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Quantum-Inspired Algorithms for Maritime Logistics Optimization

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Abstract. Maritime logistics involves closely connected decisions in vessel operations, port calls, cargo handling, and container transport. Many of these decisions give rise to optimization problems that combine continuous and discrete variables under operational, resource, time, and cost constraints. This paper reviews the application of quantum-inspired algorithms to maritime logistics optimization, focusing on quantum-behaved particle swarm optimization and quantum genetic algorithms. Three application areas are considered: vessel speed optimization, berth allocation and vessel scheduling, and multi-resource scheduling at container terminals. Rather than comparing reported results directly, the review considers how these problems are formulated, how quantum-inspired mechanisms are introduced into the solution procedures, and how the resulting methods are tested. Existing studies suggest that such algorithms can be adapted to both continuous and combinatorial problems in maritime logistics. Their reported performance, however, is sensitive to encoding schemes, parameter choices, problem size, and the treatment of constraints. The available results are also difficult to compare because the studies use different datasets, objectives, benchmarks, and evaluation criteria. In addition, empirical validation is often limited to a particular route, port, or predefined operating scenario, while uncertainties arising from vessel arrivals, weather, and equipment availability are less frequently represented. More evidence from operational data, together with consistent comparisons against established optimization methods, is therefore needed to assess when quantum-inspired approaches offer practical advantages for maritime logistics problems.

Keywords: quantum-inspired algorithms, maritime logistics, vessel speed optimization, berth allocation and vessel scheduling, coordinated multi-resource scheduling

1. Introduction

Maritime logistics is a complex system comprising vessel transportation, port calls, cargo handling, and container collection and distribution. Vessel speed affects sailing time, fuel consumption, transport cost, and carbon emissions, and consequently influences the estimated time of arrival and subsequent berthing arrangements. Berth allocation determines vessel waiting time, time in port, and berth utilization. The scheduling of quay cranes, terminal tractors, yard cranes, and other equipment directly affects handling efficiency, operational continuity, and resource utilization. These operations

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are interdependent and are jointly constrained by sailing time, fuel consumption, berth capacity, equipment availability, operating sequences, time windows, and port conditions. As shipping volumes and port workloads increase, speed planning, berth allocation, and equipment scheduling involve more decision variables and constraints, while the coupling among resources becomes more pronounced. Coordinating transport efficiency, operating cost, resource utilization, environmental emissions, and service reliability has therefore become an important problem in maritime logistics management.

Previous studies have applied mathematical programming, heuristic algorithms, and metaheuristics to vessel speed optimization, berth allocation, and port resource scheduling. As problems grow in size and their constraint structures become more complex, exact methods may require substantially more computation, while the performance of conventional metaheuristics may depend on the search range, parameter settings, and constraint-handling strategy. Quantum-inspired algorithms have consequently attracted increasing attention. Their central premise is to adapt selected representation and search mechanisms associated with quantum computing to improve conventional optimization procedures [1]. Prior reviews have examined the basic mechanisms of intelligent optimization methods from a quantum perspective and summarized the characteristics and application domains of different quantum optimization algorithms [2, 3]. Unlike quantum algorithms that rely on physical qubits and quantum-gate operations, quantum-inspired algorithms generally run on classical computers [4]. This family now encompasses quantum genetic algorithms, quantum-behaved particle swarm optimization, and other quantum-inspired metaheuristics [5]. Quantum-behaved particle swarm optimization uses probabilistic position representations and update rules to improve the search process, and several variants have been developed [6]. In maritime logistics, related methods have been applied to vessel speed optimization under different emission-reduction policies [7]. The quantum approximate optimization algorithm has also been explored for the joint design of vessel speed and routing; however, that method belongs to the quantum-computing paradigm and differs from the quantum-inspired algorithms considered in this paper [8]. In port scheduling, hybrid quantum genetic algorithms have been applied to joint berth and tugboat scheduling, while quantum-inspired optimization methods have been used for integrated berth, quay-crane, and truck scheduling [9, 10]. Subsequent studies have incorporated tidal conditions, environmental factors, and uncertainty into multi-resource allocation models and have explored quantum-behaved heuristics for berth allocation and quay-crane scheduling [10, 11]. Nevertheless, substantial differences in data sources, decision variables, constraints, and evaluation metrics limit comparison across studies. Some applications still rely on predefined parameters, simulated data, or a single port or route; the available evidence is therefore insufficient to establish the general applicability of these algorithms across maritime logistics tasks.

This paper synthesizes the literature and analyzes representative studies of three tasks: vessel speed optimization, berth allocation and vessel scheduling, and coordinated multi-resource scheduling at container terminals. It examines how quantum-inspired algorithms have been applied, how the algorithms have been designed, and under what conditions they have been validated. It also discusses limitations in the use of operational data, the modeling of dynamic operations, algorithm comparison, and engineering application. Rather than presuming that quantum-inspired algorithms outperform classical optimization methods, the analysis focuses on how their algorithmic characteristics align with different maritime logistics tasks and assesses both the available evidence and its limitations.

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2. Fundamentals of quantum-inspired algorithms

2.1. Definition and operating mechanisms

Quantum-inspired metaheuristics introduce concepts from quantum mechanics into classical optimization methods [1-3]. Depending on the algorithm, these concepts may appear in the representation of candidate solutions, the sampling process, or the rules used to update the population. Common examples include qubit representations, probability amplitudes, and probabilistic search operators. These algorithms are nevertheless executed on classical computers and do not require physical qubits or quantum gates [4]. In this respect, they differ from quantum algorithms such as Shor's and Grover's algorithms and from optimization methods implemented on quantum annealing hardware [4, 5]. Here, "quantum-inspired" describes classical algorithms that borrow particular concepts from quantum mechanics for search and solution representation.

The implementation of these concepts differs across algorithm families. Qubit-based evolutionary algorithms represent a candidate solution using probability amplitudes, so that the representation is not restricted to a single fixed state [1, 2]. Quantum-behaved algorithms instead describe candidate positions probabilistically and generate new positions by sampling from an associated distribution. Accordingly, the update process may involve rotation gates, probabilistic sampling, or position-update equations derived from a quantum-behavior model [2, 3]. These mechanisms affect how the algorithm explores the search space and how the search changes over successive iterations. In many implementations, a wider search is maintained during the early iterations and gradually narrowed as the population approaches promising regions. The actual balance between exploration and exploitation, however, is governed by the specific update rule and parameter settings.

Parameter selection can have a substantial effect on this search process. In quantum-behaved particle swarm optimization (QPSO), for example, the contraction–expansion coefficient affects the distribution of particle positions and the range over which new solutions are sampled [6]. In algorithms using quantum rotation gates, the rotation angle controls the change in probability amplitudes between successive updates [6]. The effect of these parameters also depends on the optimization problem being considered. Different variable types, constraint structures, and objective functions may require different representations and parameter settings. Consequently, reported performance cannot be attributed simply to the use of a quantum-inspired mechanism; the formulation of the problem and the implementation of the algorithm are also important [4, 5].

2.2. Principal algorithms and suitable problem types

QPSO and quantum genetic algorithms (QGA) are among the most frequently studied quantum-inspired metaheuristics [1, 5]. QPSO modifies the search process of conventional particle swarm optimization (PSO). Standard PSO updates particle velocity and position separately, whereas QPSO describes particle positions probabilistically and generates new positions according to a quantum-behavior model [6]. As a result, no explicit velocity variable is required. QPSO is commonly formulated in a continuous search space and is therefore well suited to problems with continuous decision variables. Examples in maritime optimization include vessel speed optimization, operational parameter tuning, and some route-parameter optimization problems [3, 6]. When the problem contains discrete assignments or other combinatorial decisions, additional encoding or hybridization is usually needed.

QGA retains the population-based framework of a genetic algorithm but changes the representation and update of individuals. Candidate solutions are represented using qubits or

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probability amplitudes, and quantum-inspired operators are used to modify the population [1, 2]. A commonly used operator is the rotation gate, which adjusts the probability of observing different candidate states [1]. This structure has been applied mainly to discrete and combinatorial optimization problems [2, 5]. In maritime logistics, relevant problems include berth assignment, operation sequencing, and the scheduling of quay cranes, yard cranes, and other terminal resources [1, 5]. For these problems, encoding and constraint handling have a direct influence on algorithm performance. A representation that frequently generates infeasible schedules, for instance, may require extensive repair operations and reduce search efficiency.

Quantum-inspired modifications have also been proposed for ant colony optimization, differential evolution, artificial bee colony algorithms, and other metaheuristics [5]. These methods differ considerably in representation and search strategy despite sharing the quantum-inspired label. In broad terms, QPSO is easier to apply when most decision variables are continuous, while QGA and related evolutionary methods provide a more direct representation for discrete and combinatorial decisions. This distinction is useful in maritime logistics because many practical problems contain both variable types.

For example, integrated vessel, berth, and equipment scheduling may involve discrete decisions on assignment and sequencing together with continuous variables for timing or operating conditions. A single search mechanism may not handle all parts of such a problem equally well. Several studies therefore combine quantum-inspired algorithms with local search, decomposition, or other optimization procedures [3, 6]. In selecting an algorithm, the main consideration is the structure of the optimization model—particularly the variable types, constraints, and interactions among decisions—rather than whether an algorithm is classified as quantum-inspired.

3. Representative maritime logistics optimization tasks

3.1. Vessel speed optimization

Vessel speed affects voyage time, fuel consumption, operating costs, and emissions, but the choice of speed is also constrained by the conditions of a particular voyage. Schedule requirements, weather and sea conditions, port time windows, and environmental regulations may all restrict the feasible range. Increasing speed can compensate for delays, usually at the cost of higher fuel consumption, while slow steaming reduces fuel use but may leave less room to accommodate subsequent disruptions. The appropriate speed is therefore closely tied to the operational and regulatory setting in which the voyage takes place.

Han et al. studied this problem under several emission-reduction measures, including emission control areas, carbon taxation, a vessel speed reduction incentive program, and virtual arrival [7]. They developed an improved QGA with bifurcation genes and an elitist strategy and applied it to a shipping route on the west coast of the United States. The resulting speed and cost varied across the policy scenarios. Applying several measures together did not necessarily yield greater benefits than applying them separately; however, the scenario incorporating virtual arrival produced further reductions in cost and emissions [7]. The study illustrates how QGA can be incorporated into a speed-optimization model in which operational decisions are made under explicit policy constraints.

The scope of the case study should nevertheless be kept in mind. The analysis was based on one route and one regulatory setting, with part of the sea-state information generated through simulation [7]. Actual voyages are less stable. Weather conditions and arrival requirements may change during sailing, while delays on earlier legs can require speed adjustments later in the voyage. It is consequently difficult to infer from this case alone how the method would perform when these

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conditions are updated repeatedly. Tests using observed voyage data across different routes and operating conditions would provide a more convincing assessment of its practical robustness.

3.2. Berth allocation and vessel scheduling

Berth allocation involves deciding both where vessels should berth and when service should begin. These decisions directly affect waiting and turnaround times and, when other terminal resources are considered, cannot be made independently of resource availability. Typical formulations include vessel arrival times and dimensions, berth characteristics, handling times, and departure requirements, while minimizing measures such as waiting time, time in port, tardiness, or operating cost.

Cai et al. investigated joint berth and tugboat scheduling under given berth, tugboat, and quay-crane conditions [9]. Their objective was to minimize vessel time in port and total tardiness, and they solved the model using a hybrid QGA–tabu search algorithm. QGA provided the population-based search, while tabu search was incorporated into the hybrid search procedure. In the reported experiments, the hybrid method reduced vessel time in port and total tardiness compared with manual scheduling and a conventional genetic algorithm [9]. Including tugboats in the formulation is operationally important because spatial and temporal berth feasibility alone does not guarantee that a vessel can actually be moved as scheduled. Tugboat availability can become an additional constraint on both berthing and departure.

The experiments were conducted under predefined scheduling conditions, whereas vessel arrivals, handling times, and resource availability may change during day-to-day terminal operations [9]. Under such conditions, the practical issue is not only whether an algorithm can produce a good initial schedule, but also how effectively that schedule can be revised as new information becomes available. The results in [9] demonstrate the performance of the proposed method on the reported instances, but do not fully establish its behavior under repeated operational rescheduling. This remains an important issue for further evaluation.

3.3. Coordinated multi-resource scheduling at container terminals

Container handling depends on the coordination of several resources rather than on the performance of any single piece of equipment. Quay cranes perform loading and discharge operations at the vessel side, trucks or terminal tractors move containers horizontally, and yard cranes and storage areas support the corresponding yard operations. Bottlenecks can therefore shift from one part of the system to another. Increasing quay-crane productivity, for instance, may have little effect on vessel handling time when horizontal transport is already operating at capacity. Conversely, adding vehicles does not necessarily improve throughput if they spend more time waiting for cranes. This interdependence is the main reason for considering multiple terminal resources within a common scheduling model.

Quantum-inspired methods have been applied to several such formulations. Li et al. jointly considered berths, quay cranes, and trucks while incorporating tidal conditions, environmental factors, and uncertainty, and solved the resulting problem using a chaotic quantum adaptive seagull optimization algorithm [10]. Li and Li considered the joint scheduling of berths and quay cranes using a quantum-behaved heuristic [11]. Taken together, these studies show a shift from optimizing individual terminal decisions toward formulations that explicitly account for interactions among several quayside resources.

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At the same time, increasing the number of coordinated resources does not necessarily amount to modeling the terminal as a complete operating system. The formulations in [10, 11] capture several important interactions around berth and quayside operations, while detailed yard-crane movements, storage-location decisions, and container-handling sequences are either simplified or outside the scope of the respective models. This distinction matters when considering practical implementation. A schedule derived from a static or partially integrated model may need substantial revision after an arrival delay, equipment failure, productivity change, or unplanned handling task. Current studies therefore provide evidence that quantum-inspired methods can solve specific integrated terminal-scheduling formulations, but evidence from continuously updated operating environments remains relatively limited. Further evaluation using time-varying vessel, equipment, and yard information would help establish whether the reported computational performance can be maintained when schedules are revised during operation.

4. Limitations and research directions

Despite the growing use of quantum-inspired algorithms in maritime logistics, the evidence available from current studies is still largely based on controlled or predefined operating conditions. Vessel speed optimization, for example, is often examined for a particular route, policy setting, or prescribed sea state, while berth allocation and vessel scheduling commonly rely on known arrival and handling times. Integrated terminal models have extended the scope of optimization to interactions among berths, quay cranes, and horizontal transport, but yard cranes, storage decisions, and detailed handling sequences are less frequently considered. These assumptions make the problems computationally manageable, but they also simplify the conditions encountered in actual operations. Vessel delays, changing weather, equipment failures, and unexpected tasks can quickly invalidate an existing plan. Results obtained from static instances consequently provide only limited evidence of how quantum-inspired methods would perform when decisions have to be updated during ongoing operations.

Comparison across the literature presents another difficulty. The reviewed studies differ substantially in their objectives, datasets, problem sizes, constraints, and performance measures. Some formulations prioritize operating cost and emissions, whereas others focus on vessel turnaround, tardiness, or resource utilization. Differences in encoding, parameter settings, constraint handling, and stopping criteria further complicate algorithm-level comparisons. Reported improvements therefore need to be interpreted within the experimental setting in which they were obtained rather than as evidence of a general advantage of quantum-inspired search. This is particularly relevant when these methods are compared with conventional optimization algorithms. For smaller instances or problems with relatively simple structures, established methods may achieve comparable solutions with less computational effort. For more complex scheduling problems, evaluation should consider not only objective values but also computation time, robustness across repeated runs, constraint satisfaction, and whether the resulting schedules can be implemented in practice.

Addressing these limitations requires stronger empirical evaluation rather than simply introducing additional algorithmic variants. Operational data from Automatic Identification System (AIS) trajectories, vessel arrivals, berth plans, equipment records, weather observations, and sea-state measurements could provide a more realistic basis for testing. Terminal models would also benefit from a broader representation of the operating system, extending beyond berths, quay cranes, and trucks to yard equipment, storage decisions, and disruptions that trigger rescheduling. Hybrid approaches are another relevant direction, particularly where continuous and discrete decisions

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coexist and different parts of the problem may be better handled by different search mechanisms. Quantum-inspired search could, for example, be combined with local search, mathematical optimization, or established metaheuristics rather than being treated as a standalone solution.

Equally important is the design of the computational experiments used for comparison. Evidence based on a single port, route, problem size, or parameter configuration provides little information about generalizability. Experiments across multiple instance sizes and operating conditions, together with common constraints, stopping criteria, and performance measures, would allow more meaningful comparisons with established methods. The central question is therefore no longer simply whether quantum-inspired algorithms can be used for maritime logistics optimization, but under which problem structures, operating conditions, and computational requirements their use is justified.

5. Conclusion

This paper reviews applications of quantum-inspired algorithms in maritime logistics optimization, with an emphasis on vessel speed optimization, berth allocation and vessel scheduling, and coordinated multi-resource scheduling at container terminals. Existing studies indicate that probabilistic representation and search mechanisms can be used to address problems with continuous and discrete variables under multiple constraints, and these methods have been applied to several maritime logistics scheduling settings. The reported performance depends not only on the particular quantum-inspired mechanism but also on parameter settings, encoding, problem size, and constraint handling. Because studies differ in their data, objective functions, and evaluation metrics, their results should not be compared without careful qualification. Many applications remain based on a specific route, a single port dataset, or predefined operating conditions and give insufficient attention to changes in vessel arrivals, weather, and equipment status. The application of quantum-inspired algorithms in maritime logistics thus requires further validation and refinement. Future research should draw more extensively on operational shipping and port data and compare quantum-inspired and classical optimization methods across problem sizes and operating conditions to clarify practical value and suitable application domains.

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