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Berth Allocation and Quay Crane Assignment Under Uncertainties

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Abstract. The integration of berth allocation problem (BAP) and quay crane assignment problem (QCAP) is an cardinal seaside operations planning, which is susceptible to uncertainties, e.g. uncertain vessels arrival and maritime market. This paper addresses the integrated optimization of BAP and QCAP under uncertainties. A stochastic programming model is formulated for minimizing the waiting time and delay departure time of vessels. Besides, numerical experiments and scenario analysis are conducted to validate the effectiveness of the proposed model.

Keywords. container terminal, stochastic programming, B&QCAP, genetic algorithm, uncertainty

1 Introduction

Maritime transportation plays an important role in driving economy growth and energizing the process of globalization, since its trade volume accounts for four fifths of the world's total merchandise trade. As the core node of maritime transportation, the efficiency of container terminal will directly affect the operation of maritime transportation. A total amount of the throughput of global container ports has achieved 802 million TEU in 2019, and it's expected to reach 973 million in 2023, according to the prediction of Drewry Shipping Consultants [1]. This means the throughput of global container ports is on the verge of a new billion era. Moreover, with increase of container vessel size, container ports are encountering another challenger, i.e. the repaid handling for mega container vessels [2].

BAP and QCAP are fundamental problems in optimizing container terminal operations, because berths and quay cranes (QCs) are the most critical resources in the front of the seaside. In particular, the integration of berth allocation and quay crane assignment secure an import position in efficient operation of container ports. Essentially, this integrated problem belongs to the intersection between the management and operations research. Up to present, plenty of studies were attempted in the integrated optimization of berth allocation and quay crane assignment in the static and deterministic environment. For a comprehensive overview, we refer to review the work given by [3,4]. However, most of the assumptions will hardly satisfied, e.g. the vessel arrival time and handling time. On the one hand, the delay of vessel arrival often occurs in the actual operation of the ports, and more than 40% of the international liners will be delayed at least one day [5]. On the other hand, the demand of maritime market has never been unchangeable, the global economic and trade, political environment and other factors have brought uncertainty to the maritime market. These uncertain events, not only made

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it difficult to determine the key parameters which are necessary for planning of berth allocation and quay crane assignment, but also lead to the baseline schedule cannot be implemented.

There are usually two strategies for coping with uncertainties: proactive and reactive strategy [6]. This paper covers both two strategies for the integrated optimization of BAP and QCAP under uncertainties. A stochastic programming model is formulated for minimizing the waiting time and delay of vessel departure. Besides, numerical experiments and scenario analysis are conducted to validate the effectiveness of the proposed model.

2 Related works

For the integration of BAP and QCAP (B&QCAP), there are many related works from different aspects, e.g. deterministic or uncertain, discrete or continuous berth, time-invariant or time variant QC assignment policy, maximizing handling efficiency or trade-off between efficiency and energy consumption, et al. In this section, we mainly reviews the studies which are highly related to the strategies for coping with the integration of BAP and QCAP under uncertainties.

Han et al. [7] studied integration of BAP and QCAP with uncertainty of container handling time and dynamic vessel arrival with different service priorities, a mixed integer programming (MIP) model is established, and a simulation based genetic algorithm search procedure is applied to generate a perturbation insensitive robust schedule proactively. Considering stochastic arrivals, Hendriks et al. [8] developed a MIP to construct a robust window-based cyclic berth plan with minimally required crane capacity in the worst vessel arrival scenario. Goliasa et al. [9] presented a mathematical model and a solution approach for the discrete berth scheduling problem, where vessel arrival and handling times are not known with certainty (given the lower and upper bounds). A robust berth schedule by minimizing the average and the range of the total service times required for serving all vessels was provided. Rodriguez-Molins et al. [10] introduced the robustness of B&QCAP by means of buffer times, which should be maximized to absorb possible incidences or break downs. To handle the uncertainty of QC productivity, the mean values of QCs were used by Shang et al. [11], and two robust models (robust optimization model and robust optimization model with price constraints) were proposed.

However, when disruptions occurred and the baseline schedule will no longer be the optimal solution, the reactive strategy should be implemented consequently. Zeng et al. [12] addressed the problem of recovering berth and quay crane schedule, the QC rescheduling strategy and berth reallocation strategy are proposed to tackle disruptions and recover the berth and QC schedule, and models for the two strategies are developed respectively. Li et al. [13] proposed a reactive recovery strategy which adjust the initial plan to handle realistic disruptions. The new berthing positions for vessels are restricted within a certain space. Quay cranes are allowed to move to other vessels before finishing current assigned vessels. Vessels requiring early dispatch are particularly considered in recovery planning. Four kinds of disruption, i.e., deviation of vessels' arrival times, deviation of vessels' operation times, calling of unscheduled vessels, and breakdown of QCs, were addressed by Xi et al. [14], and a reactive strategy was proposed, which takes the baseline schedule as the reference schedule, to deal with disruptions and minimize recovery cost. A rolling horizon heuristic is presented to derive good feasible solutions.

3 Model formulation

3.1 Notation definition

***Sets and parameters*:** V represents the set of all vessels; T represents the set of all periods; Q represents the set of all QCs; B represents the total number of berth segments; Ω represents the set of all future scenarios; M represents a large positive number; ETA_i represents the estimated arrival time of vessel i; ETD_i represents the estimated departure of vessel i; R_i^{max} represents the maximum number of QCs that can be assigned to vessel i; R_i^{min} represents the minimum number of QCs that should be assigned to vessel i; m_i represents the handling volume of vessel i (units: TEU); b_i represents the desired berthing position of vessel i; γ_q represents the handling efficiency of a QC per unit time when q QCs simultaneously serve the same vessel (units: move/h); ξ represents the handling efficiency of a QC (units: h/move); μ represents the average value of containers where a QC handled per move (units: TEU/move); L represents the length of the wharf; l_i represents the length of vessel i, including horizontal safe distance; $p(w)$ represents the probability of scenario w; $ETA_i(w)$ represents the estimated arrival time of vessel i in scenario w; $ETD_i(w)$ represents the estimated finishing time of vessel i in scenario w; $R_i^{max}(w)$ represents the maximum number of QCs that can be assigned to vessel i in scenario w; $R_i^{min}(w)$ represents the minimum number of QCs that should be assigned to vessel i in scenario w; $m_i(w)$ represents the handling volume of vessel i in scenario w (units: TEU).
***Decision variables*:** s_i represents the start berthing time of vessel i; $\mathrm{y_i}$ represents the actual berthing position of vessel i; $\mathrm{e_i}$ represents the end berthing time of vessel i; $s_i^+(w)$, $s_i^-(w)$ represent the increment and decrement of s_i in scenario w respectively; $y_i^+(w)$, $y_i^-(w)$ represent the increment and decrement of y_i in scenario w respectively; $e_i^+(w)$, $e_i^-(w)$ represent the increment and decrement of e_i in scenario w respectively; $s_i^{\Delta+}(w)$, $s_i^{\Delta-}(w)$ represent the increment and decrement with represent to $(s_i - \mathrm{EAT_i})$ in scenario w respectively; $y_i^{\Delta+}(w)$, $y_i^{\Delta-}(w)$ represent the increment (or decrement) with respect to $|y_i - \mathrm{b_i}|$ in scenario w respectively; $e_i^{\Delta+}(w)$, $e_i^{\Delta-}(w)$ represent the increment (or decrement) with respect to $(e_i - EFT_i)$ in scenario w respectively; $\triangle b_i$ represents the segment deviation of vessel i between the actual berthing position and preferred berthing position; $\triangle b_i(w)$ represents the segment deviation of vessel i between the actual berthing position and preferred berthing position in scenario ω ; X_{ij} is 0-1 decision variable, $X_{ij} = 1$, if Vessel i is located in the left of Vessel j in the 2-dimensional berth-time plane; $X_{ij} = 0$, otherwise; Y_{ij} is 0-1 decision variable, $Y_{ij} = 1$, if Vessel i is located below Vessel j in the 2-dimensional berth-time plane; $Y_{ij} = 0$, otherwise; $X_{ij}(w)$ is 0-1 decision variable, $X_{ij} = 1$, if Vessel i is located in the left of Vessel j in the 2-dimensional berth-time plane in scenario w; $X_{ij} = 0$, otherwise; $Y_{ij}(w)$ is 0-1 decision variable, $Y_{ij} = 1$, if Vessel i is located below Vessel j in the 2-dimensional berth-time plane in scenario w; $Y_{ij} = 0$, otherwise; r_{it} is 0-1 decision variable, $r_{it} = 1$, if at least one QC is assigned to vessel i in period t; $r_{it} = 0$, otherwise; $r_{it}(w)$ is 0-1 decision variable, $r_{it} = 1$, if at least one QC is assigned to vessel i in period t in scenario w; $r_{it} = 0$, otherwise; r_{itq} is 0-1 decision variable, $r_{itq} = 1$, if q QCs are assigned to

vessel i in period t; $r_{itq} = 0$, otherwise; $r_{itq}(w)$ is 0-1 decision variable, $r_{itq} = 1$, if q QCs are assigned to vessel i in period t in scenario w; $r_{itq} = 0$, otherwise.

3.2 Mathematical model

The objective function of the model is to minimize the sum of waiting time and delayed finishing time of baseline schedule and the expected value of the adjusting time in each scenarios.

$$\begin{aligned}\min f = &\sum\nolimits_{i=1}^{N}[(s_i - ETA_i) + (e_i - ETD_i)]\\ &+\sum\nolimits_{w=1}^{W}\left\{p(w)\sum\nolimits_{i=1}^{N}\left[\Delta s_i^+(w) - \Delta s_i^-(w) + \Delta e_i^+(w) - \Delta e_i^-(w)\right]\right\}\end{aligned} \tag{1}$$

$$e_i \le s_j + M(1 - X_{ij}),\quad \forall i, j \in V, i \ne j \tag{2}$$

$$\mathrm{y}_i + l_i \le y_j + M(1 - Y_{ij}),\quad \forall i, j \in V, i \ne j \tag{3}$$

$$X_{ij} + Y_{ij} + X_{ji} + Y_{ji} \ge 1,\quad \forall i, j \in V, i \ne j \tag{4}$$

$$y_i + l_i \le L,\quad \forall i \in V \tag{5}$$

$$s_i \ge ETA_i,\quad \forall i \in V \tag{6}$$

$$\sum\nolimits_{i\in V}\sum\nolimits_{q\ne Q} q\cdot\varphi_{itq} \le |Q|,\quad \forall t \in T \tag{7}$$

$$\sum\nolimits_{q\in Q} q\cdot\varphi_{itq} \le R_i^{\max}\cdot\zeta_{it},\quad \forall i \in V, t \in T \tag{8}$$

$$\sum\nolimits_{q\in Q} q\cdot\varphi_{itq} \ge R_i^{\min}\cdot\zeta_{it},\quad \forall i \in V, t \in T \tag{9}$$

$$\sum\nolimits_{q\in Q} \varphi_{itq} = \zeta_{it},\quad \forall i \in V, t \in T \tag{10}$$

$$\zeta_{it}\cdot(t+1) \le e_i,\quad \forall i \in V, t \in T \tag{11}$$

$$\zeta_{it}\cdot t + M\cdot(1 - \zeta_{it}) \ge s_i,\quad \forall i \in V, t \in T \tag{12}$$

$$\sum\nolimits_{k=1}^{B} \Delta b_{ik}\cdot k \ge |y_i - b_i|,\quad \forall i \in V \tag{13}$$

$$\sum\nolimits_{k=1}^{B} \Delta b_{ik} \le 1,\quad \forall i \in V \tag{14}$$

$$\sum_{t\in T}\sum_{q\in Q} q\cdot\varphi_{itq}\cdot\gamma_q \ge \frac{m_i}{\mu}\cdot\Delta b_i^{0.14},\quad \forall i \in V \tag{15}$$

$$\sum\nolimits_{t\in T}\sum\nolimits_{q\ne Q} q\cdot\varphi_{itq}\cdot\gamma_q \ge \frac{m_i}{\mu},\quad \forall i \in V \tag{16}$$

$$\sum\nolimits_{t\in T} \zeta_{it} = e_i - s_i,\quad \forall i \in V \tag{17}$$

$$e_i + e_i^+(w) - e_i^-(w) \le s_j + s_j^+(w) - s_j^-(w) + M\left[1 - X_{ij}(w)\right], \quad \forall i, j \in V, i \ne j, w \in \Omega \tag{18}$$

$$y_i + y_i^+(w) - y_i^-(w) + l_i \le y_j + y_j^+(w) - y_j^-(w) + M\left[1 - Y_{ij}(w)\right], \quad \forall i, j \in V, i \ne j, w \in \Omega \tag{19}$$

$$X_{ij}(w) + Y_{ij}(w) + X_{ji}(w) + Y_{ji}(w) \ge 1, \quad \forall i, j \in V, i \ne j, w \in \Omega \tag{20}$$

$$l_i \le y_i + y_i^+(w) - y_i^-(w) + l_i \le L, \quad \forall i \in V, w \in \Omega \tag{21}$$

$$s_i + s_i^+(w) - s_i^-(w) \ge ETA_i(w), \quad \forall i \in V, w \in \Omega \tag{22}$$

$$s_i - ETA_i + \Delta s_i^+(w) - \Delta s_i^-(w) = s_i + s_i^+(w) - s_i^-(w) - ETA_i(w), \quad \forall i \in V, w \in \Omega \tag{23}$$

$$\left|y_i - b_i\right| + \Delta y_i^+(w) - \Delta y_i^-(w) = \left|y_i + y_i^+(w) - y_i^-(w) - b_i\right|, \quad \forall i \in V, w \in \Omega \tag{24}$$

$$e_i - ETD_i + \Delta e_i^+(w) - \Delta e_i^-(w) = e_i + e_i^+(w) - e_i^-(w) - ETD_i(w), \quad \forall i \in V, w \in \Omega \tag{25}$$

$$\sum\nolimits_{i \in V} \sum\nolimits_{q \notin Q} q \cdot \varphi_{itq}(w) \le |Q|, \quad \forall t \in T, w \in \Omega \tag{26}$$

$$\sum\nolimits_{q \in Q} q \cdot \varphi_{itq}(w) \le R_i^{\max}(w) \cdot \zeta_{it}(w), \quad \forall i \in V, t \in T, w \in \Omega \tag{27}$$

$$\sum\nolimits_{q \in Q} q \cdot \varphi_{itq}(w) \ge R_i^{\min}(w) \cdot \zeta_{it}(w), \quad \forall i \in V, t \in T, w \in \Omega \tag{28}$$

$$\sum\nolimits_{q \in Q} \varphi_{itq}(w) = \zeta_{it}(w), \quad \forall i \in V, t \in T, w \in \Omega \tag{29}$$

$$\zeta_{it}(w) \cdot (t+1) \le e_i(w) + e_i^+(w) - e_i^-(w), \quad \forall i \in V, t \in T, w \in \Omega \tag{30}$$

$$\zeta_{it}(w) \cdot t + M \cdot \left[1 - \zeta_{it}(w)\right] \ge s_i + s_i^+(w) - s_i^-(w), \quad \forall i \in V, t \in T, w \in \Omega \tag{31}$$

$$\sum\nolimits_{k=1}^{B} \Delta b_{ik}(w) \cdot k \ge \left|y_i(w) + y_i^+(w) - y_i^-(w) - b_i\right|, \quad i \in V, w \in \Omega \tag{32}$$

$$\sum\nolimits_{k=1}^{B} \Delta b_{ik}(w) \le 1, \quad i \in V, w \in \Omega \tag{33}$$

$$\sum_{t \in T} \sum_{q \in Q} q \cdot \varphi_{itq}(\omega) \cdot \gamma_q \ge \Delta b_i(\omega)^{0.14} \frac{m_i(\omega)}{\mu}, \quad i \in V, \omega \in \Omega \tag{34}$$

$$\sum\nolimits_{t \in T} \sum\nolimits_{q \notin Q} q \cdot \varphi_{itq}(w) \cdot \gamma_q \ge \frac{m_i(w)}{\mu}, \quad i \in V, w \in \Omega \tag{35}$$

$$\sum\nolimits_{t \in T} \zeta_{it}(w) = e_i + e_i^+(w) - e_i^-(w) - \left[s_i + s_i^+(w) - s_i^-(w)\right], \quad \forall i \in V, w \in \Omega \tag{36}$$

$$\Delta b_i = \left|y_i - b_i\right| / L_s, \quad \forall i \in V \tag{37}$$

$$X_{ij}, Y_{ij}, X_{ij}(w), Y_{ij}(w) \in \{0,1\}, \quad \forall i, j \in V, w \in \Omega \tag{38}$$

$$\zeta_{it}, \varphi_{itq}, \zeta_{it}(w), \varphi_{itq}(w) \in \{0,1\}, \quad \forall i \in V, t \in T, q \in Q, w \in \Omega \tag{39}$$

$$\Delta b_i, \Delta b_i(w) \in \{0,1\}, \quad \forall i \in V, w \in \Omega \tag{40}$$

$$s_i(w), s_i^+(w), s_i^-(w), e_i(w), e_i^+(w), e_i^-(w) \geq 0, \quad \forall i \in V, w \in \Omega \tag{41}$$

$$\Delta s_i^+(w), \Delta s_i^-(w), \Delta e_i^+(w), \Delta e_i^-(w), y_i \geq 0, \quad \forall i \in V, w \in \Omega \tag{42}$$

Constraints (2)-(3) define the berth position and order of any two vessels. Constraint (4) ensures there is no overlap among all vessels in the 2-dimensional berth-time plane. Constraint (5) ensures the positions of all vessels are restricted by the length of the terminal. Constraint (6) implies that the start berthing time cannot earlier than the expected arrival time. Constraint (7) ensures that the number of QCs assigned to all vessels cannot exceed the total number of available QCs in any time segments. Constraints (8)-(9) ensure that the number of QCs assigned to a vessel must not be greater than the maximum number of QCs allowed to serve simultaneously, and not be smaller than the minimum number of QCs should be assigned. Constraint (10) determines the relationship between r_{itq} and r_{it}. Constraint (11) ensures that there is no QC assigned to vessel i after it departs. Constraint (12) ensures that there is no QC is assigned to vessel i before it arrives. Constraints (13) defines the number of berth deviation segments of vessel i. Constraint (14) ensures that the number of berth deviation segments of vessel i takes only one specific value. Constraints (15) ensure that QC assignments for a vessel must satisfy the vessel's real QC hours demand considering the QCs' idle times as the result of berthing deviation. Constraint (16) ensures that QC assignments for a vessel must satisfy the vessel's QC hours demand without the berthing deviation. Constraint (17) determines the relationship between the handling time and the start berthing time or the end berthing time. Constraints (18)-(19) define the berth position and order of any two vessels after adjusting vessels' schedules. Constraint (20) implies there is no overlap among all vessels in the 2-dimensional berth-time plane after adjusting vessels' schedules. Constraint (21) ensures the positions of all vessels are restricted by the length of the terminal in varied scenario. Constraint (22) implies that the newly planned start berthing time cannot earlier than the expected arrival time. Constraint (23) builds the relationship between the adjustments of start berthing time ($s_i^+(w), s_i^-(w)$) and the change of waiting time ($s_i^{\Delta+}(w), s_i^{\Delta-}(w)$). Constraint (24) builds the relationship between the adjustments of actual berthing position ($y_i^+(w), y_i^-(w)$)) and the change of deviation from the best berthing position ($y_i^{\Delta+}(w), y_i^{\Delta-}(w)$). Constraint (25) builds the relationship between the adjustments of end berthing time ($e_i^+(w), e_i^-(w)$) and the change of delayed finishing time ($e_i^{\Delta+}(w), e_i^{\Delta-}(w)$). Constraint (26)-(27) ensure that the newly planned number of QCs assigned to a vessel must not be greater than the maximum number and not be smaller than the minimum number of QCs should be assigned. Constraint (28) ensures that the newly planned number of QCs assigned to all vessels cannot exceed the total number of available QCs in any time segments. Constraint (29) determines the relationship between $r_{itq}(w)$ and $r_{it}(w)$. Constraint (30) ensures that there is no QC assigned to vessel i after it departs. Constraint (31) ensures that there is no QC assigned to vessel i before it arrives. Constraint (32) defines the newly planned number of berth deviation segments of vessel i. Constraint (33) ensures that the newly planned number of berth deviation segments of vessel i takes only one specific value. Constraint (34) ensure that QC assignments for a vessel must satisfy the vessel's real QC hours demand considering berthing deviation in varied scenario. Constraint (35) ensures that QC assignments for a vessel must satisfy the vessel's QC hours demand without the berthing deviation in varied scenario. Constraint (36) determines the relationship between handling time and newly planned actual start berthing time or actual end berthing time. Constraints (37) calculates the deviation of berthing position. (38)-(42) define the integer or binary variables.

4 Numerical experiments

To verify the effectiveness of the proposed model, we compare the results between the proposed model (M1) and the traditional model (M2), which only the proactive strategy is used (the recovery schedule is not included). Table 1 and Table 2 are the comparison results with vessels delay and containers increased respectively, and it shown that the proposed model has a better efficiency to deal with uncertainties.

Table 1. Results with vessels delay.

$\lvert V \rvert$	$\lvert \Omega \rvert$	Delayed Vessels	Delay time	M1	M2	$GAP(\%)$
8	5	1	1 h	390	450	15.38
8	5	2	1 h	420	480	14.29
8	5	3	1 h	450	510	13.33
8	5	1	2 h	420	480	14.29
8	5	2	2 h	480	540	12.50
8	5	3	2 h	540	600	11.11
8	5	1	3 h	450	510	13.33
8	5	2	3 h	540	600	11.11
8	5	3	3 h	630	690	9.52

Table 2. Results with vessel containers increased.

$\lvert V \rvert$	$\lvert \Omega \rvert$	Altered Vessels	Altered volume	M1	M2	$GAP(\%)$
8	5	0.10	40	360	420	16.67
8	5	0.10	40	360	420	16.67
8	5	0.10	40	360	420	16.67
8	5	0.10	80	372	432	16.13
8	5	0.10	80	378	438	15.87
8	5	0.10	80	402	462	14.93
8	5	0.10	120	390	450	15.38
8	5	0.10	120	426	486	14.08
8	5	0.10	120	450	510	13.33

5 Conclusions

This paper studied the integrated optimization of BAP and QCAP under uncertainties. A stochastic programming model is formulated for minimizing the waiting time and delay departure time of vessels. Besides, numerical experiments and scenario analysis are conducted to validate the effectiveness of the proposed model. The results can help port operators to generate a better schedule for dealing with the impact of various uncertainties. Furthermore, it will improve operational efficiency, reduce operating costs and bring economic benefit to terminal operators. However, there are still some limitations in this paper. For example, the increase of uncertain parameters will increase the scale of the experiment in geometric series. The scale of the experiment is also limited to small-scale experiments. In addition to the above factors, we will concern the impact of the probability fluctuation of the scene on the plan as well in the future.

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