

# A Review on Integrated Optimization of Berth and Quay Crane Resources in Container Terminals: Coordination Mechanisms and Uncertainty Handling

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**Abstract:** This paper presents a systematic review of 43 studies on the integrated optimization of berth and quay crane (QC) resources in container terminals published over the past decade. Building upon previous reviews, this paper focuses on three core directions: (1) integrated optimization of berth allocation, QC assignment/scheduling; (2) collaborative optimization with other terminal decisions such as yard space allocation; and (3) optimization under uncertain environments. Regarding the core integration, three sub-streams are identified: time-invariant QC assignment suitable for stable scenarios, time-variant QC assignment that better captures dynamic operations, and QC scheduling addressing conflict avoidance and efficiency improvement. Collaborative optimization has expanded from simple berth-crane integration to multi-resource coordination involving yard, trucks, tugboats, pilotage, shore power, and tides, while also incorporating green port objectives. For uncertainty handling, three mainstream paradigms are summarized: robust optimization, reactive rescheduling, and distributionally robust optimization. Despite significant progress, current research still faces limitations, including insufficient depth of multi-decision coupling, inadequate refinement in handling multi-source uncertainties, and a gap between research scenarios and real-world operations. Future research should focus on constructing full-chain coordination mechanisms, accurately addressing multi-source uncertainties, expanding novel operational scenarios, and enhancing the practicality of solution algorithms, thereby promoting deeper integration of theoretical models with practical terminal operations.

**Keywords:** Berth allocation; quay crane assignment/scheduling; Integrated optimization; Container terminal operations; Uncertainty; Literature review

## 1. Introduction

Port operation efficiency is a core issue in the global shipping and supply chain domain. Berths and quay cranes (QCs) are the two most critical types of resources for

container terminals to serve vessels. The corresponding decisions—berth allocation, QC assignment, and QC scheduling—directly determine vessel operation efficiency, terminal service level, and operation costs. Therefore, their integrated optimization has become a research focus in the field of port operation management.

Several literature reviews have systematically surveyed the research on berth allocation and QC assignment problems. Among them, Bierwirth and Meisel classified and reviewed over 120 publications on the integrated optimization of berth allocation, QC assignment, and scheduling published between 2009 and 2014, identifying research trends, solution methods, and evaluation approaches, and outlining future research directions [1]. Rodrigues and Agra provided a systematic review of studies on berth allocation and its integration with QC assignment/scheduling under uncertainty, covering the period from 2006 to 2021. That review categorized the relevant literature into three main classes: proactive, reactive, and proactive/reactive strategies, summarized methods such as stochastic programming, robust optimization, and fuzzy programming, and identified sources of uncertainty, objective functions, solution methods, as well as future research directions [2]. Building on the above reviews, this paper continues to analyze the literature on the integrated optimization of berth allocation, QC assignment/scheduling published in the past decade (approximately 2017 to present), focusing on the following three directions: (1) integrated optimization of berth allocation, QC assignment/scheduling; (2) collaborative optimization of this integrated problem with decisions such as yard space allocation; and (3) optimization of this integrated problem under uncertain environments.

## 2. Introduction Integrated Optimization of Berth Allocation and Quay Crane Assignment/Scheduling

The integrated optimization of berth allocation and QC assignment/scheduling is a core component of efficient operations in container terminals, directly determining terminal operation efficiency, vessel turnaround speed, and resource utilization. This section systematically reviews and summarizes the research status of the berth-

crane integrated optimization problem from three perspectives: time-variant QC assignment strategy, time-invariant QC assignment strategy, and QC scheduling.

### 2.1. Time-Invariant Quay Crane Assignment Strategy

Under the time-invariant assumption for QC assignment, a vessel is assigned a fixed number and fixed set of cranes throughout its entire operation period. The resulting model is structurally concise and facilitates the development of exact solution methods, making it suitable for medium- to long-term scheduling scenarios where operational plans are relatively deterministic with few disruptions. Correcher et al. addressed the time-invariant BACAP and BACASP under continuous berth environments by formulating a MILP model that does not require spatial discretization of the terminal. They strengthened the model with several families of valid inequalities and designed an iterative solution framework along with a branch-and-cut exact algorithm, capable of solving instances with up to 50 vessels to optimality [3]. Cheimanoff et al. tackled a specific time-invariant QC assignment problem under continuous berths. They proposed a compact MILP model that avoids both spatial and temporal discretization while considering the non-crossing constraint of QCs. A GVNS heuristic was developed to improve solution efficiency, with the objective of minimizing berth deviation cost, vessel waiting cost, and delay cost [4]. Correcher et al. incorporated crane travel time and setup time into the time-invariant scheduling framework, proposing the BACASP-S model. They introduced an alternative path-based modeling approach and combined BRKGA with a multi-model hybrid exact solution framework, achieving a significant improvement in computational efficiency without sacrificing solution accuracy [5].

### 2.2. Time-Variant Quay Crane Assignment Strategy

Unlike the static assignment mode, time-variant QC assignment allows dynamic adjustment of the number and assignment of cranes throughout a vessel's operation period. It can respond to real-time disruptions such as dynamic vessel arrivals, operation delays, and changes in resource status, thus more closely resembling the actual operational logic of modern terminals. Iris et al. addressed the integrated berth and QC optimization problem under time-variant crane assignment. Considering the feature of diminishing marginal productivity of cranes as the assigned number increases, they improved the MILP model and strengthened it with valid inequalities, and designed an ALNS algorithm to adapt to large-scale dynamic scheduling scenarios, enhancing solution quality and stability [6]. Wang et al. developed a joint berth and QC allocation model under time-variant operating conditions, incorporating two types of time-dependent carbon tax policies. A customized branch-and-bound algorithm was used to achieve the collaborative optimization of operational cost and carbon emission cost over the time dimension [7]. He et al. focused on time-variant operating conditions by incorporating day-night efficiency differences, dynamic energy consumption

variations, and driver time costs into the optimization objectives. They formulated a mixed-integer programming model and adopted a GA-based metaheuristic to achieve dynamic balanced allocation of crane resources across different time periods [8]. Thanos et al. investigated a time-variant dedicated crane assignment strategy supporting flexible departure times that can be adjusted over time. They optimized the dynamic crane assignment scheme over the time horizon to minimize the total accumulated container transshipment distance [9]. Yu et al. combined time-variant crane assignment with dynamic vessel speed optimization, constructing a bi-level dynamic model with upper-level berth-crane allocation and lower-level speed adjustment. A Nested NSGA-II algorithm was employed to dynamically match vessel arrival sequences with crane service rhythms [10].

Li et al. developed a joint berth-crane-experimental task allocation model based on time-variant scheduling rules, adaptively responding to dynamic time windows and task sequence constraints. The dynamic scheduling problem was transformed into an optimization problem with time windows and solved using an improved genetic algorithm [11]. Yue et al. compared fixed and mobile shore power systems under a time-variant crane allocation framework, characterizing the temporal relationships among dynamic berthing sequences, crane operation periods, and energy consumption. Their results validated the cost and emission reduction advantages of mobile shore power under highly dynamic vessel density scenarios [12]. Xu et al. addressed the lifelong time-variant berth-crane allocation problem by adopting an adaptive rolling horizon decomposition for dynamic tasks and incorporating incremental learning to transfer historical decision knowledge, thereby improving the performance and efficiency of long-term dynamic optimization [13]. Li et al. constructed a time-variant scheduling environment based on an event-triggered MDP, built a GRU policy network with an attention mechanism, and proposed the ERL-DDE evolutionary reinforcement learning framework to achieve adaptive joint decision-making for berth and crane allocation under dynamic events. Parallel to the above studies, other researchers have conducted comparative analyses of time-variant and time-invariant crane assignment within a unified framework [14]. Xiang et al. for the first time in a discrete berth environment, studied both time-invariant and time-variant crane assignment modes. They transformed the time-invariant problem into a RCPSP and solved it exactly using branch-and-cut. For the time-variant problem, they designed a two-phase algorithm combining initial solution construction with VNS. Through unified experimental comparisons, they verified the differences between the two modes in terms of solution efficiency, solution quality, and scenario applicability [15].

### 2.3. Quay Crane Scheduling

QC scheduling, building upon berth allocation and QC assignment, further optimizes the crane operation

sequence, movement paths, non-crossing constraints, and safety distances. It constitutes a deeply integrated optimization of berth and QC resources (BACASP), directly determining terminal handling efficiency and the level of operation conflicts. Agra and Oliveira addressed continuous berths, heterogeneous cranes, and non-crossing constraints by formulating a relative position model (RPF) and its discretized version (DRPF). They combined a rolling horizon heuristic with a branch-and-cut algorithm to minimize the total vessel service completion time [16]. Tasoglu and Yildiz considered mixed berth layouts under stochastic operation times, dynamic vessel arrivals, crane coverage ranges, and non-crossing constraints. They proposed a conflict-free QC scheduling algorithm (CFQCSA) and integrated simulated annealing with a simulation model to optimize the makespan [17]. Malekahmadi et al. incorporated tidal constraints, crane safety distances, and non-crossing constraints into a continuous berth setting, formulated an integer programming model, and designed a RTPSO algorithm to minimize total vessel waiting time and handling time [18]. Ji et al. addressed dynamic scenarios with unannounced vessels, considering crane non-crossing and interference constraints. They built a MILP model and proposed a hybrid rolling horizon strategy based on rescheduling margins, combined with a discretization mechanism and an ALNS algorithm to achieve dynamic scheduling [19].

Zheng et al. focused on uncertainties such as vessel delays and unscheduled arrivals, considering tidal time window constraints. They proposed intra-terminal transfer and inter-terminal transfer strategies, constructed a rescheduling model, and employed ALNS to minimize disruption costs [20]. Ran et al. addressed time-variant crane scheduling under emergency scenarios, considering crane non-crossing constraints and movement energy consumption. They developed a bi-objective MILP model and proposed an IPSO-BP algorithm integrating two-dimensional bin packing and feasibility checking to balance makespan and energy consumption [21]. Amirifar et al. deeply integrated berth allocation, QC assignment, and QC scheduling, comparing functional integration and deep integration frameworks. They designed a dedicated QCSP scheduling algorithm and adopted a hybrid PSO and DP algorithm to obtain optimal costs in large-scale instances [22]. Correcher et al. simultaneously optimized berth allocation, time-invariant crane assignment, and scheduling processes, incorporating crane travel time and setup time, forming a hybrid solution system combining exact algorithms and heuristics [23]. Khalilpoor et al. unified crane scheduling, preventive maintenance, vessel service priority, and energy consumption control into a single model. They constructed a bi-objective MILP model and employed NSGA-II, MOGWO, and MOPSO to achieve the collaborative optimization of operational cost and green crane utilization [24].

### 3. Collaborative Optimization of the Integrated Problem with other Decisions

#### 3.1. Considering Yard Space Allocation

Simultaneously optimizing berth allocation, QC assignment/scheduling, and yard space allocation/yard subblock allocation has become the most mainstream research direction in integrated terminal scheduling. Studies in this category argue that berth positions and crane operation schedules directly determine container transfer distances and yard space requirements, and that making these decisions in isolation can easily lead to truck congestion, low yard utilization, and prolonged vessel turnaround times. Liu focused on transshipment hub terminals and developed a tripartite simultaneous allocation model integrating discrete berths, time-variant cranes, and yard space, while considering transshipment containers, import/export container operations, and crane interference-induced productivity losses. A MILP model was formulated with the objective of minimizing total cost, and an iterative heuristic algorithm combined with an adaptive crane profile strategy was proposed for solution [25]. Guo et al. extended the research context to multiple coordinated terminals, integrating continuous berths, time-variant cranes, and shared yard allocation. Distinguishing between import/export and transshipment container flows, they constructed a MINLP model and employed an ALNS algorithm embedded with column generation to achieve cross-terminal resource coordination [26]. Yang et al. for the first time within a continuous-time framework, unified the optimization of continuous berths, time-variant cranes, and yard block allocation. They designed an exact Benders decomposition algorithm enhanced with valid inequalities and an M-tightening acceleration strategy, and demonstrated that a vertical yard layout offers greater advantages in reducing transshipment costs [27]. Zhang et al. addressed the integrated berth-crane-yard allocation problem and proposed a branch-and-price exact algorithm enhanced by deep reinforcement learning. A tree MDP and a tripartite graph state representation were employed to improve branching efficiency, achieving significantly better performance on large-scale instances compared to commercial solvers such as Gurobi [28].

#### 3.2. Considering other Decisions

In addition to the yard, berth and QC decisions are deeply coupled with factors such as trucks, drivers, tugboats, pilotage, shore power, and tides, forming a multi-dimensional extended integrated optimization system. In terms of horizontal transportation and human resources, Chargui et al. were the first to introduce QC operator performance differences and truck configuration into the Berth Allocation and QC Assignment/Scheduling Problem. They formulated a MILP model and solved it using Variable Neighborhood Search, demonstrating that integrated decisions significantly outperform separated ones [29]. Li et al. addressed a tidal environment by constructing a joint berth-crane-truck scheduling model, simultaneously considering the dual uncertainties of

vessel arrival time and truck speed. With the objectives of minimizing vessel turnaround time and carbon emissions, they proposed a Chaotic Quantum Adaptive Seagull Optimization Algorithm for solution. Regarding port auxiliary operations [30], Yang et al. integrated tugboat scheduling with berth and QC allocation, building an E-BUQC model that accounts for stochastic economic factors. A Chaotic Quantum Adaptive Satin Bowerbird Optimization Algorithm was employed to achieve multi-objective cost optimization [31]. Xiao et al. for the first time, integrated pilotage scheduling with berth allocation and time-variant QC allocation, considering channel capacity and pilot resource constraints. They formulated an integer programming model and designed an ALNS algorithm, significantly reducing vessel delays and total operational costs. In the context of tidal and green port operations [32], Bouzekri et al. addressed tidal multi-terminal ports by integrating tactical-level Laycan allocation with operational-level continuous berth and time-invariant QC allocation, considering tidal draft and non-operational time window constraints. Predicate modeling was adopted to improve solution efficiency [33]. Wang et al. combined shore power allocation with continuous berth and time-variant QC optimization, taking into account carbon taxes and carbon emission targets. They formulated a MILP model and proposed an Adaptive Immune Clonal Selection Algorithm to balance efficiency and low-carbon requirements [34].

#### 4. Optimization of the Integrated Problem under Uncertain Environments

In actual container terminal operations, factors such as vessel arrival times, QC operation efficiency, renewable energy output, and unexpected disruptions exhibit significant uncertainty, making the integrated berth-crane schedule prone to deviations from the baseline plan, conflicts, and delays. Current research revolves around three mainstream paradigms: robust optimization, reactive rescheduling, and distributionally robust optimization.

##### 4.1. Robust Optimization

Robust optimization aims to ensure feasibility and performance robustness under worst-case scenarios. By constructing uncertainty sets and introducing buffer resources or controlling constraint conservativeness, it renders the schedule immune or resilient to disturbances, representing a proactive uncertainty management strategy. Shang et al. addressed the BACAP problem with uncertain crane efficiency by building a robust optimization model, controlling conservativeness through price constraints, and solving it using a genetic algorithm combined with insertion heuristics, thereby balancing robustness and operational cost [35]. Iris and Lam introduced recoverable robustness into weekly berth and crane planning, setting buffer resources and recovery schemes, and solved the problem using an ALNS algorithm, achieving significantly better performance than traditional strict robust approaches [36]. Rodrigues and Agra focused on the BACASP with uncertain vessel arrival times, establishing a two-stage robust model and proposing an

exact decomposition algorithm combined with a rolling horizon strategy to efficiently solve large-scale instances [37]. Chargui et al. considered renewable energy uncertainty, built a multi-objective two-stage robust model, and solved it using exact decomposition and a VILS algorithm, guaranteeing solution feasibility under worst-case scenarios [38]. Chargui et al. integrated time-of-use electricity tariffs and energy efficiency optimization, established a two-stage robust model, and applied an improved exact decomposition algorithm, effectively reducing total cost while avoiding berth reallocation [39].

##### 4.2. Reactive Rescheduling

Reactive rescheduling focuses on rapid recovery and adjustment after disruptions, aiming to minimize deviation costs, recovery costs, and delay costs. It is a reactive strategy suitable for sudden disturbances and scenarios where the baseline plan fails. Xiang et al. constructed a behavior-aware reactive rescheduling model for multiple disruptions, solving it using prospect theory combined with a rolling horizon algorithm. In low-uncertainty environments, this approach outperformed proactive strategies [40]. Zheng et al. addressed complex disruption scenarios by incorporating cargo consolidation status and proposing a cross-terminal coordination strategy. They designed ALNS and dynamic programming algorithms, significantly reducing rescheduling costs [41].

##### 4.3. Distributionally Robust Optimization

Distributionally robust optimization utilizes only partial distributional information, such as moment information, of uncertain parameters and optimizes the expected performance under the worst-case distribution. It combines robustness with economic efficiency, overcoming the excessive conservativeness of traditional robust optimization and the reliance on exact distributions in stochastic programming. Wang et al. introduced distributionally robust chance constraints into the BACAP, characterizing uncertainty using moment-based ambiguity sets, and applied a decomposition branch-and-bound algorithm to achieve high-service-level schedules at low cost [42]. Wang et al. proposed a two-stage distributionally robust optimization model, optimizing the baseline schedule and adjustment costs in stages, and solved it using the C&CG method and approximation algorithms, achieving lower total cost than both stochastic programming and robust optimization [43].

## 5. Conclusion

This paper systematically reviews 43 studies on the integrated optimization of berth and QC resources in container terminals published over the past decade. Focusing on three core dimensions—the integrated optimization of berth and QC operations, multi-decision collaborative optimization, and uncertainty handling—the review comprehensively summarizes the research status, key achievements, and existing limitations in this field, and briefly discusses future research directions, aiming to

provide a reference for subsequent studies and practical terminal operations. Regarding the core integration of berth and QC operations, three sub-directions have emerged: time-invariant QC assignment, time-variant QC assignment, and QC scheduling. Time-invariant assignment suits medium- to long-term stable scenarios, time-variant assignment better aligns with dynamic terminal operation requirements, and QC scheduling focuses on conflict avoidance and efficiency improvement, with solution algorithms becoming increasingly sophisticated. Multi-decision collaborative optimization has expanded from a simple berth-crane integration to coordination with multiple elements such as yard, trucks, tugboats, and pilotage, while also addressing terminal operational efficiency and green, low-carbon development needs. In terms of uncertainty handling, three mainstream paradigms have been established: robust optimization, reactive rescheduling, and distributionally robust optimization, effectively supporting terminals in responding to various disruptions, including vessel arrivals and operational efficiency fluctuations.

Nevertheless, significant limitations remain in current research: the depth of multi-decision collaboration is insufficient, with the intrinsic coupling relationships among various decisions not fully explored; the refinement of uncertainty handling is inadequate to accommodate the dynamic evolution of multiple disturbance sources; and the alignment between research scenarios and actual terminal operations needs further improvement. Future research should focus on constructing full-chain coordination mechanisms, accurately addressing multi-source uncertainties, expanding novel operational scenarios, and enhancing the practicality of solution algorithms, thereby promoting deeper integration of theoretical models with real-world terminal operations and further improving the operational efficiency and overall competitiveness of container terminals.

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