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Research Article

An Efficient Procedure for Inserting Buffers to Generate Robust Berth Plans in Container Terminals

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Uncertainty is an inevitable aspect of seaside operations in container terminals. Operators therefore need to find robust plans that can resist the impact of uncertainties. Instead of solving a stochastic berth allocation problem, this paper proposes an efficient procedure for inserting buffers into baseline berth plans to strengthen the schedule stability. Such a method is highly versatile and compatible with various solutions to berth allocation problem with different objectives. Numerical results obtained by using simulation on a representative set of instances of the problem are reported; these indicate that the proposed procedure not only increases the flexibility of operations with minor loss of resource utilization but also addresses the impact of service priority. Hence, the contribution in this paper will provide a short path that bridges the gap between berth allocation problem in deterministic and stochastic circumstances.

1. Introduction

Nowadays, average container terminal utilization levels have risen markedly across almost all regions of the world. On one hand, despite the spiral trade protectionism effect created by US-China trade tensions and Brexit, a milestone with total seaborne trade volumes amounting to 11 billion tons was reached in 2018, and an estimated 793.26 million TEUs were handled in container terminals worldwide. Moreover, with sustained deliveries of mega container ships, container fleet supply capacity increased by 6% in 2018 as compared to 4% in 2017 [1]. On the other hand, container terminal capacity expansion remains relatively subdued following lower investment willingness of port investors and government in recent years. The increasing traffic along with fierce competition between neighboring ports has forced port operators to promote operation efficiency [2]. Among the optimization decisions, solving the berth allocation problem (BAP), which consists in assigning vessels to berths subject to vessel arrival and departure times and size constraints, is the very first level of terminal planning. A proper berth plan can reduce the total vessel stay time, which reflects the service quality, and increase the overall competitiveness of the terminal [3].

In addition, operations in container terminals often suffer from uncertain events, including vessel arrival delays, variations in loading/unloading process times, mechanical failures, and others. These uncertainties can interrupt the baseline schedules and negatively affect the overall efficiency of ports; they can incur high recovery costs such as contract penalties, as well as additional labour and equipment. Methods to generate robust berth plans are therefore desirable for port operators.

Many studies of BAP have been published over the past two decades. For detailed reviews, the reader is referred to Bierwirth and Meisel [4, 5] and Carlo et al. [6]. Among various performance measures of berth allocation models, minimizing tardy vessel departures is considered as one of the most significant [7, 8]. On the contrary, Zhen [9] and Kordic et al. [10] argued that each vessel had a preferred berthing time or operation starting time, and it should be regarded as benchmark instead of departure time for a berth plan, i.e., a cost penalty applied if the vessel berthed late. Such idea is consistent with the concept of schedule stability in project scheduling, which will be adopted as the performance measure in this research.

Only a handful of research has addressed the BAP under stochastic circumstance, most of which adopted the robust optimization (RO) method. For example, Han et al. [11] proposed a simulation-based genetic algorithm and solved the integrated berth allocation and quay crane assignment problem. A similar method was adopted by Golias et al. [12] to minimize the performance differences between best and worst cases. More recently, Xiang et al. [13] incorporated customer satisfaction with economic performances and introduced a bi-objective model; they solved the problem by an adapted grey wolf algorithm. Problems with similar objectives were also studied in their additional papers [14, 15]. Furthermore, Liu et al. [16] used uncertainty sets to describe the possible scenarios without depending on probabilistic information and adopted a two-stage robust optimization approach. Another common technique, stochastic programming, was also reported in publications. Zhen et al. [17] formulated the problem as a scenario-based mixed integer programming model. In the following research, the tactical BAP was studied by using a similar method [9]. Ursavas and Zhu [18] characterized optimal policies for different types of calling vessels. Besides, some researchers have made contributions to reactive strategies to deal with uncertainties. Schepler et al. [19] built a dynamic management procedure with a rolling horizon algorithm to adjust the baseline schedules, while Umang et al. [20] proposed a series of recovery strategies. Meanwhile, Xiang et al. [21] addressed a reactive strategy for integrated berth allocation and quay crane assignment problem.

Generating robust schedules by building buffers in the operational plan has been recognized as a powerful tool and applied in various scheduling problems. Research can be found in the area of machine scheduling [22], project scheduling [23], and flight scheduling [24]. Buffer time was introduced in BAP by Xu et al. [25], in which an identical buffer was added to each vessel. Another method of inserting buffers was proposed in Zhen and Chang [26]; they presented a modified objective to maximize the idle time between successive vessels. Both papers incorporated buffers into their models and solved the problems by heuristics, which derived suboptimal solutions and might be time-consuming when problem scales were large due to the NP-hardness of BAP [27]. Hence, an efficient method regardless of the model is needed.

Combining the production practices and a literature review, we see a need for a more efficient way of inserting buffers. Therefore, unlike the aforementioned studies, the present study focuses on improving the robustness of predefined berth plans by proposing a novel float factor model for berth plan adjustments [28]. The main contribution is twofold: an efficient procedure for inserting buffers is developed to generate robust baseline schedules with acceptable economic performances and solution stability in the presence of stochastic operation times, and the impact of critical attributes of BAP, such as service priority, and the choices of scheduling strategies are thoroughly analyzed. This study is crucial not only for bridging the gap between deterministic BAP and stochastic BAP in academic research but also for the practical value for seaside operations in container terminals.

2. Methods

In this section, we briefly explain how berth plans work in container terminals at first. Then, the procedure for inserting buffers is presented in detail.

2.1. Problem Description. In general, a berth plan is presented in a time-space two dimensional diagram as shown in Figure 1, where each rectangle represents the operation of corresponding vessel. Port operators will make a berth plan in advance based on the estimated information of all V vessels calling at the port in next planning horizon. For vessel $i \in V$, two decisions should be made simultaneously. The first is the berthing time, or operation starting time s_i, which is related to vessel arrival time a_i, processing time p_i, and required departure time in timetable d_i. It should be noted that earlier departure is welcomed by shipping liners because it promotes the flexibility of following voyage [29]. Besides, it is also encouraged by port operators since it releases quay space and cranes for other vessels, which can improve the overall operation efficiency. Hence, d_i should be considered as a reference instead of a constraint. The second is the berthing position b_i, which concerns the availability of quay space, the assignment of yard template, the and physical constraints, such as water depth and quay crane service range. A berth plan is feasible if no overlaps of rectangles exist in the diagram. Furthermore, a berth plan with smaller total departure delays, *i.e.*, $\sum_i (s_i + p_i - d_i)^+$, where $(\bullet)^+$ indicates $\max(\bullet, 0)$ is recognized as a better plan. All the notations used for berth plans are listed in Table 1.

Due to uncertainties, the actual schedule might vary from the original plan. In Figure 1, vessel 1 is supposed to berth at s_1. However, an uncertain event, e.g., late arrival, forces vessel 1 to start its operation at s_1^r. Consequently, vessel 3 must wait until vessel 1 releases the quay space to start its own operation since reassigning a berthing position requires a reschedule for entire systems including quay cranes, yard templates, and inner transportation trucks, which can yield unacceptable recovery cost. Furthermore, extra time is needed to finish vessel 3's operation because of uncertain events such as shortage of available cranes (frequently happens to delayed vessels in practice), resulting in a late departure for vessel 3 at d_3^r. Such chain reaction in coastal operations can negatively affect the overall performance of the berth plan and eventually leads to low customer satisfaction. Thus, methods for generating robust berth plans should be developed to leave more space for potential adjustment. Particularly, given the uncertainties during execution, one would like the actual schedule to resemble the baseline schedule as much as possible. In this paper, the deviation of actual operation starting time s_i^r from the assigned value s_i for vessel i is adopted as the indicator of robustness.

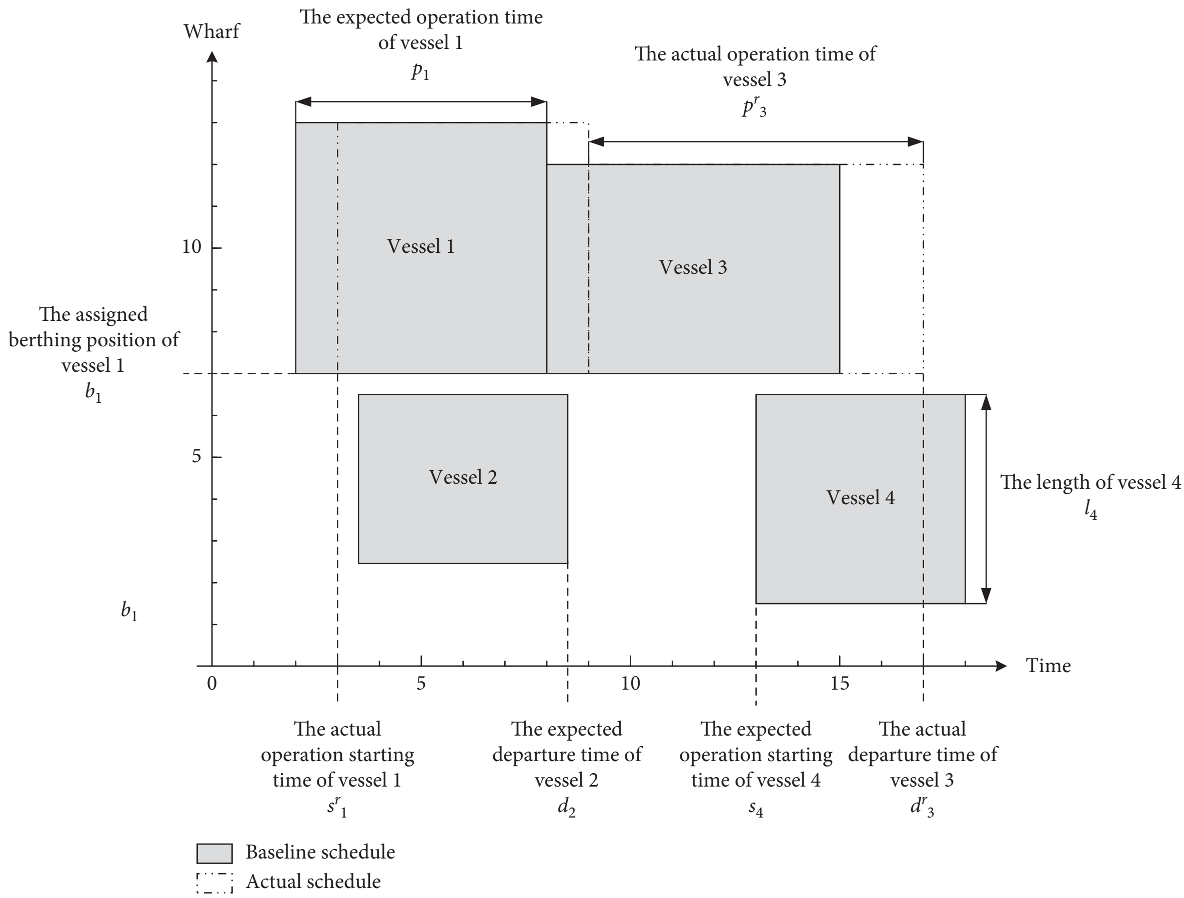

Figure 1: Time-space two dimensional diagram for a berth plan.

Table 1: The notations used for berth plans.

V	The set of vessels, $i, j \in V = \{1, 2, \ldots, \lvert V\rvert\}$
a_i	The estimated arrival time of vessel i
p_i	The estimated processing time of vessel i
d_i	The required departure time of vessel i
l_i	The length of vessel i
s_i	The assigned operation starting time of vessel i
b_i	The assigned berthing position of vessel i
a_i^r	The actual arrival time of vessel i in reality
p_i^r	The actual processing time of vessel i in reality
d_i^r	The actual departure time of vessel i in reality

Table 2: Data settings of the example instance.

Vessel no.	a_i	p_i	l_i	d_i	b_i	s_i	w_i
1	11	18	11	42	0	11	1
2	32	34	13	104	0	36	1
3	4	13	10	22	34	4	1
4	37	38	14	119	13	37	1
5	15	22	12	55	22	15	1
6	21	26	12	72	34	21	1
7	34	36	13	111	33	47	1
8	15	21	11	54	11	15	1
9	43	42	14	136	46	57	1
10	27	30	13	89	47	27	1

2.2. Procedure for Inserting Buffers. In the canonical float factor model in project scheduling developed by Tavares et al. [28], the starting time of activity i is calculated as $s_i = s_i(\mathrm{ES}) + \alpha[s_i(\mathrm{LS}) - s_i(\mathrm{ES})]$, where $\alpha \in [0, 1]$ is defined as float factor and $s_i(\mathrm{ES})$ and $s_i(\mathrm{LS})$ denote the earliest possible starting time and latest allowable starting time of activity i, respectively. As discussed before, the canonical method cannot be applied on berth plan directly because of the more complex constraints. Therefore, a modified procedure with four steps is proposed in this paper.

To clarify the details, an example instance of 10 vessels with identical weight coefficients $w_i = 1$ is adopted as the vehicle of demonstration. Table 2 lists the data settings of the example instance. Meanwhile, an optimal solution with the objective of minimizing total vessel delays is obtained by using optimization software CPLEX; the mathematical model of the deterministic BAP is provided in the first subsection of Supplementary Materials, and the corresponding time-space diagram is depicted in Figure 2. It should be noted that the example instance adopts the so-called continuous berth, in which vessels are allowed to moor anywhere within the quay space. The other type of berth is the discrete berth, where the wharf is divided into a finite set of berth segments so that one berth can serve only one vessel at a time. As reported in literature, the continuous berth can lead to better quay utilization, yet the related problem is more complex to solve [5]. The proposed

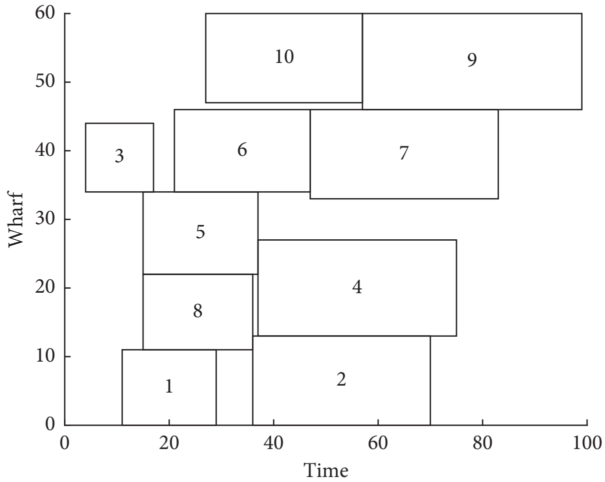

Figure 2: The baseline berth plan of the example instance.

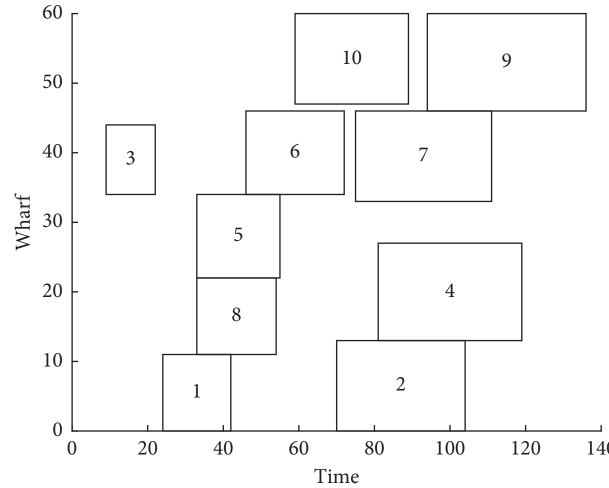

Figure 3: The right-justified berth plan of the example instance.

procedure in this study is suitable for both types of problems because the assigned berthing position for each vessel, i.e., b_i, remains unchanged throughout the procedure, which means the adjustments of baseline berth schedule will not incur any conflicts with berth boundaries. We here choose the continuous berth in the example instance to present a more thoroughly illustration of the procedure.

2.2.1. Generating the Right-Justified Plan. The first step of the proposed procedure is to obtain the latest allowable operation starting time s_i^l of each vessel i, i.e., moving the rectangles in the time-space diagram to their right-most positions without exceeding the required departure times. Meanwhile, the non-overlapping constraints should still be followed to maintain the feasibility of the adapted berth plan. Therefore, a heuristic is developed for generating the right-justified plan and described as follows:

Step 1: sort all the vessels in descending order of $s_i + p_i$ $(i \in V)$, i.e., the departure time in baseline plan. Define set R to restore the vessels that have been right-justified. Denote parameter t as time reference.

Step 2: for the ith vessel, if $s_i + p_i \geq d_i$, set $s_i^l = s_i$ and go to Step 5.

Step 3: define set A to restore the successors of vessel i, $A = \left\{ j \in R | b_j < b_i + l_i, b_i < b_j + l_j, s_i + p_i \leq s_j^l \right\}$. If $A = \emptyset$, set $t = \infty$. Otherwise, set $t = \min\left\{ s_j^l | j \in A \right\}$.

Step 4: if $d_i \leq t$, set $s_i^l = d_i - p_i$. Otherwise, set $s_i^l = t - p_i$.

Step 5: add i into R and move to the next vessel in V unless all the vessels have been right-justified in the diagram.

Figure 3 presents the right-justified berth plan of the example instance in Figure 2, where each vessel has been moved to the right-most allowable position without changing the berthing position by using the above heuristic. Such plan maintains feasible yet is not efficient enough. Therefore, further adjustments need to be carried out.

2.2.2. Updating the Weight Coefficients. The weight coefficient reflects the service priority of each vessel. A more important costumer's vessel will have a higher service priority; this is guaranteed by assigning a larger weight coefficient to the vessel. For those vessels with large coefficients, their operations should resemble the baseline schedule as much as possible to increase the customer satisfaction. However, considering the original and right-justified berth plans, the operations of some vessels are not likely to be affected due to physical constraints. Consequently, their weight coefficients should be set to 0 for the convenience of calculation. The detailed method for recognizing such vessels are as follows:

Step 1: for the ith vessel in V, define set B to restore neighboring vessels of i, $B = \left\{ j \in V | b_j < b_i + l_i, b_i < b_j + l_j, s_j < s_i < s_j^l + p_j \right\}$. If $B = \emptyset$, set $w_i = 0$.

Step 2: repeat Step 1 until all the vessels in V have been checked.

The updated weight coefficients of the example instance are presented in Table 3. Since only 10 vessels are considered, the berth plan is quite "loose" and the weight coefficients of 5 vessels are set to 0. This simple method can sufficiently reduce the searching space in following operations, especially when more vessels are calling at the port.

2.2.3. Calculating the Accumulative Weights. Before obtaining the weight coefficient-based float factor for each vessel, the two key parameters, i.e., the accumulative weights of predecessor vessels α_i and successor vessels β_i for vessel i should be calculated. However, in a berth plan, not only the transitive predecessors and successors but also other vessels that share the same quay space should be considered. Therefore, two heuristics are designed to search for related vessels forwards and backwards, respectively. The first heuristic is responsible for calculating α_i and is described as follows:

Step 1: sort all the vessels in V in ascending order of s_i. Define set $F(i)$ to restore the predecessor vessels of i.

Table 3: Calculation of starting times for example instance.

Vessel no.	s_i	s_i^l	ft_i	w_i	α_i	β_i	λ_i	s_i^r
1	11	24	13	0	0	6	0	11
2	36	70	34	1	1	5	0.167	42
3	4	9	5	0	0	7	0	4
4	37	81	44	1	1	5	0.167	44
5	15	33	18	0	0	7	0	15
6	21	46	25	1	1	6	0.143	25
7	47	75	28	1	2	5	0.286	55
8	15	33	18	0	0	7	0	15
9	57	94	37	1	1	5	0.167	63
10	27	59	32	0	0	6	0	27

Step 2: for the ith vessel in V, if $w_i = 0$, set $\alpha_i = 0$, $F(i) = \varnothing$, and go to Step 4.

Step 3: set $F(i) = \{j \in V | b_j < b_i + l_i, b_i < b_j + l_j, s_j < s_i\}$. For each $j \in F(i)$, reset $F(i) = F(i) \cup F(j)$, and remove the duplicate vessels from $F(i)$. Then calculate $\alpha_i = \sum_{j \in F(i)} w_j + w_i$.

Step 4: repeat Steps 2 and 3 until all the vessels have been checked.

Likewise, the second heuristic is developed to calculate β_i and is described as follows:

Step 1: denote W as the total weight of all vessels, $W = \sum_{i \in V} w_i$. Sort all the vessels in V in descending order of s_i. Define set $B(i)$ to restore the successor vessels of i.

Step 2: set $B(i) = \{j \in V | b_j < b_i + l_i, b_i < b_j + l_j, s_i < s_j, w_j \neq 0\}$. For each $j \in B(i)$, reset $B(i) = B(i) \cup B(j)$, and remove the duplicate vessels from $B(i)$.

Step 3: if $B(i) = \varnothing$, set $\beta_i = W$. Otherwise, set $\beta_i = \sum_{j \in B(i)} w_j + W$.

Step 4: repeat Step 2 and 3 until all the vessels have been checked.

The results of the example instance are listed in Table 3. By now, the main parameters that impact the starting time of each vessel have been obtained, which lays the foundation for generating the robust berth plan.

2.2.4. Obtaining the Robust Plan. In this final step, the operation starting time s_i^r of each vessel i in the robust berth plan is calculated based on s_i, s_i^l, α_i, and β_i. The process is as follows:

Step 1: calculate the float time ft_i by $\text{ft}_i = s_i^l - s_i$.

Step 2: calculate the float factor λ_i by $\lambda_i = \alpha_i / (\alpha_i + \beta_i)$.

Step 3: calculate the operation starting time s_i^r by $s_i^r = s_i + \lambda_i \cdot \text{ft}_i$.

Again, the results of example instance are shown in Table 3, in which s_i^r is rounded to the nearest integer, and the robust berth plan generated by the above procedure is presented in Figure 4. Compared with the original plan in Figure 2, buffers to resist the impact of possible delays have been inserted between successive vessels, while the expected departure time of each vessel is not as late as in the right-justified plan in Figure 3.

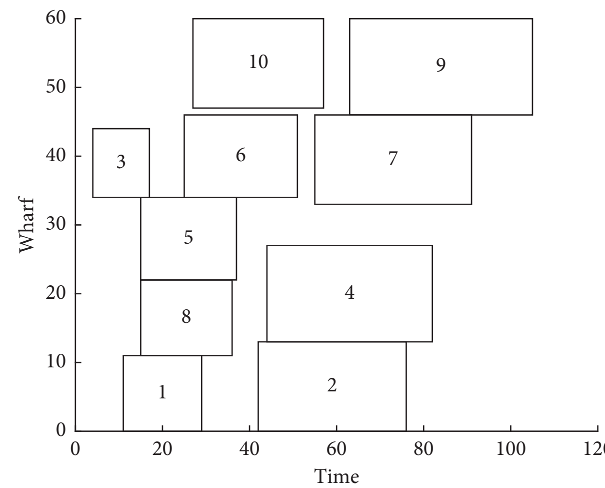

Figure 4: The robust berth plan of the example instance.

3. Results and Discussion

In this section, the berth plans generated by proposed procedure will be validated by using simulation studies. And, the total deviation of operation starting time in randomly generated scenarios with uncertain factors is chosen as the indicator of robustness. If at time s_i (or time s_i^r in robust plans), vessel i cannot start its operation due to the delays of predecessor vessels; it should wait until the assigned quay space becomes available and the actual operation starting time is denoted as $\tilde{s}_i$. Such policy is commonly referred to as right-shift strategy in BAP [13] or railway scheduling [30]. Evidently, late arrival of one vessel can also lead to delayed operation starting time. However, such delay is not caused by the berth plan and therefore should not be included when testing the plan performances with aforementioned indicator. Hence, in following experiments, only the uncertain operation time is considered.

In this study, the data are generated based on Xiang et al. [13] and Xu et al. [25], in which the experiments consider a 1200 meters wharf on a weekly basis. A length unit of 20 meters and a time unit of 5 minutes are adopted. The arrival time a_i, estimated operation time p_i, vessel length l_i, and required departure time in timetable d_i are randomly generated in the intervals [1, 2016], [60, 252], [10, 15] and $[a_i, a_i + p_i + 60]$ (time units), respectively.

Denote the original berth plans as S_1; these are generated by a genetic algorithm (GA) developed by Frojan et al. [31] since CPLEX cannot solve large scale problems in acceptable time. The main procedure of GA is presented in Supplementary Materials, and the robust berth plans derived by the proposed procedure are denoted as S_2. Both S_1 and S_2 will be tested on ω identical scenarios that are randomly generated with actual vessel operation time $\tilde{p}_i$ in $[p_i, 1.1p_i]$ (time units). For each test with different numbers of vessels (V = 15, 20, 25, 30, 35, 40), $\omega = 1000$ scenarios are generated and the average values are reported in Table 4, in which the

Table 4: Average performances of solutions to 1000 scenarios.

Number of vessels V	Δs(time units)		IR(%)
	S_1	S_2	
15	9.24	1.39	84.96
20	15.94	8.44	47.05
25	20.42	14.62	28.40
30	51.32	39.97	22.12
35	59.94	52.39	12.60
40	111.59	95.35	14.55

deviations of operation starting time is calculated as $\Delta s(S_1) = (1/\omega)\sum_{\omega}\sum_i(\tilde{s}_i - s_i)$, $\Delta s(S_2) = (1/\omega)\sum_{\omega}\sum_i(\tilde{s}_i - s_i^r)$, and the improvement ratio $\mathrm{IR} = ((\Delta s(S_1) - \Delta s(S_2))/\Delta s(S_1)) \times 100\%$.

The results show satisfied robustness improvement of the proposed procedure under uncertainty. For small scale problems, the total deviation of operation starting time of S_1 can be reduced by up to more than 80%. While with more vessels calling at the port, the problem of congestion may lead to unstable berth plans, whereas S_2 still outperforms S_1 with $\mathrm{IR} > 10\%$.

The distribution of the total operation starting time deviation for problem with 30 vessels in 1000 scenarios is presented in Figure 5, in which in 67.2% of all cases, S_2 can guarantee a total operation starting time deviation that is less than 40 and this number is 41.9% for S_1. Meanwhile, in only 4.6% of all cases the deviation is larger than 55 for S_2, compared to 17.7% for S_1. Figure 6 presents the results in 20 scenarios with 30 vessels. The two curves have a similar pattern, which indicates that uncertain events may have the same impact on both types of berth plans. Yet, S_2 always outperforms S_1 regardless of the scenarios. Therefore, it can be concluded that the berth plan generated by proposed procedure is more robust than the original plan without buffers.

Besides, the proposed procedure can generate S_2 in negligible computational time. In additional tests, the procedure takes less than one second to deal with 100 vessels instances. In Xu et al. [25], they reported that when integrated buffer time into BAP model, the optimization solver Lingo can only solve problems with less than 20 vessels, and the heuristic algorithm they developed can find approximate optimal solutions for 30 vessels instances in less than 5 minutes. Nevertheless, the computational results in Frojan et al. [31] showed that a 40 vessels instance without considering uncertain factors can be solved in 5 seconds. Therefore, by incorporating the proposed procedure into deterministic BAP is more time-efficient to generate robust berth plan.

As the results showed satisfied improvement, we then take further steps to discuss the influences of the service priority and the structure of original berth plan, respectively.

3.1. The Impact of Service Priority. In above experiments, the weight coefficient of all vessels is set to 1, which indicates that all vessels have an equal service priority. However, in practice, some vessels may be more important and their schedules should be held stable. Hence, additional experiments are needed to demonstrate the impact of different service priorities.

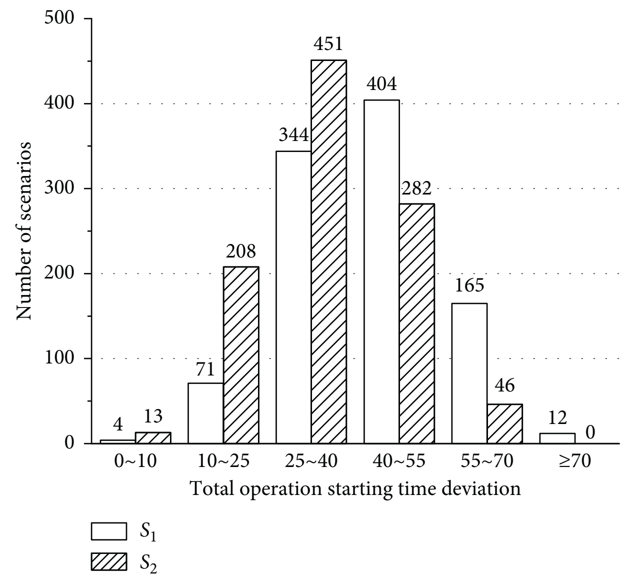

Figure 5: Distribution of total operation starting time deviation for 1000 scenarios.

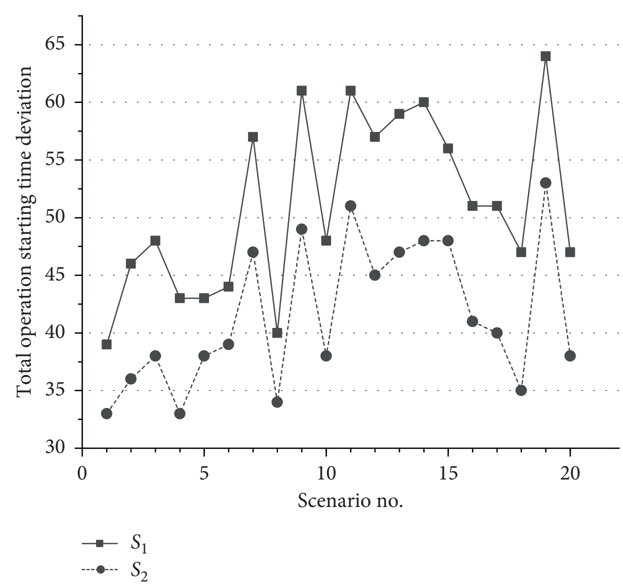

Figure 6: The total operation starting time deviation of S_1 and S_2.

In this experiment, an instance with 20 vessels is used, in which the weight coefficient of 15 vessels are set to 1 while 5 vessels are randomly selected as the important vessels. Weight coefficients ranging from 1 to 40 are assigned to selected vessels one at a time to generate different robust berth plans; these are tested by 1000 rounds of simulation with random scenarios. The average performances, i.e., the operation starting time deviation, are presented in Figure 7.

As shown in Figure 7, the operation starting time deviation of selected vessels decreases significantly with the weight coefficient increases from 1 to 5. Then, the descending trend slows down and the indicator becomes

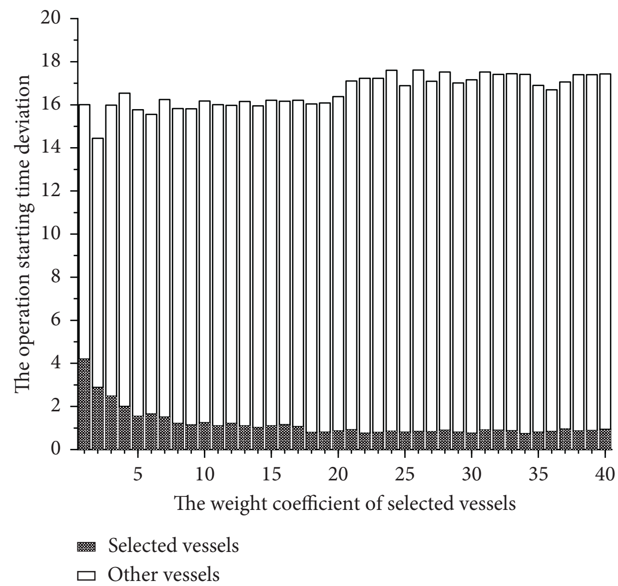

Figure 7: The operation starting time deviation for vessels with different weight coefficients.

Table 5: The performances of robust berth plans based on different original plans.

	S_1^r	S_2^r	S_3^r	S_4^r	S_5^r
Δs	15.70	13.17	26.13	18.08	28.55
RD (%)	19.21	0	98.41	37.28	116.78

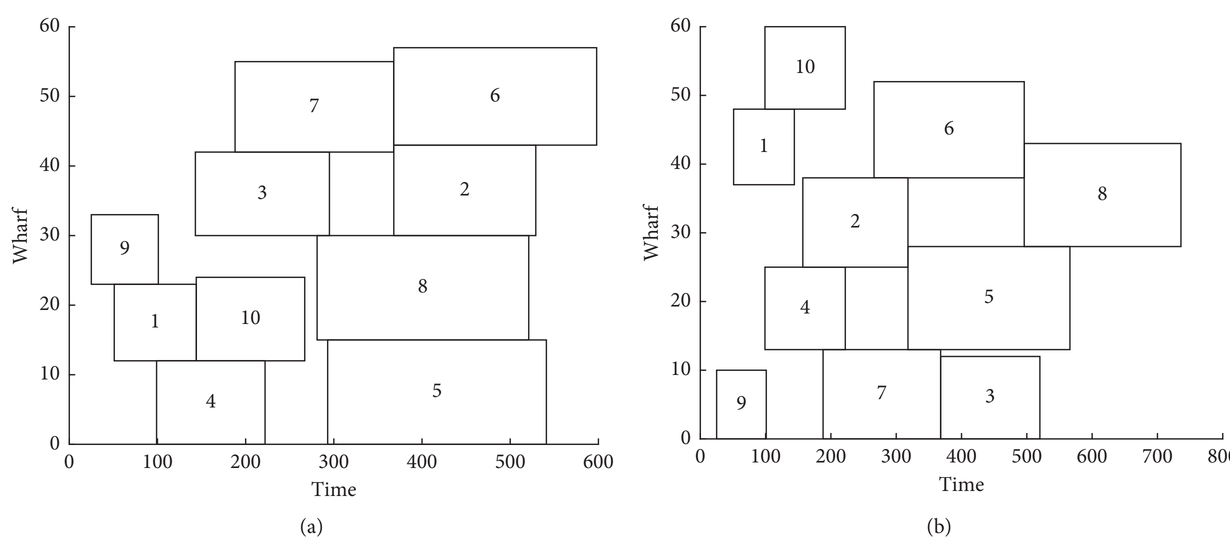

Figure 8: The (a) best and (b) worst original berth plans.

stable when the weight coefficient is around 20. On the other hand, there is a slight increase in the total operation starting time deviation of all vessels, which indicates that the operation starting time deviation of vessels with small weight coefficients (1 in the case) is increasing. These findings show that the higher service priority will lead to a more stable schedule for one vessel. However, this may affect the schedule robustness of other vessels or even the robustness of overall berth plan. Hence, one should avoid assigning too large weight coefficients to vessels.

3.2. The Impact of Original Berth Plan. Given a set of vessels, there can be more than one optimal berth plans with different structures and identical vessel total designed delays. Since the proposed procedure in this study is based on the original berth plan, the performances of obtained robust berth plans may be affected when different original berth plans are adopted.

To test the impact, 5 original berth plans denoted as S_1^r, S_2^r, S_3^r, S_4^r, and S_5^r are generated with a set of 10 vessels. In each of these plans, all the vessels can finish the operations before required departure times in timetable. Then, robust berth plans based on the original plans are generated with proposed procedure and are tested in 1000 rounds of simulation. The average total operation starting time deviations Δs are given in Table 5, along with the relative difference (RD) defined as $\mathrm{RD}_{\mathrm{plan}} = ((\mathrm{RD}_{\mathrm{plan}} - \mathrm{RD}_{\mathrm{best}})/\mathrm{RD}_{\mathrm{best}}) \times 100\%$.

As shown in Table 5, S_2^r derives the best performance while S_5^r obtains the worst performance. The relative difference can be more than 110%, which indicates the importance of original berth plan. To further investigate the berth plan structure, S_2^r and S_5^r are depicted in Figures 8(a) and 8(b), respectively. Comparing the two berth plans, the major difference is the location of the right-most vessels. In S_5^r, although vessels 3 and 8 are scheduled to finish their operations in time, the designed departure times are very close to their required departure times, which leaves little space for adjustments and eventually leads to low robustness plans. While in S_2^r, most of the right-most vessels maintain the possibility for right-justify. Therefore, when determining the original berth plans, one should pay extra attention to the rightmost vessels. The Earliest Due Date (EDD) policy [32] in machine scheduling should be recommended for this problem.

4. Conclusions

This research addresses the problem of generating a robust berth plan in container terminals, which is important for seaside operational systems in practice. An efficient procedure for inserting buffers is proposed, in which the operation starting time for each vessel in a predefined berth plan is reassigned. The procedure preserves the required departure times in timetable and the assigned berthing positions so that the entire terminal operational system as well as the schedules of shipping liners will not be affected. While the flexible time in a berth plan is organized as buffers to resist the impact of uncertainties, numerical experiments prove that such procedure can significantly increase the robustness of original berth plans even in congested situations. In addition, the procedure takes the service priority into consideration and can automatically promote the schedule stability for vessels with higher service priority. The trade-off between individual plan robustness and overall robustness is also demonstrated in experiments. Finally, the impact of original berth plan is discussed and the test results indicate that the right-most vessels have major influences on the performances of generated robust berth plans.

In the future, several valuable research directions can be considered. Since the proposed procedure relies on the original berth plan, it is worthy of modifying the BAP model so that solutions suitable for adopting this procedure can be obtained. The integration method may lead to better robust berth plans. Besides, with reassigned operation starting times, the quay crane schedules also need adjustments. Hence, an adaptive procedure for quay crane rescheduling should be developed. Finally, there are other ways to insert buffers, such as critical chain buffer management (CC/BM) method, the comparison of methods under different measures of robustness may provide more insights of the problem.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

The first subsection of supplementary materials provides the details of the mathematical model of BAP that we used to derive the original berth plan, in which additional notations are defined in Table S1 and the objective function as well as constraints is presented. While the genetic algorithm we adopted to solve large-scale BAPs is introduced in the second subsection of supplementary materials, where the pseudocode shows the process of the algorithm and Figure S1 presents an example of crossover operation in the algorithm to clarify the detailed procedure. (*Supplementary Materials*)

References

[1] UNCTAD, *Review of Maritime Transport 2019*, United Nations Conference on Trade and Development, Geneva, Switzerland, 2019.

[2] J. Wawrzyniak, M. Drozdowski, and É. Sanlaville, “Selecting algorithms for large berth allocation problems,” *European Journal of Operational Research*, vol. 283, no. 3, pp. 844–862, 2020.

[3] S.-W. Lin, C.-J. Ting, and K.-C. Wu, “Simulated annealing with different vessel assignment strategies for the continuous berth allocation problem,” *Flexible Services and Manufacturing Journal*, vol. 30, no. 4, pp. 740–763, 2018.

[4] C. Bierwirth and F. Meisel, “A survey of berth allocation and quay crane scheduling problems in container terminals,” *European Journal of Operational Research*, vol. 202, no. 3, pp. 615–627, 2010.

[5] C. Bierwirth and F. Meisel, “A follow-up survey of berth allocation and quay crane scheduling problems in container terminals,” *European Journal of Operational Research*, vol. 244, no. 3, pp. 675–689, 2015.

[6] H. J. Carlo, I. F. A. Vis, and K. J. Roodbergen, “Seaside operations in container terminals: literature overview, trends, and research directions,” *Flexible Services and Manufacturing Journal*, vol. 27, no. 2-3, pp. 224–262, 2015.

[7] F. Meisel and C. Bierwirth, “A framework for integrated berth allocation and crane operations planning in seaport container terminals,” *Transportation Science*, vol. 47, no. 2, pp. 131–147, 2013.

[8] K. Wang, L. Zhen, S. Wang, and G. Laporte, “Column generation for the integrated berth allocation, quay crane assignment, and yard assignment problem,” *Transportation Science*, vol. 52, no. 4, pp. 812–834, 2018.

[9] L. Zhen, "Tactical berth allocation under uncertainty," *European Journal of Operational Research*, vol. 247, no. 3, pp. 928–944, 2015.

[10] S. Kordic, T. Davidovic, N. Kovac, and B. Dragovic, "Combinatorial approach to exactly solving discrete and hybrid berth allocation problem," *Applied Mathematical Modelling*, vol. 40, no. 21-22, pp. 8952–8973, 2016.

[11] X.-l. Han, Z.-q. Lu, and L.-f. Xi, "A proactive approach for simultaneous berth and quay crane scheduling problem with stochastic arrival and handling time," *European Journal of Operational Research*, vol. 207, no. 3, pp. 1327–1340, 2010.

[12] M. Golias, I. Portal, D. Konur, E. Kaisar, and G. Kolomvos, "Robust berth scheduling at marine container terminals via hierarchical optimization," *Computers & Operations Research*, vol. 41, pp. 412–422, 2014.

[13] X. Xiang, C. Liu, and L. Miao, "A bi-objective robust model for berth allocation scheduling under uncertainty," *Transportation Research Part E: Logistics and Transportation Review*, vol. 106, pp. 294–319, 2017.

[14] C. Liu, X. Xiang, C. Zhang, and L. Zheng, "A decision model for berth allocation under uncertainty considering service level using an adaptive differential evolution algorithm," *Asia-Pacific Journal of Operational Research*, vol. 33, no. 6, pp. 1–28, 2016.

[15] C. Liu, X. Xiang, and L. Zheng, "Two decision models for berth allocation problem under uncertainty considering service level," *Flexible Services and Manufacturing Journal*, vol. 29, no. 3-4, pp. 312–344, 2017.

[16] C. Liu, X. Xiang, and L. Zheng, "A two-stage robust optimization approach for the berth allocation problem under uncertainty," *Flexible Services and Manufacturing Journal*, vol. 32, no. 2, pp. 425–452, 2020.

[17] L. Zhen, L. H. Lee, and E. P. Chew, "A decision model for berth allocation under uncertainty," *European Journal of Operational Research*, vol. 212, no. 1, pp. 54–68, 2011.

[18] E. Ursavas and S. X. Zhu, "Optimal policies for the berth allocation problem under stochastic nature," *European Journal of Operational Research*, vol. 255, no. 2, pp. 380–387, 2016.

[19] X. Schepler, S. Balev, S. Michel, and É. Sanlaville, "Global planning in a multi-terminal and multi-modal maritime container port," *Transportation Research Part E: Logistics and Transportation Review*, vol. 100, pp. 38–62, 2017.

[20] N. Umang, M. Bierlaire, and A. L. Erera, "Real-time management of berth allocation with stochastic arrival and handling times," *Journal of Scheduling*, vol. 20, no. 1, pp. 67–83, 2017.

[21] X. Xiang, C. Liu, and L. Miao, "Reactive strategy for discrete berth allocation and quay crane assignment problems under uncertainty," *Computers & Industrial Engineering*, vol. 126, pp. 196–216, 2018.

[22] D. Briskorn, J. Leung, and M. Pinedo, "Robust scheduling on a single machine using time buffers," *IIE Transactions*, vol. 43, no. 6, pp. 383–398, 2011.

[23] G. Ma, J. Jia, T. Zhu, and S. Jiang, "A critical design structure method for project schedule development under rework risks," *Sustainability*, vol. 11, no. 24, p. 7229, 2019.

[24] Y. Hong, B. Choi, K. Lee, and Y. Kim, "Dynamic robust sequencing and scheduling under uncertainty for the point merge system in terminal airspace," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 9, pp. 2933–2943, 2018.

[25] Y. Xu, Q. Chen, and X. Quan, "Robust berth scheduling with uncertain vessel delay and handling time," *Annals of Operations Research*, vol. 192, no. 1, pp. 123–140, 2012.

[26] L. Zhen and D.-F. Chang, "A bi-objective model for robust berth allocation scheduling," *Computers & Industrial Engineering*, vol. 63, no. 1, pp. 262–273, 2012.

[27] A. Lim, "The berth planning problem," *Operations Research Letters*, vol. 22, no. 2-3, pp. 105–110, 1998.

[28] L. V. Tavares, J. A. Antunes Ferreira, and J. Silva Coelho, "On the optimal management of project risk," *European Journal of Operational Research*, vol. 107, no. 2, pp. 451–469, 1998.

[29] X. Jiao, F. Zheng, M. Liu, and Y. Xu, "Integrated berth allocation and time-variant quay crane scheduling with tidal impact in approach channel," *Discrete Dynamics in Nature and Society*, vol. 2018, Article ID 9097047, 19 pages, 2018.

[30] B. C. Yan, J. G. Jin, X. N. Zhu, D. H. Lee, L. Wang, and H. Wang, "Integrated planning of train schedule template and container transshipment operation in seaport railway terminals," *Transportation Research Part E: Logistics and Transportation Review*, vol. 142, Article ID 102061, 2020.

[31] P. Frojan, J. F. Correcher, R. Alvarez-Valdes, G. Koulouris, and J. M. Tamarit, "The continuous berth allocation problem in a container terminal with multiple quays," *Expert Systems with Applications*, vol. 42, no. 21, pp. 7356–7366, 2015.

[32] Q.-K. Pan, M. Fatih Tasgetiren, P. N. Suganthan, and T. J. Chua, "A discrete artificial bee colony algorithm for the lot-streaming flow shop scheduling problem," *Information Sciences*, vol. 181, no. 12, pp. 2455–2468, 2011.