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A goal-programming based optimal port docking scheme under COVID-19

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ABSTRACT

The Covid-19 epidemic, has caused a large-scale congestion in many ports around the world. This increases the cost of port docking, as well as delays the loading and unloading of goods, which affects the price and timely supply of many products. Although scholars have carried out in-depth discussion and analysis on the port congestion problem from different perspectives, there is still no appropriate model and algorithm for the large-scale comprehensive port docking problem. This paper presents a new mixed integer programming model for optimal docking of ships in ports that is comprehensive enough to include four essential objectives. It discusses the generalization and application of the model from the perspectives of the shortest overall waiting time of ships, the balance of tasks at each berth, completion of all docking tasks as soon as possible and meeting the expected berthing time of ships. We demonstrate the results of our models using relevant examples and show that our model can obtain the optimal docking scheme based on different perspectives and relevant objectives. We also show that the scale of the exact solution can reach tens of thousands of decision variables and more than a million constraints. This fully reflects the possibility that the model can be put into use in any real life scenario. This model can not only effectively improve the docking efficiency of the port, but is also suitable for the complex queuing problem of multi window and the same type of service.

1. Introduction

In early 2020, the Coronavirus pandemic (COVID-19) began to spread around the world. Under the continuous influence of the epidemic, the economic development of many countries has stagnated or regressed to varying degrees. This has also led to structural changes in the global economic pattern that was formed after decades of development, and adversely impacted many industries to varying degrees (Hisaka et al., 2020). The port and shipping industries, particularly, have suffered heavily. In the era of globalization, widespread world trade has stimulated division of labor of global industries, resulting in the development of regional economy. It has also integrated the resources of countries all over the world, and formed a world economic pattern that countries all over the world cannot escape (Fatema, 2020). The development of port and shipping industry is directly related to and has become an important link in global trade, preventing it from quickly responding in time, thus exposing many systemic problems of port management (Gray, 2020). This shows that the development of global trade has also brought great challenges for the control of the epidemic. Like in the case of SARS in 2003, many countries have adopted strict quarantine and prevention measures for ports to control the spread of the epidemic as quickly as possible, which forced ships to remain in ports for too long (Grainger, 2014). Because of the sudden outbreak of COVID-19, countries could not respond in time, thus exposing many systemic problems of port management (Gray, 2020), for example, wastage of resources, increased time cost, port congestion and other problems. These problems also affect the operational efficiency of the port, preventing it from quickly accepting incoming and outgoing trade ships and providing timely berthing and loading services. All these problems not only have an adverse impact on the development of national trade, but also hinder the further expansion of world trade.
The outbreak of COVID-19, has exposed the inadequacies of a successful response to epidemic control in some developed countries in Europe and the United States, resulting in severe interruption of supply chain in these countries and regions. For example, the reduction of slaughterhouse workers in fast-food chains such as KFC in the United States led to a shortage of chicken supplies. In this case, the prices of raw materials also increased significantly. At the same time, world energy prices are also rising, resulting in increasing manufacturing and transportation costs. However, the control of the epidemic in some parts of Asia has shown remarkable results, leading European and American countries to sign a large number of product purchase orders from China and other Asian countries. For example, China’s exports of goods increased by 4% in 2020 and 29.9% in 2021. The direct impact of these increased product orders led to an increased pressure on the transportation industry, which, in turn, were making the main ports extremely congested. These include Yantian port in China and Los Angeles port in the United States. The ships cannot enter the dock in time, hence the goods cannot be transported out of the dock in time, so that even though the port berth is idle, the ships cannot berth. Therefore, the problem now is to solve this port congestion problem urgently so that the terminal operation is improved.

This paper analyzes the problem of port congestion caused by the increase of cargo volume, the increase in port berthing time and the increase of uncertain arrival of ships during the period of COVID-19. It addresses the urgency of this problem by proposing an efficient model and a solution algorithm for the port congestion problems. It is necessary to consider all the key factors for this congestion such as the arrival rate of ships, the service capacity of the berth, the waiting time of ships, the balancing of berth tasks, the earliest completion time of all tasks of each berth, and matching with the expected docking time of ships. Our proposed model takes into account all these factors and has strong application value to effectively mitigate the pressure of port docking, thus avoiding the sharp rise of docking costs of shipping companies and stabilizing the sustainable and healthy development of world trade.

The rest of the paper is organized as follows. The related and relevant literature is reviewed in Section 2. In Section 3, we introduce our notations and models. In Section 4, we proposed a case study based on several different assumptions. Section 5 concludes the paper with a summary of our findings and future research directions.

2. Literature review

As COVID-19 continues to spread, the pressure on ports is increasing. First, incoming and outgoing ships cannot transport goods to the destination port in time, which increases the sailing time of ships, causes huge waste of energy resources and increases the operations cost. Secondly, for the port terminals, the loading and unloading of goods cannot be completed in time, resulting in systematic problems of port parking congestion and chaotic management, which greatly affects the operational efficiency of the port. Therefore, many scholars have conducted in-depth research on how to solve the problem of port congestion and improve the efficiency of port operations. This section will make an in-depth analysis of the relevant literature on improving port operational efficiency. The main methods used in literature include Shipping Union, improving loading and unloading efficiency, port regional cooperation and extending working hours. We will first survey these four methods as proposed in literature, and then present a comparative analysis of these methods showing the types of models and algorithms they use and their respective computational efficiency.

2.1. Establish Shipping Union

Shipping Union refers to various alliances formed between shipping liner companies in the field of transportation services, such as complementary routes and affiliated ports, shipping schedule coordination, mutual rental of shipping spaces, mutual sharing of information in the field of transportation auxiliary services, joint construction of common terminals and storage yards, and sharing of inland logistics system. The formation of a Shipping Union is expected to result in the reduction of the required number of transport ships and the arrival rate of ships, so as to alleviate the problem of port congestion.

Shi and Voss (2008) used the non-cooperative game as the theoretical framework to study the liner shipping strategic alliance and its establishment and transformation, revealed the cooperation motivation among multiple liner shipping companies, and put forward methods to improve the stability of the alliance. Tan and Thai (2014) believe that high-quality strategic alliances have contributed to the exploration of the impact of alliance networks on enterprise performance. Through an exploratory method, this paper reveals the knowledge sharing mechanism and the role of information sharing in the liner shipping alliance network in promoting enterprise performance. Zheng et al. (2017) proposed a mixed integer linear programming model that comprehensively considers liner network design with fleet deployment, variable demand allocation, capacity exchange between liner operators and container routing, so that liner carriers can find the optimal cooperative solution. Dulebenets (2018) believes that cooperation among enterprises can be strengthened and ships with the same technical characteristics can be combined for transportation. A mixed integer nonlinear model for solving ship scheduling problem of non-uniform fleet is constructed and solved by nonlinear optimization method, with an objective of reducing energy costs and improving the efficiency of port transportation efficiency. Chen et al. (2017) believes that the most important thing of the freight alliance is the sharing and allocation of container spaces between carrier ships. They developed an integer programming LOTCO allocation model to optimize the container capacity sharing and co-allocation. Notteboom et al. (2017) analyzed the impact of changes in shipping organization practices (formation of shipping alliance and vertical integration of container business) on the choice of liner service ports of call, and discussed the reasons for the formation of transportation alliance, providing new ideas for port managers and shipping professionals in port strategy and planning. Zheng et al. (2017) discussed the transportation cost calculation methods based on duality, inverse optimization and Shapley value, and proposed a cost sharing scheme of container shipping alliance with economies of scale. Liu and Wang (2019) believe that alliance among shipping companies is conducive to reducing carrier service competition, reducing port service price and weakening port monopoly advantage. On this basis, a combined contract which can effectively coordinate the interests of both parties is proposed to improve the efficiency of transportation. Zheng and Luo (2021) constructed a dynamic game model, analyzed the strategic relationship between shipping companies (competition and alliance according to cournot model) and port cooperation, considered the economies of scale of shipping companies, and found that enterprise alliance with the help of third-party cooperative transportation is conducive to reducing costs and increasing transportation capacity.

From the above analysis of literature, we find that many scholars have conducted in-depth research on how to build a shipping enterprise union. They mainly focus on how to strengthen cooperation among enterprises and mitigate transportation pressure through theoretical research. We find that there is little research on how to alleviate the pressure on arrival in port after enterprise cooperation. The research on how to coordinate the arrival time between enterprises is of utmost importance. When the ship arrival time is further optimized, it can alleviate the pressure on the port and improve its operational efficiency.

2.2. Improve the efficiency on loading and unloading

The second main method found in the literature is improving loading and unloading efficiency. It refers to reducing the loading and unloading time of ships in the port, reducing their berthing time, so as to provide more time and free berths for more ships. Scholars in this field mainly focus on the time planning of transport vehicles and cranes in improving
loading and unloading efficiency. Skinner et al. (2013) focused on the container scheduling problem, coded the problem with two-part chromosome method and solved it through improved genetic algorithm, which reduced the time cost of automatic container terminal transfer and improved the loading and unloading efficiency. Yang et al. (2018) proposed a comprehensive scheduling method for the path of handling equipment and automatic guided vehicle (AGV), established a bi-level programming model with the goal of minimizing the maximum completion time, and solved it by a bi-level genetic algorithm based on congestion prevention rules to reduce the loading, unloading and handling time. Debjit and Rene (2018) developed a new comprehensive stochastic model to analyze the performance of overlapping loading and unloading operations, found random interaction between wharf, vehicle and transportation process, solved the model by using the iterative algorithm based on parameter decomposition approximation, and gave the best yard layout configuration. Lu et al. (2018) studied the crane scheduling problem of the new automatic container terminal system based on multi-layer bridge, constructed a mathematical model for the scheduling problem of terminal crane and bridge crane, and developed a meta heuristic algorithm to solve it. Lu et al. (2019) considered the two aspects of AGV path overlap and loading and unloading time, constructed an interference model and container handling task scheduling model respectively, and solved it by particle swarm optimization algorithm based on graph theory model, so as to avoid the problems of vehicle congestion and time waste. Jin and Mi (2019) constructed a multi-objective integer programming model with the objective of minimizing the sum of container handling capacity, AGV movement and weight differences between containes, and they transformed it into linear constraints for solution, which has great practical value for improving port productivity. Ma et al. (2020) established a mathematical model for the operation of multi load AGV in the automatic container terminal with the minimum moving distance as the goal, and used a mutation frog jump algorithm based on priority rules to solve it, which is of great significance to improve the operational efficiency. Xu et al. (2020) pointed out that efficient AGV scheduling is the key to improving the throughput of automated container terminals, and the realization of two-way loading of AGV can significantly improve the port handling efficiency. Consequently, an AGV path planning model for cargo loading is constructed and solved by a simulated annealing algorithm. Zhong et al. (2020) established the minimum driving distance model of AGV, considered the problems of vehicle conflict, congestion and long waiting time, solved the model through Dijkstra depth first search algorithm, planned the optimal driving path, and greatly improved the loading and unloading efficiency of the port. Tan et al. (2021) decomposed the process of terminal crane automation in the automated container terminal, and developed a hybrid integrated planning model to improve the port operational efficiency. Yu et al. (2021) constructed an integer programming model to minimize the total waiting time of AGV and the external truck waiting time in the future container retrieval process, and solved it by a kind of simulated embedded genetic algorithm, which improved the loading and unloading efficiency of the port.

The above literature analysis shows that several scholars have entered into in-depth discussions and research on improving loading efficiency. This research is mainly about simplifying the workflow, efficient uses of AGV and the shortening of the occupation time at port. However, port congestion is not only due to the low loading and unloading efficiency, but also due to the unreasonable berth arrangement. When the loading and unloading efficiency is improved, the residence time in the port will be greatly shortened. However, we need to further realize the optimal allocation of berths and reduce their unreasonable allocation. Only then will we be able to reduce the port congestion and improve the operation efficiency of the port.

2.3. Port regional cooperation

The third method in literature is the port regional cooperation which refers to the use of relevant national and government policies to encourage and guide cooperation between ports at the port level, so that ships can reach the cooperative ports in a balanced manner and improve port operational efficiency.

Mclaughlin and Fearon (2013) proposed a new concept cooperation/competition matrix to provide an evaluation tool for port cooperation and competition. Gianfranco et al. (2014) used the hierarchical clustering method based on WARD method to quantitatively evaluate the relationship between ports, put forward new cooperation policies for ports in the same cluster, and also put forward new cooperation schemes between different clusters according to different characteristics. Wang et al. (2015) studied the current development of China’s port integration strategy and believe that spatial planning and port competition with hinterland can promote the construction of port integration, which has a high reference significance for future port cooperation. Galvao et al. (2018) believe that cooperation between ports should be based on common port characteristics. Simple cooperation will not increase port work efficiency and can even hinder port development. Huo et al. (2018) analyzed the current situation of China’s port cooperation strategy, and pointed out that China should develop a cooperation incentive mechanism and trend, so as to lay the foundation for further port cooperation in the future. Kristijan et al. (2018) believe that, if there are ports with a common hinterland, a mutually beneficial cooperation strategy should be formulated, and a cooperation matrix should be used to draw the current and potential cooperation directions. Shinohara and Saika (2018) took three ports in Japan as an example, defined the role sharing among them, defined the boundary of competition and cooperation, and built a reference for the development of other ports in the world. Wu and Yang (2018) pointed out the disadvantages of the current development model of “one port, one city” in China, and believed that ports should not only compete for more goods, but should strengthen port cooperation and integration to realize the framework of systematic integration of shipping models. Lin et al. (2019) put forward the need to build a game theory based model on the basis of integration and coordination mechanism. With the goal of maximizing the interests of both sides, the cooperation game models of two host countries and China port were constructed, and an optimal cooperation mode was finally obtained, that solved the congestion problem of a single port. Kavirathna et al. (2020) discussed the cooperation effect between terminal operators of a single port, established a mixed integer programming model with the goal of minimizing the total penalty cost and maximizing the total profit in combination with the decision-making of game theory. They found that cooperation in the operation stage reduces berthing delay and improves the utilization rate of the ports compared with non-cooperation.

Cooperation between ports contributes to sharing between port berths and benefits by reducing the waiting time of ships. However, in the process of cooperation, if the setting of time window is unreasonable, even if the number of berths and the sharing of idle times are increased, it may not be able to ensure the effective improvement of the overall cooperation efficiency. Therefore, it is still necessary to explore a general port docking model to effectively provide regional cooperation efficiency between ports.

2.4. Extending working hours

The extension of working hours refers to the reasonable planning of the arrival time of ships. Through reasonable time arrangement, ships can berth within a short time, load and unload goods quickly, so as to accept the maximum number of ships within the specified time. In current literature, scholars usually set the port time window to solve the problem. Wang et al. (2014) considered the availability of each port in a week, established a mixed integer nonlinear nonconvex optimization model
considering liner route planning and design, and proposed an effective algorithm to solve for the global optimal. The results show that the port time window affects the optimal number of deployed ships and optimal scheduling. Jesica et al. (2015) studied the ship scheduling problem with discrete time window and believed that ships arriving irregularly should determine the time window that should be used to perform the provisions of the contract, so as to minimize the total cost. Aydin et al. (2016) established a dynamic programming model for liner shipping speed optimization with the goal of minimizing total fuel consumption considering the characteristics of random port time and time window. The results show that the reasonable arrangement of time window can significantly reduce fuel consumption and time cost. De et al. (2017) proposed a mixed integer nonlinear programming model considering various scheduling and path constraints, loading and unloading constraints and ship constraints. They introduced time window constraints to restrict ships to arrive only within the time window, and solved it by particle swarm optimization difference algorithm, which alleviated the problem of port congestion and improved the efficiency of port operation. De et al. (2019) proposed a mixed integer nonlinear programming model (MINLP) considering the concept of time window, discrete programming level and draft limitation of loading and unloading operations. They solved the multi-objective mathematical model by using non-dominated sorting genetic algorithm (NSGA-II) and multi-objective particle swarm optimization algorithm (MOPSO). The problem of port congestion is solved by imposing a fine on the unexpected arrival time of the time window. Ghasemi-Sardabrud et al. (2019) described a specific type of traveling salesman problem (TSP) with loading and unloading, time window and draft constraints, carried out integer linear programming and forward dynamic programming through GAMS software, and analyzed different motion states of ships. They obtained the optimal route under the optimal arrival time, and alleviated the problem of port congestion. Lu et al. (2019) proposed a nonlinear mixed integer programming model for container liner comprehensive planning, which can simultaneously determine the segment access time, segment operation speed and cargo distribution, and developed a heuristic algorithm to solve it. De et al. (2020) studied a ship routing problem considering the concept of time window and fuel management, established a mixed integer linear programming model, and proposed a new particle swarm optimization algorithm (called BVNS-PSO) to solve it, so as to realize reasonable arrangements of ship berthing. Jiang et al. (2020a,b) proposed the need to optimize the shift route and shipping schedule design at the same time. Under the constraint of port time window, a mathematical programming model is established to minimize the total operation cost, which considers the optimization of port docking sequence, ship arrival time and speed of each leg at the same time, and is transformed into a mixed integer programming model to obtain the optimal solution. It is found that different time windows will affect the call order of the optimal port. Jiang et al. (2020a,b) also proposed a soft time window considering customer preferences, constructed a mixed integer nonlinear nonconvex model comprehensively considering how to balance the total operating cost of ships and the penalty cost for violating the weekly soft time window, and transformed it into a mixed integer linear optimization model for solution, and determined the optimal ship arrival time and alleviated port congestion.

Setting a time window helps to restrict the arrival time of ships and tries to avoid a surge in the number of ships arriving at the port in one time period causing idleness in other time periods. However, in the previous literature, few scholars have reasonably optimized the berth assignment of the port. If a detailed ship assignment scheme is not given, congestion will occur even within the time window, so how to reasonably assign port berths is very important.

2.5. Comparative analysis of different literature results

The main parameters to be considered in the berthing of ships in the port include the number of ships arriving every day, the number of berths in the port and the working hours in a day. Aiming at the improvement of port operation efficiency, scholars put forward relevant optimization models from different perspectives, and provided relevant algorithms and examples. We have summarized the current research in the form of a comparison table (see Table 1) that will show the different methods in current literature at a glance.

It can be seen from Table 1 that, in the research on ships’ berthing in ports, current research either did not fully consider all factors, or failed to effectively solve the large-scale ship docking optimization problem.

To sum up, many scholars have conducted in-depth research on how to alleviate port congestion and improve port operations efficiency, and also elaborated and analyzed the problem of constructing port time window. However, these results are basically from research on the improvement of port docking efficiency from a theoretical perspective. Managers will possibly find them to be difficult to implement in real life. Although there are a few practical application cases, they are either small scale or consider an insufficient number of constraints. In view of the above shortcomings in theory and application, this paper intends to propose a model that fully considers all factors of port congestion to formulate a mixed integer programming model. We develop algorithms and a graphic display technology that will show the specific docking strategies of relevant ports to managers in a visual form, achieving the goal of the perfect combination of theory and practice. The generality of

| Model related issues | Model type | Algorithm type | Calculation scale |
|----------------------|------------|----------------|------------------|
| Kavirathna et al. (2020) | MIPO Mixed integer programming model | Genetic algorithm Taboo search | 3 × 365 |
| Lin et al. (2019) | Game model | cloud genetic algorithm | 5 |
| De et al. (2020) | Mixed linear integer programming model | PSO-CP Composite particle swarm optimization algorithm | 4 × 3 × 2 |
| De et al. (2019) | Mixed integer nonlinear programming model | PSO-CP Composite particle swarm optimization algorithm | 10 × 6 |
| Jiang et al. (2020) | Mixed integer linear programming model | Heuristic algorithm | 2000 × 9 |
| Ghasemi-Sardabrud et al. (2019) | Linear integer programming model | ILP algorithm | 20 |
| De et al. (2017) | Mixed integer nonlinear model | Non dominated sorting genetic algorithm Multi objective particle swarm optimization algorithm | 3 × 4 × 3 × 15 |
| Jesica et al. (2015) | Nonlinear mixed integer programming model | GRASP-VNS Hybrid heuristic algorithm | 14 × 8 |
| Wang et al. (2014) | Mixed integer nonlinear programming model | Heuristic algorithm | 10 × 30 |
| Jiang et al. (2020) | Mixed integer linear programming model | MILP algorithm | 1800 × 9 |
the model is verified by a numerical example. Compared with the previous literature, it is found that the operations scale has been greatly improved, and the factors considered are more comprehensive. These results are not only applicable to the port docking problems, but are also suitable for complex queuing problems with multi-window and single-service mode.

Based on the literature review, we summarize the main contributions of our paper as follows:

1. This paper proposes a mixed integer programming model that fully considers all relevant factors of port congestion. In this model, the balance of the docking time of ships and the balance of ship transportation routes are innovatively realized, and the comprehensive problems of ship size, berth number and berthing time period are addressed simultaneously, which has immense practical value.

2. This paper proposes algorithms of the models based on GUROBI software, with greatly improved operational scale. Compared with previous literature, the model and algorithm can obtain the optimal solutions on a larger scale. The computational efficiency is also greatly improved.

3. The model has a wide range of applications. It is not only suitable for the optimization of port ship docking in emergency scenarios, but also for queuing problems with multiple-service windows and single-type service tasks.

3. Design of optimal port docking model

In this section, we will establish a port docking model based on several different docking goals. In our model, we attempt to include analyses of all the factors that can affect the docking efficiency. For example, the concept of docking time is innovatively proposed, and a mixed-integer programming model of port ship docking is proposed for the first time, which simultaneously considers the number of vessels, the number of berths, the size and type of vessels for each time period. As the model is more comprehensive, it has wider applicability. The following is the detailed explanation of the model:

3.1. Description of basic parameters and variables

3.1.1. Model parameters and data description

The parameters and description of models are as follows:

\[m\] Total number of time periods of each day, in fact the different values can be selected for the duration of each period, such as 1 h or half an hour;

\[n\] Total number of ships to arrive at the port in a day;

\[B_k\] The earliest working time period of berth \(k\), \(k \in \{1,2,\ldots,t\}\);

\[E_k\] The latest off-duty period of berth \(k\), usually \(E_k \geq m\), \(k \in \{1,2,\ldots,t\}\);

\[i\] The number of the time period, \(i \in \{1,2,\ldots,m\}\);

\[j\] The number of the ship, \(j \in \{1,2,\ldots,n\}\);

\[k\] The number of the berth, \(k \in \{1,2,\ldots,t\}\);

\[\{s\}\] The number of the time period, \(s \in \{2,3,\ldots,m\}\);

\[T_d\] The docking period of the ship \(j\), \(j \in \{1,2,\ldots,n\}\);

\[T_b\] The size and type of the ship \(j\), \(j \in \{1,2,\ldots,n\}\);

\[B_i\] The size and type of ships that can be docked in the berth \(k\), \(k \in \{1,2,\ldots,t\}\);

\[E_i\] The latest arrival time period of the ship \(j\), \(j \in \{1,2,\ldots,n\}\);

\[E_i\] The latest arrival time period of the ship \(j\), \(j \in \{1,2,\ldots,n\}\);

\[TM_i\] The expected arrival time period of the ship \(j\), \(j \in \{1,2,\ldots,n\}\);

\[d_{ij}\] The length of time period of ship \(j\) when the actual arrival time period is later than the latest arrival time period, \(j \in \{1,2,\ldots,n\}\);

\[d_{ij}\] The length of time period of ship \(j\) when the actual arrival time period is earlier than the latest arrival time period, \(j \in \{1,2,\ldots,n\}\);

\[x_{ijk}\] The length of time period of berth \(k\) when the berthing time period is less than the average berthing time period, \(k \in \{1,2,\ldots,t\}\);

\[x_{ijk}\] The length of time period of berth \(k\) when the berthing time period is greater than the average berthing time period, \(k \in \{1,2,\ldots,t\}\);

\[x_{ijk}\] Whether the ship \(j\) is scheduled to dock at the berth \(k\) in the time period, if so \(x_{ijk} = 1\), otherwise, \(i \in \{1,2,\ldots,m\}, j \in \{1,2,\ldots,n\}, i \in \{1,2,\ldots,t\}\).

3.2. Ship docking assignment model that minimizes the total waiting time

Based on the efficient utilization of berths, the proposed arrival time window of each ship shall be met as far as possible without exceeding the upper limit of berthing task of each berth. However, when the arrival time periods of each ship are relatively concentrated, there will still be excessive number of ships arriving in some time periods, which will inevitably make some ships wait. The key point of ship docking assignment model is to arrange which ship to dock in which berth at which time period. The required docking time period cannot be earlier than the latest arrival time period of the ship, but can be later than the latest arrival time period of the ship. When the scheduled docking time period of the ship is later than the latest arrival time period of the ship, the docking time period will be generated. An effective ship assignment model will minimize the total waiting time periods of all ships. Keeping all these requirements in mind, we establish the following optimal docking assignment model as shown in Model 1.

\[\text{Model 1}\]
\[
\begin{align*}
\text{min} & \sum_{i,j} d_{ij} \\
\text{s.t.} & \sum_{i} x_{ijk} = 1, j \in \{1,2,\ldots,n\} \\
& \sum_{j} x_{ijk} \leq 1, i \in \{B_k, B_k + 1,\ldots,m\}, k \in \{1,2,\ldots,t\} \\
& x_{ijk} + (1 - x_{ijk})E_k \geq T_b, j \in \{B_k, B_k + 1,\ldots,m\}, j \in \{1,2,\ldots,n\}, k \in \{1,2,\ldots,t\} \\
& T_d + d_{ij} - d_{ij} \geq x_{ijk} \cdot (1 - x_{ijk}), i \in \{B_k, B_k + 1,\ldots,m\}, \forall j \in \{1,2,\ldots,n\}, k \in \{1,2,\ldots,t\} \\
& x_{ijk} \leq 1 - x_{ijk}, j \in \{B_k, B_k + 1,\ldots,m\}, h \in \{1,2,\ldots,n\}, k \in \{1,2,\ldots,t\} \\
& Tyb x_{ijk} \leq Tyb, i \in \{B_k, B_k + 1,\ldots,m\}, j \in \{1,2,\ldots,n\}, k \in \{1,2,\ldots,t\} \\
& d_{ij} \geq 0 \\
& x_{ijk}, d_{ij} \in \{0,1\}
\end{align*}
\]

\[(\text{continued on next page})\]
In Model 1, the objective function 1.0 minimizes the total waiting time of all ships. Constraint 1.1 means that each ship must be scheduled to dock within a day. Constraint 1.2 means that at most one ship can be docked at each berth in each time period. Constraint 1.3 means that the docking time period of each ship is later than the earliest arrival time period, which is automatically satisfied when \( x_{ik} = 0 \). When \( x_{ik} = 1 \), this constraint becomes \( i \geq T_{Ek} \), which is the constraint that the ship’s docking time is later than the earliest arrival time. Constraint 1.4 is the constraint of the latest berth time period. When \( x_{ijk} = 0 \), this constraint becomes \( T_{Lk} + d_{ij}^* - d_{ij} \geq E_{yk} \), since the maximum value of \( d_{ij}^* \) is \( E_{yk} \), the constraint is obviously established. When \( x_{ijk} = 1 \), this constraint becomes \( T_{Lk} + d_{ij}^* - d_{ij} \geq 1 \). In this case, if the time period \( i < T_{Lk} \), then the scheduled time period should be earlier than the latest arrival time period of the ship. Thus, in the pursuit of the goal of minimizing \( \sum \) the \( j \), to meet \( d_{ij}^* = 0 \), \( d_{ij} = T_{Lk} - i \) will mean that there will not be any additional waiting time. If \( i > T_{Lk} \), this will mean that the docking time period of the ship \( j \) is arranged after its latest arrival time period, resulting in waiting \( d_{ij}^* > 0 \). In Constraint 1.5, the ship \( j \) is scheduled to dock at the berth \( k \) in the time period \( \) when \( x_{ijk} = 1 \). Since the docking time of the ship \( j \) is \( T_{Lk} \), no other ship can be scheduled to dock in the next period \( T_{Lk} - 1 \), \( x_{ijk} \leq 0 \). When \( x_{ijk} = 0 \), this constraint does not affect the corresponding \( x_{ik} \) to take the value of 0 or 1. Constraint 1.6 is the size constraint of the ship stopping at the berth. Generally, the small ship can stop at the berth where the large ship stops, but the large ship cannot stop at the berth where the small ships stop. Constraint 1.7 means that the latest docking completed time period of each ship must be earlier than the latest off-duty time period of the berth. Constraint 1.8 is variable constraint.

3.3. Ship docking assignment model which balances the docking tasks of each berth after considering the minimization of total waiting time

Through Model 1, we can realize the design of ship docking scheme with the least total waiting time. However, in real life problems, there will still be a situation where the ship cannot arrive as scheduled, that is, the arrival time period of the ship will be uncertain. Although the rate of ships not arriving at the appointed time period can be effectively reduced by penalizing ships not arriving at the appointed time period, there will still be some ships not arriving at the appointed time period. In view of the above situation, we further consider balancing the docking tasks of each berth to deal with the additional docking time period of ships that do not arrive at the appointed time period. The main principle is to further balance the berthing tasks of each berth on the premise of ensuring the least total waiting time period of ships. At this time, each berth will have some slack of berthing time period to deal with the uncertainty of ship arrival time period. The relevant model is shown in Model 2.

\[
\text{Model 2} \quad \min \big( t^{*} \max \{ E_{k} \} + \sum_{k=1}^{n} \sum_{i=1}^{t} d_{ij}^* + \sum_{j=1}^{n} (d_{ij}^* + dx_{jk}^*) \big) \quad \text{subject to constraints 1.1 to 1.7} \quad \text{1.9}
\]

The first term in objective function 1.9 in Model 2 \( t^{*} \max \{ E_{k} \} + \sum_{k=1}^{n} \sum_{i=1}^{t} d_{ij}^* \) is the objective of minimizing the total waiting time of all ships. The coefficient \( t^{*} \max \{ E_{k} \} \) is set to give priority to the objective of minimizing the total waiting time of all ships. If the minimization of the overall waiting time of ships and the balanced design of berthing tasks at each berth are considered at the same time, the coefficient \( t^{*} \max \{ E_{k} \} \) can be properly modified. The second term \( \sum_{j=1}^{n} (d_{ij}^* + dx_{jk}^*) \) in objective function 1.9 is the total amount of berthing tasks of each berth greater than or less than the average berthing tasks, which is introduced based on the balanced design of berthing tasks of each berth. Constraint 1.10 is a constraint on the assignment of balanced tasks to each berth, where \( dx_{jk}^* \) represents the number of tasks assigned to the berth \( k \) lower than the average berthing assignment tasks, and \( dx_{jk}^* \) represents the number of tasks assigned to the berth \( k \) higher than the average berthing assignment tasks. In Constraint 1.11, two groups of variable constraints are added on the basis of Constraint 1.7 in Model 1.

3.4. Ship docking assignment model that minimizes the total waiting time of ships after first considering the earliest docking task completion time

Although the balanced docking target of each berth docking task is achieved through Model 2, the slack docking time is still distributed in the early time period, so it cannot be used reasonably.

If the slack docking time of each berth can be distributed in the later time period, the slack time of the later period can be used when the ships scheduled to dock in front cannot arrive as scheduled, so as not to occupy the cross period of time. Therefore, it is necessary to further establish a mathematical model to complete the docking task of all berths as soon as possible. The specific model is shown in Model 3.

\[
\text{Model 3} \quad \min \big( n^{*} \max \{ E_{k} \} \cdot M + \sum_{j=1}^{n} d_{ij}^* \big) \quad \text{subject to constraints 1.1 to 1.6} \quad \text{1.12}
\]

The first term \( n^{*} \max \{ E_{k} \} \cdot M \) in the objective function in Model 3 means that the smaller the earliest completion time of all tasks, the better. The coefficient \( n^{*} \max \{ E_{k} \} \) is introduced to ensure that we first consider the earliest docking task completion time and then minimize the total waiting time of all ships. Constraint 1.13 in Model 3 is obtained by modifying the constant term \( E_{k} \) in Constraint 1.7 in Model 1 to decision variable \( M \). In Constraint 1.14, the constraint of new variable \( M \) is added on the basis of the constraint of Model 1 reason.

3.5. Ship docking assignment model which meets the expected docking time of ships after considering the minimization of total waiting time

In the previous three models, we assume that the arrival time of each ship can be flexibly selected within the earliest and latest arrival time period provided by it. However, during actual navigation, it may be difficult for the ship to arrive at the designated time. Therefore, in the process of setting the docking time node for ships, it may be necessary to approach the expected arrival time of each ship as much as possible, so as to achieve the goal that each ship can arrive according to the expected time node. Therefore, a mixed integer programming model as shown in Model 4 can be established.

\[
\text{Model 4} \quad \min \big( n^{*} \max \{ E_{k} \} + \sum_{j=1}^{n} d_{ij}^* + \sum_{j=1}^{n} (dy_{ij}^* + dy_{ij}^*) \big) \quad \text{subject to constraints 1.1 to 1.7} \quad \text{1.15}
\]

The last term in the objective function of Model 4 \( n^{*} \max \{ E_{k} \} + \sum_{j=1}^{n} d_{ij}^* + \sum_{j=1}^{n} (dy_{ij}^* + dy_{ij}^*) \) term is the sum of
3.6. The flexible use of all of our models

In Models 1 through 4, we propose multiple objectives: minimizing the sum of the total berthing time periods of each ship, balancing the tasks of each berth, minimizing the latest completion time period of all berths, and meeting the expected berthing time period of all ships as much as possible. The flexible adjustment of the model objective function can realize the new scheme design under different docking tasks and different docking objectives. After combining the Models 1 through 4, an optimization model considering multiple objectives as shown in Model 5 is obtained.

\[
\text{Model 5: } \min \sum_{j} \sum_{t} d_{jt}^2 + \sum_{j} \sum_{t} (dx_{jt}^2 + dy_{jt}^2) + \alpha M + \alpha \sum_{j} \sum_{t} (dx_{jt}^2 + dy_{jt}^2)
\]

Constraints 1.1 to 1.6, Constraints 1.10, 1.13, 1.16

\[x_{jt} = 0 \text{ or } 1, d_{jt}^2, dx_{jt}^2, dy_{jt}^2, M \geq 0, t \in \{1, 2, \ldots, t\} \]

In the objective function of Model 5, we give a weight to each objective pursuit. In the actual decision-making process, the weight can be flexibly selected according to the number of docking tasks. All constraints after the objective function are those in Models 1 through 4, which will not be introduced again.

4. Case study

In this section, we use real-life examples to prove the universality of our mixed integer programming model and develop a GUROBI precise algorithm to solve it. The results show that the scale of operation has been greatly improved compared with previous literatures. Finally, the docking results obtained by several different models in the example are visualized by MATLAB software to clearly show the advantages of the model in dealing with the problem.

We demonstrate the procedure of our models using a real-life case and successively applying our models to the data therein to obtain optimum ship docking schedules. In Table 2, we give the basic information of 36 ships to arrive on a certain day. The data is assumed to be provided by the ship enterprise according to its own docking demand. At present, it is assumed that there are 12 berths available, and ships can dock in 24 time periods. The earliest docking time period of each berth is unified as 1, the latest ship docking completion period is unified as 25. The first five berths are of Type 1, while the other berths are of Type 2. Therefore, in the previous model we have:

\[
m = 24, n = 36, t = 24, B_1 = \{1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1\},\]

\[E_1 = \{25, 25, 25, 25, 25, 25, 25, 25, 25, 25, 25, 25\},\]

\[T_{b1} = \{1, 1, 1, 1, 1, 2, 2, 2, 2, 2, 2\}.\]

### Table 2

| Ship number | Earliest arrival time of vessel | Expected arrival time of ship | Latest arrival time of ship | Length of ship berthing | Ship type |
|-------------|--------------------------------|-----------------------------|--------------------------|------------------------|-----------|
| 1           | 3                              | 4                           | 5                        | 6                      | 1         |
| 2           | 1                              | 2                           | 4                        | 10                     | 2         |
| 3           | 14                             | 15                          | 17                       | 4                      | 1         |
| 4           | 2                              | 3                           | 4                        | 12                     | 2         |
| 5           | 4                              | 6                           | 8                        | 4                      | 1         |
| 6           | 1                              | 2                           | 3                        | 8                      | 2         |
| 7           | 10                             | 11                          | 13                       | 4                      | 1         |
| 8           | 2                              | 3                           | 4                        | 2                      | 1         |
| 9           | 8                              | 10                          | 13                       | 8                      | 2         |
| 10          | 2                              | 3                           | 5                        | 5                      | 1         |
| 11          | 2                              | 3                           | 4                        | 9                      | 2         |
| 12          | 11                             | 12                          | 13                       | 7                      | 2         |
| 13          | 6                              | 8                           | 9                        | 7                      | 2         |
| 14          | 8                              | 11                          | 14                       | 8                      | 2         |
| 15          | 14                             | 18                          | 20                       | 6                      | 2         |
| 16          | 7                              | 8                           | 9                        | 12                     | 2         |
| 17          | 5                              | 9                           | 12                       | 6                      | 1         |
| 18          | 6                              | 7                           | 8                        | 12                     | 2         |
| 19          | 5                              | 7                           | 8                        | 5                      | 1         |
| 20          | 1                              | 2                           | 3                        | 6                      | 1         |
| 21          | 11                             | 12                          | 13                       | 6                      | 1         |
| 22          | 2                              | 5                           | 8                        | 14                     | 2         |
| 23          | 3                              | 4                           | 6                        | 6                      | 1         |
| 24          | 6                              | 9                           | 12                       | 5                      | 1         |
| 25          | 5                              | 8                           | 9                        | 7                      | 2         |
| 26          | 2                              | 4                           | 6                        | 7                      | 2         |
| 27          | 12                             | 14                          | 16                       | 6                      | 1         |
| 28          | 3                              | 5                           | 7                        | 3                      | 1         |
| 29          | 4                              | 5                           | 6                        | 3                      | 1         |
| 30          | 15                             | 16                          | 18                       | 2                      | 1         |
| 31          | 2                              | 3                           | 5                        | 3                      | 1         |
| 32          | 4                              | 5                           | 6                        | 2                      | 1         |
| 33          | 14                             | 15                          | 17                       | 3                      | 1         |
| 34          | 2                              | 4                           | 5                        | 2                      | 1         |
| 35          | 3                              | 4                           | 5                        | 2                      | 1         |
| 36          | 3                              | 4                           | 6                        | 2                      | 1         |

**Fig. 1.** Graphical display of docking assignment of ships which minimizes the total docking waiting time.

**Fig. 1.** Graphical display of docking assignment of ships which minimizes the total docking waiting time.

upper left corner indicates that the ship No. 1 will stop for 6 time periods, and the waiting time before docking is 0. It is not difficult to find that the earliest arrival period of the ship No. 1 is 3 and the latest arrival period is 5, so there will be no docking waiting time when it is docked in
the third period. The two numbers in purple brackets below the arrow line in Fig. 1 represent the expected docking time period and the actual docking time period of the ship. As shown in Fig. 1, the purple number (4,3) in the upper left corner indicates that the expected docking time period of the ship No. 1 is 4 and the actual docking time period is 3. The green number on the far right in Fig. 1 represents the overall docking time periods of all ships which docked on the berth of this row. For example, the total number of berthing periods on the 12th berth is 18. The numerical interpretation in subsequent figures is the same as that in Fig. 1.

Through Fig. 1, it is not difficult to find that all ships have no docking waiting time. This further shows the effectiveness of our proposed model. However, it is not difficult for us to find some unreasonable berthing, such as that the latest completion time of ship berthing in the sixth berth is too late, the tasks of each berth are unbalanced, and the berthing period of each ship is not consistent with its expected berthing period. We, therefore, resort to Model 2 and those results are shown next.

4.2. Result analysis of model 2

Considering the unbalanced docking tasks that appear in Model 1, it is further considered to use Model 2 to assign the berthing tasks of each berth in a balanced manner. Using Model 2 and its corresponding GUROBI algorithm, the design of the balanced assignment scheme of each ship docking can be obtained as shown in Fig. 2. It can be seen from Fig. 2 that the waiting time of all ships have not changed, but the maximum working hours of each berth are reduced from 23 to 19, which can effectively deal with the special situation that some ships fail to arrive according to the appointed time window.

4.3. Result analysis of model 3

It can be seen from Fig 2 that although we have realized the balanced design of berthing tasks of each berth in Model 2, the latest completion period of berthing tasks of berth 11 is 25. At this time, if ship No. 15 fails to arrive within the appointed time period, it is likely that it will be unable to complete all docking tasks within the 25th time period. Therefore, we use Model 3 to optimize the completion time of the latest docking task. The relevant results are shown in Fig. 3.

It can be seen from Fig. 3 that the latest docking task completion period of all berths is improved from the 25th time period in Model 1 and Model 2 to the 20th time period, but the total docking waiting time of all berths are unchanged.

4.4. Result analysis of model 4

In Model 1, Model 2 and Model 3, we do not consider the goal of matching the docking time period of each ship with its expected docking time period as much as possible. Therefore, we use Model 4 to further optimize the matching degree between the docking time period and its expected docking time period of each ship. The relevant results are shown in Fig. 4.

It can be seen from Fig. 4 that we have met the expected docking time period of 16 ships, and the total time period gap between the expected docking time period and the actual docking time period is 26. Compared with Models 1 through 3, the matching degree of the expected docking time period has improved. However, although we optimized the expected berthing time period of ships, the docking problems reappear, such as the imbalance of docking tasks and late completion time of docking tasks.

4.5. Result analysis of model 5

From the results of Models 1 through 4, it can be seen that each of these schemes has one or more shortcomings. Considering that the priority completion of all docking tasks is very important in real life
problems, we set the weight $\alpha_3$ of decision variable $M$ as $\alpha_2 = \alpha_4 = 1$. These results are shown in Fig. 5.

It can be seen from Fig. 5 that although the overall waiting time of ships has increased by 1 period, we have achieved the goal of minimizing the earliest docking completion time and balancing the docking tasks of each berth. In addition, the gap between the actual docking time of each ship and its expected docking time is 30, which is only inferior to the result of Model 4.

4.6. Result analysis in first come first served docking strategy

In this subsection, we consider another docking strategy that is popularly used in practice. This is the first come, first served (FCFS) strategy. If the port management department adopts the FCFS strategy, all ships will consider arriving at the port as soon as possible and then wait for docking. Therefore, the earliest arrival period, the latest arrival period and the expected arrival period of the ships will all be the early arrival period, that means $T_{Lj} = T_{Mj} = T_{Ej}$. Under the FCFS strategy, the ship will dock as soon as there is a free berth. Using the corresponding algorithm, we obtain the ship docking assignment result as shown in Fig. 6.

4.7. Comparison and analysis of different docking strategies

For the purpose of comparative analysis, we summarize the key data of different results after optimizing the ship docking time period using Models 1 through 5 and the results of the FCFS strategy. This comparison is shown in Table 3. It can be seen from Table 3 that Model 5 is the best performing strategy, and this result is also better than the FCFS strategy on each of the goals. At the same time, because Model 5 also generates specific docking period of ships, we can effectively avoid potential port congestion caused by too many ships arriving at the same time period.

4.8. Discussion on further generalization and application of the model

In the example provided in this section, we see that the length of the total berthing periods of all ships is close to the total berthing service periods that can be provided by each berth. But, in real life problems, actual arrival rate of ships could be higher or lower. We will consider these two cases in turn next.

(1) Model selection when the arrival rate of ships is less

When the arrival rate of ships is relatively small, the average docking task of each berth is relatively low. Therefore, Model 2 can be used to balance the work tasks of each berth. At this time, the parameter $E_k$ in the model can also be appropriately reduced to realize the final task assignment, so as to deal with the special case of late arrival of ships. When the arrival rate of ships is lower, we can even consider reducing the number of berths so as to give well-deserved rest to the berth staff in turn.

(2) Selection of model when the arrival rate of ships is high

When the arrival rate of ships is high, the average berthing task of each berth becomes higher, so we should give priority to completing the berthing task of each berth as soon as possible. At this point, Model 3 seems more appropriate. Of course, a more reasonable assignment using Model 5 can also be considered. But, as the number of variables in Model 5 is the largest, it is also the most difficult for obtaining the optimal solution when the number of ships is large. Model 3, therefore, could be an appropriate model for this case.

(3) Discussion and analysis of the solution scale of the models

In this example, we use GUROBI to find the optimal solution of the ship docking model with $12 * 24 * 36 + 2 * 12 + 4 * 36 + 1 = 10537$ decision variables and 1418797 constraints. In order to test the applicability of the model for a large scale problem, we use a computer with
Intel® Core™ i7-10700KF CPU@3.80 gigahertz, 32 gigabytes memory and a 64-bit Windows 10 operating system, with a quad-core CPU having eight logical processors. The experimental results show that the maximum decision variables and constraints that our algorithm can solve in 56 h can reach 20201 and 3943593. We also compare the results obtained by several different software. The solving scale of mixed integer programming calculated by MATLAB is very small and the calculation speed is slow. CPLEX can obtain the exact solution of a larger scale model, but it often stops due to insufficient memory. We found that GUROBI is 10% or more faster than CPLEX for solving the same model.

In order to solve problems much larger than the current port docking scale, we follow the following procedure. First, according to the port capacity, the number of ships to arrive and the docking scale that the computer can calculate at present, we estimate the number of port docking location blocks. Second, the optimal assignment result of each block docking task is obtained by using the correlation algorithm. Finally, a heuristic algorithm is used to exchange docking tasks to improve the overall efficiency of port docking.

(4) Application of the model in an emergency scenario

Because the model established in this paper considers the time period when the arriving ships can start to dock with the berth and the latest off-duty time period of the berth, the model can also be used to re-optimize the docking task in the emergency scenario. The deletion or addition of relevant constraints can achieve the goal of maximizing the docking efficiency in emergency scenarios without affecting the overall docking plan.

(5) Generalization and application of the model in other fields

The ship docking model proposed in this paper is essentially a complex queuing problem with multiple service desks and multiple passenger sources. There are many similar queuing problems in engineering practices, such as the sharing and use of equipment in the medical field. Therefore, the model proposed in this paper has strong general applicability.

5. Conclusion

In this paper, we propose for the first time a mixed integer programming model that has the goal of improvement of port berthing efficiency, considering the number of ships, the number of berths, the size and type of ships and a number of time periods. In addition, for the matching of the total berthing time of the ship and the total berthing time of the berth, we introduce different models based on the objectives of shortest total berthing time, balanced berthing tasks of each berth, completing all berthing tasks as soon as possible and meeting the expected berthing time of each ship as far as possible. Finally, a multi-objective programming model considering all of the above four objectives is introduced.

In order to verify the applicability of the model proposed in this paper, we have compiled the model solution algorithm based on GUROBI, and combined with the actual data of some ports, we have obtained a docking scheme of ships in different periods and berths that are better than those in the current literature. At the same time, we produce the optimization results through MATLAB on a visual display technology. This visual technology would help the managers in the field to understand the models and the results much better. This display also shows the advantages and disadvantages of different docking schemes. The experimental results show that the performance of the ship docking strategy based on multi-objective is better than that of the ship docking strategy based on first come first served for each goal. At the same time, it will effectively avoid the port congestion caused by seizing berths under the first come first served strategy because of its predetermined docking time. Finally, we find that the scale of the exact solution solved by our model is significantly larger than those in the previous literature, which further shows the potential of our model to be highly beneficial in real life scenarios.

In this case, it can be found that the model is more practical. However, due to the different sizes of ports, in the face of larger port berths, the number of ships docking, the number of berths will become more, and the type of ships will become difficult to estimate. Due to the limited level of computer development, the operation scale is sometimes difficult to meet the requirements of larger ports. If the application of this model still fails to better allocate ships to berths, we can adopt the following method to improve port operation efficiency. First, it can improve the efficiency of port loading and unloading and reduce the time of ships in port. Second, it can be done by establishing a global shipping alliance, through the establishment of shipping alliances, more ship enterprises can cooperate, and ship docking positions can be more efficiently mobilized. Finally, transport cooperation between ports can be strengthened at the governmental level, on the premise of a common economic hinterland of course.

This paper mainly addresses the problems of increased port traffic and low port efficiency due to the outbreak of COVID-19. However, the model has strong universality, for example, the port congestion problem appears under special circumstances such as war and national policy inclination. In addition, the general model proposed in this paper can also be applied to the queuing problem of single type of service tasks in multiple service windows, such as the queuing problem of charging caused by the increase in the sales of renewable energy vehicles caused by the rising oil price, or the scheduling problem of urban public transport.

The port docking mixed integer programming model proposed in this paper is not only suitable for the optimization of port docking efficiency during the epidemic, and also suitable for the optimization of port ship docking in emergency scenarios, but it is also suitable for the queuing problem with multiple service windows and single type service tasks. In future, the further promotion of the model proposed in this paper in different practical problems and the research on the solution algorithm of larger scale model have strong research value.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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