCs guaranteed for the vessel. The remaining constraints of $\mathcal{M}\_\mathcal{B}_\mathrm{n}$ can be grouped into five main categories:

a. Non-overlapping constraints:

$$\varepsilon_i + \sum_{p\in P_i} \gamma_{i,p} \cdot h_{i,p} \le \varepsilon_j + (1 - \delta_{i,j}^T) \cdot M \qquad \forall i, j \in V, i \ne j \qquad (7)$$

$$\beta_i + (\mu_i + \mu_j)/2 \le \beta_j + (1 - \delta_{i,j}^B) \cdot M \qquad \forall i, j \in V, i \ne j \qquad (8)$$

$$\delta_{i,j}^T + \delta_{j,i}^T + \delta_{i,j}^B + \delta_{j,i}^B \ge 1 \qquad \forall i, j \in V, i \ne j \qquad (9)$$

Constraint (7) ensures $\delta_{i,j}^T$ is set to 1 if vessel j starts after the completion of vessel i. Constraint (8) ensures $\delta_{i,j}^B$ is set to 1 if vessel *i* berth completely on the right side of vessel *j* along the quay. Constraint (9) guarantees at least one of the above relationships is valid among vessels *i* and *j*.

b. Berthing position constraint:

Since the quay is divided into a set of quay sections C, SL_c and EL_c are introduced to represent the starting point and ending point of each section $c \in C$, and the length is calculated by $(EL_c - SL_c)$. Constraint (10) is used to ensure the feasibility of berthing position β_i for $i \in V$ in each quay section.

$$SL_c + \mu_i/2 - (1 - y_{ic})M \le \beta_i \le EL_c + (1 - y_{ic})M - \mu_i/2, \qquad \forall i \in V, \forall c \in C \qquad (10)$$

c. QC constraints:

$$\sum_{p\in P_i} \gamma_{i,p} = 1 \qquad \forall i \in V \tag{11}$$

$$\eta_{i,p,t,c} \geq \gamma_{i,p} + \pi_{i,t} + \ y_{ic} - 2 \qquad \forall i \in V, \forall p \in P_i, \forall t \in T, \forall c \in C \tag{12}$$

$$\rho_{tc} = \ \sum_{i\in V} \sum_{p\in P_i} \sum_{h=max(1;\, t-h_{ip}-1)}^{t} q_{ip(t-h+1)} \cdot \eta_{i,p,h,c} \qquad \forall t \in T, \forall c \in C \tag{13}$$

$$\rho_{tc} \leq Q_{tc} \qquad \forall t \ \in \ \{1, 2, \dots\ H\}, \forall c \in C \tag{14}$$

$$\rho_{tc} + \rho_{(t+H)c} \leq Q_{tc} \qquad \forall t \ \in \ \{1, 2, \dots\ E\}, \forall c \in C \tag{15}$$

Constraint (11) ensures one QC-profile is selected for each vessel. Constraint (12) ensures QCs cannot be transferred from one section to another section due to the quay discontinuities or curves. Therefore, the number of QCs available for service is also affected, and it should be counted individually in each section. Constraint (13) sums up the number of QCs used in each time step. Constraint (14) and (15) ensure the number of QCs used at each time step will not exceed the available number of QCs in that section.

d. Time constraints:

$$\sum_{t\in T} \pi_{i,t} = 1 \qquad \forall i \in V \tag{16}$$

$$\varepsilon_i = \sum_{t\epsilon T} \pi_{i,t} \cdot t \qquad \forall i \in V \tag{17}$$

$$\varepsilon_i + \sum_{p\in P_i} \gamma_{i,p} \cdot h_{i,p} - 1 = \ \sigma_i \qquad \forall i \in V \tag{18}$$

$$\varepsilon_i \geq a_i^M \qquad \forall i \in V \tag{19}$$

$$\sigma_i \leq b_i^M \qquad \forall i \in V \tag{20}$$

Constraint (16) defines the starting time step of each vessel, and constraint (17) sets the relationship between the variables ε_i and $\pi_{i,t}$. Constraint (18) calculates the ending time of each vessel. Constraints (19) and (20) guarantees the starting and the ending time are within the feasible turnaround time interval of the vessel.

e. Other constraints:

$$\beta_i + u_i/2 - s \cdot (b-1) \leq \ \zeta_{i,b}^U \cdot M \qquad \forall b \in B, \forall i \in V \tag{21}$$

$$s \cdot b - \beta_i + u_i/2 \leq \ \zeta_{i,b}^L \cdot M \qquad \forall b \in B, \forall i \in V \tag{22}$$

$$\zeta_{i,b} \geq \ \zeta_{i,b}^U + \zeta_{i,b}^L - 1 \qquad \forall b \in B, \forall i \in V \tag{23}$$

$$o_b \leq \varepsilon_i + (1 - \zeta_{i,b}) \cdot M \qquad \forall b \in B, \forall i \in V \tag{24}$$

$$d_b \geq \sigma_i + (\zeta_{i,b} - 1) \cdot M \qquad \forall b \in B, \forall i \in V \tag{25}$$

$$d_b - o_b \leq H - 1 \qquad \forall b \in B \tag{26}$$

Constraints (21) – (26) are set up for consideration of re-planning based on the periodicity of the vessel schedule. Constraints (21) – (23) define the berth segment b that is occupied by vessel i. Constraints (24) – (26) ensure the gap between o_b and d_b is within the planning horizon.

Yard template model constraints ($\mathcal{M}\_\mathcal{Y}$):

The $\mathcal{M}\_\mathcal{Y}$ constraint is actually the same as the one in Zhen et al. (2011). For details, please refer to the original paper. Here we will briefly introduce the mechanism and constraints used. After $\mathcal{M}\_\mathcal{B}_n$ is solved, $\omega_{i,b}$ and $\theta_{i,t}$ are obtained, where $\omega_{i,b} \in [0, 1]$ set to 1 if $\beta_{i\in V}$ is in berth segment $b \in B$, and 0 otherwise, and $\theta_{i,t} \in [0, 1]$ set to 1 if vessel $i \in V$ is loading in time step t, and 0 otherwise. Accordingly, the yard template decision ($\varphi_{i,k}$) is to assign subblocks k to vessels i with consignment strategy, which dedicates certain subblocks to each vessel. Both the export and transshipment containers, which will be loaded onto the same vessel, are stored in its dedicated subblocks. This strategy undoubtedly reduces the number of re-handling operations of containers inside the yard. A number of containers are transshipped from vessel i to vessel j (c_{ij}), the length of unloading routes ($\lambda_{i,j}^U$), which is the average of the distances between the subblocks k dedicated to vessel j and the berth segment where vessel i berths per a TEU of unloading container, and the length of loading routes (λ_j^L), which is the average of the distances between the subblocks k dedicated to vessel j and the berth segment where vessel j berths at per a TEU of loading container, are taken into account in the yard related operation cost. The constraints are shown as follows:

<u>Input Data</u>

K	set of the available subblocks, $K = \{1,2,3,\ldots K\}$
N	set of the pairs of subblocks that are neighbor, $N = \{1,2,3,\ldots N\}$
G	set of the groups of five subblocks that belong to the same subblock, $G = \{1,2,3,\ldots G\}$
r_i	number of subblocks reserved for vessel i, $i \in V$
$D_{k,b}^U$	length of unloading route from berth segment b to subblock k, $b \in B$, $k \in K$
$D_{k,b}^L$	length of loading route from subblock k to berth segment b, $b \in B$, $k \in K$
$\omega_{i,b} \in [0, 1]$	set to 1 if $\beta_{i\in V}$ is in berth segment b, and 0 otherwise, $b \in B$
$\theta_{i,t} \in [0, 1]$	set to 1 if vessel i is loading in time step t, and 0 otherwise, $i \in V$

Variables

$\xi_{i,t,k}$	$\in [0, 1]$	set to 1 if vessel i is loading in time step t and subblock k is reserved for vessel i, and 0 otherwise, $i \in V$, $t \in T$, $k \in K$
$\varphi_{j,k,i,b}$	$\in [0, 1]$	set to 1 if vessel i moors at berth segment b and subblock k is reserved for vessel j, and 0 otherwise, $i \neq j \in V$, $b \in B$, $k \in K$
$\varphi_{j,k,b}$	$\in [0, 1]$	set to 1 if vessel j moors at berth segment b and subblock k is reserved for vessel j, and 0 otherwise, $i \neq j \in V$, $b \in B$, $k \in K$
$\lambda^U_{i,j}$	≥ 0	the average of unloading route length between the berth position of vessel i and all the subblocks reserved for vessel j, $i \neq j \in V$
λ^L_j	≥ 0	the average of loading route length between the berth position of vessel j and all the subblocks reserved for vessel j, $j \in V$

Decision variables

$\varphi_{i,k}$ $\in [0, 1]$ set to 1 if subblock k is reserved for vessel i, and 0 otherwise, $k \in K$, $i \in V$

Constraints

$$\sum_{i \in V} \varphi_{i,k} \leq 1 \qquad \forall k \in K \qquad (27)$$
$$\sum_{k \in K} \varphi_{i,k} = r_i \qquad \forall i \in V \qquad (28)$$
$$\xi_{i,t,k} \geq \varphi_{i,k} + \theta_{i,t} - 1 \qquad \forall i \in V, \forall t \in T, \forall k \in K \qquad (29)$$
$$\sum_{k \in n} \sum_{i \in V} \xi_{i,t,k} \leq 1 \qquad \forall t \in \{E+1, \ldots H\}, \forall n \in N \qquad (30)$$
$$\sum_{k \in g} \sum_{i \in V} \xi_{i,t,k} \leq 1 \qquad \forall t \in \{E+1, \ldots H\}, \forall g \in G \qquad (31)$$
$$\sum_{k \in n} \sum_{i \in V} \xi_{i,t,k} + \sum_{k \in n} \sum_{i \in V} \xi_{i,t+H,k} \leq 1 \qquad \forall t \in \{1, \ldots E\}, \forall n \in N \qquad (32)$$
$$\sum_{k \in g} \sum_{i \in V} \xi_{i,t,k} + \sum_{k \in n} \sum_{i \in V} \xi_{i,t+H,k} \leq 1 \qquad \forall t \in \{1, \ldots E\}, \forall g \in G \qquad (33)$$
$$\lambda^U_{i,j} = \left(\sum_{k \in K} \sum_{b \in B} \varphi_{j,k,i,b} \cdot D^U_{k,b}\right)/r_j \qquad \forall i, j \in V, i \neq j \qquad (34)$$
$$\lambda^L_j = \left(\sum_{k \in K} \sum_{b \in B} \varphi_{j,k,b} \cdot D^L_{k,b}\right)/r_j \qquad \forall j \in V \qquad (35)$$
$$\varphi_{j,k,i,b} \geq \varphi_{j,k} + \omega_{i,b} - 1 \qquad \forall i, j \in V, i \neq j, \forall k \in K, \forall b \in B \qquad (36)$$
$$\varphi_{j,k,b} \geq \varphi_{j,k} + \omega_{j,b} - 1 \qquad \forall j \in V, \forall k \in K, \forall b \in B \qquad (37)$$
$$\varphi_{j,k,i,b}, \varphi_{j,k,b} \in \{0,1\} \qquad \forall i, j \in V, i \neq j, \forall k \in K, \forall b \in B \qquad (38)$$
$$\varphi_{i,k}, \xi_{i,t,k} \in \{0,1\} \qquad \forall i \in V, \forall t \in T, \forall k \in K \qquad (39)$$
$$\lambda^U_{i,j}, \lambda^L_j \geq 0 \qquad \forall i, j \in V, i \neq j \qquad (40)$$

Constraint (27) ensures one subblock can only be assigned at most to one vessel. Constraint (28) ensures a sufficient number of subblocks can be assigned to each vessel. Constraint (29) links variables $\varphi_{i,k}$ and $\theta_{i,t}$ by $\xi_{i,t,k}$. Constraints (30) and (31) ensure two subblocks, which share the same truck path or belong to the same block, cannot have a simultaneously loading process at each time step in the planning horizon.

Constraints (32) and (33) consider periodicity. Constraint (34) calculates the average of the loading route length between the berth position of vessel i and all the subblocks reserved for vessel j. Constraint (35) calculates the average loading route length between the berth position of vessel j and all the subblocks reserved for vessel j. Constraint (36) links variables $\varphi_{j,k}$ and $\omega_{i,b}$ by $\varphi_{j,k,i,b}$, while constraint (37) links variables $\varphi_{j,k}$ and $\omega_{j,b}$ by $\varphi_{j,k,b}$. Constraints (38) – (40) define the variables.