Tugboat scheduling problem in large container ports: A case study of the Singapore port

Haocheng Yu
School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, Hubei, 430070, China
E-mail: 653784505@qq.com

Abstract. In recent years, more and more container ports have become congested because of the large number of visiting ships to the ports. This causes a difficult dispatching and management problem for port operators, that is, the tugboat scheduling problem. To solve the problem effectively from the operational viewpoint, this study proposes an interesting tugboat scheduling problem in a large container port. A mixed-integer linear programming (MILP) model is built for the problem with the objective function of minimizing the total processing cost for container ships. We also consider the constraints of horsepower limitation of tugboats, utilization time limit of tugboats, etc. By using the commercial solver CPLEX to solve the built MILP model in a case study of the Singapore Port, the efficiency of the MILP model is presented. It takes less than 18 hours to reduce the optimality gap to a maximum of 0.9% for solving a real-size instance with 12 tugboats and 100 ships. Moreover, the results of extensive computational experiments also show the applicability and effectiveness of the MILP model to handle real-world tugging operations.

1. Introduction

Tugboats are important to container ports and container ships. When container ships approach port berths, tugboats need to push or pull them through crowded fairways to ensure safety and work efficiency [1]. Tugboats work according to their schedules, which explicitly include the allocation of container ships to each tugboat, as well as the exact pushing/pulling time for each container ship. However, it is difficult to make a good tugboat schedule and implement it as strictly as possible at the same time [2]. This is because fairways are congested and scheduling should take into account many practical situations such as collision avoidance and operation efficiency [3]. To do so, this paper develops a mixed-integer linear programming (MILP) model for the tugboat scheduling problem with the objective function of minimizing the total processing cost for container ships under the limitation of tugboat horsepower, tugboat utilization, etc. In this case, we can achieve effective tugboat operations and management that are imperative for large and busy container ports.

In the past two decades, according to our literature review, there are a limited number of studies on tugboat scheduling: three article papers and two conference papers. Xu et al. [4] formulated the tugboat scheduling problem as a multiprocessor task scheduling model and Kang et al. [5] addressed the tugboat scheduling problem considering uncertainty in both container ship arrival and tugging process times for large container ports by using a finite set of discrete scenarios to represent the uncertain ship arrival and tugging process times based on historical port traffic data. Zhen et al. [6] formulated the tug scheduling as a MILP model, in which they assigned one or more barges to one tug.
The two conference papers studied the basic tugboat scheduling problem. Both Wang et al. [7] and Chang et al. [8] formulated them as mixed-integer nonlinear programming models with the objective functions of minimizing the overall tugboat operation time.

2. Problem statement
Figure 1 shows a typical tugboat service network, which consists of two anchorages, three berths, and two tugboat bases [6]. Let $I$ be the set of tugging jobs for incoming ships, where $I = \{i|i = 1, 2, ..., n\}$, and let $K$ be the set of tugboats, where $K = \{k|k = 1, 2, ..., m\}$. In this service network, the working processes of tugboats will be introduced in detail as follows.

The tugging processes can be regarded as a bi-directional job scheduling operation; that is, anchorage-to-berth and berth-to-anchorage. The following content formally introduces the tugboat scheduling. A scheduled ship trip in a container port is defined by the given arrival and departure nodes (anchorage + berth), as well as the arrival and departure times of the ship. For a given set of scheduled ship trips (anchorage-to-berth and berth-to-anchorage trips) at the container port, the tugboat’s scheduling consists of combining ship trips to tugboat duties in such a way that each trip is covered exactly once and each tugboat performs a feasible sequence of ship trips. Furthermore, each tugging operation must start and end at the same anchorage. The tugging schedule must meet other special requirements, such as the minimum tugboat fleet size for a certain number of ships and tonnages [6]. The operational costs (such as the total processing time of the tugboat and the tugging delay) are expected to be minimized [9]. In the case of multiple ship types and/or multiple anchorages, the corresponding tugboat scheduling can be NP-hard.

3. Model formulation
As introduced, each tugging operation is defined as a job in this study. That is, a ship tugged from an anchorage to a berth or vice versa. Ships arriving at anchorages and departing from berths are scheduled by time. Thus, all jobs can be sorted with an increasing time sequence in a job set $J$. We first formulate the basic tugboat scheduling problem as a MILP model, namely, MILP-TSM (tugboat scheduling model).

\[ \text{[MILP-TSM]}: \quad \min \sum_{j \in J} \sum_{k \in K} x_{jk} \]
subject to

\[ x_{jk} - \sum_{i \in I} (w_i \cdot p_{ik} \cdot u_{ij}) - \sum_{i \in I} [u_j \cdot (1 - \sigma_j) \cdot M] \geq 0, \forall j, \forall k \in K \quad (2) \]

\[ t_{(j+1)k} - t_{jk} - \sum_{i \in I} (p_{ik} \cdot u_j) \geq 0, \forall j, \forall k \in K \quad (3) \]

\[ t_{jk} + \sum_{i \in I} (p_{ik} - d_i) \cdot u_j \leq 0, \forall j, \forall k \in K \quad (4) \]

\[ \sum_{i \in I} u_j \leq 1, \forall j \quad (5) \]

\[ \sum_{i \in I} u_j \cdot U_i = 1, \forall j, \forall i \in I \quad (6) \]

\[ \sum_{i \in I} U_i \leq \xi \quad (7) \]

\[ u_j \in [0, 1], \forall j, \forall i \in I \quad (8) \]

\[ U_i \in \{0, 1\}, \forall i \in I \quad (9) \]

Objective (1) minimizes the total processing cost for container ships, where the weighted processing time of the \( j \)th container ship by tugboat \( k \) is calculated using Equation (2). The term \( \sum_{i \in I} [u_j \cdot (1 - \sigma_j) \cdot M] \) represents the penalty added to the tugboat when the horsepower of the tugboat \( k \) is less than the tonnage of the \( j \)th ship. That is, \( x_{jk} = M \) if the tugboat \( k \) cannot handle the \( j \)th ship in terms of horsepower. Otherwise, \( x_{jk} \geq \sum_{i \in I} (w_i \cdot p_{ik} \cdot u_j) \). Equation (3) enforces that the tugging job scheduled in the \((j+1)\)th position by tugboat \( k \) cannot start until its preceding tugging job is completed. Equation (4) guarantees that scheduled tugging jobs must be completed before their due times. Equation (5) ensures that each tugging job can only be scheduled at most once. Equation (6) states that tugging jobs are either scheduled on time or late. However, the maximum number of delayed jobs is constrained by Equation (7) to ensure schedule efficiency. Equation (8) and (9) show the domains of the decision variables. By introducing the auxiliary variable \( U_i \), this formulation requires only \( n^2 \) positional variables, regardless of the number of tugboats involved.

4. Numerical studies

Figure 2 shows a real tugboat service network, based on which we conduct experiments and solve the MILP model. The tugboat service network consists of one anchorage, one tugboat base, two berths, and two channels between the anchorage and berths.

![Figure 2. A real tugboat service network [9].](image)

Sixteen scenarios (No.1-16) with different numbers of tugboats and ships are created. The container ships’ calling times are generated randomly through MATLAB. As can be seen in Table 1,
the number of tugboats ranges from 5 to 12, and the number of ships is between 40 and 100. This problem size is equivalent to the half-day workload of the Singapore port approximately. The model was solved in a desktop with a 4×2.5 GHz CPU and 32 GB of RAM. We show the efficiency of the above model in three aspects: objective value, optimization gap (\(\text{gap} = \frac{\text{Best integer} - \text{Best bound}}{\text{Best bound}} \times 100\%\)), and CPU time, as shown in Figure 3 (A-C). Based on the reported gap, the MILP model can be solved almost optimally. However, the efficiency of the model in different sizes is quite different. For small instances such as “5 tugboats and 40 ships”, the MILP model can be solved optimally within 32 sec. When problem sizes increase to “7 tugboats and 40 ships”, “9 tugboats and 40 ships”, and “12 tugboats and 40 ships”, it takes 41 sec, 618 sec, and 945 sec respectively to solve the MILP model. In particular, the CPU time frantically increases to 93959 sec to solve a large-sized problem (12 tugboats and 100 ships). Based on these extensive computational experiments, we can find the applicability and effectiveness of the model to handle real-world tugging operations.

Table 1. Results of the model.

| Scenario | Problem size | MILP Performance |
|----------|--------------|------------------|
|          | Tugboats   | Ships | Objective (min) | Gap  | CPU time (sec) |
| 1        | 5          | 40    | 249             | 0.10% | 32              |
| 2        | 5          | 60    | 866             | 0.20% | 118             |
| 3        | 5          | 80    | 1484            | 0.20% | 1243            |
| 4        | 5          | 100   | 2163            | 0.30% | 2557            |
| 5        | 7          | 40    | 213             | 0.50% | 41              |
| 6        | 7          | 60    | 797             | 0.40% | 1502            |
| 7        | 7          | 80    | 1387            | 0.60% | 7745            |
| 8        | 7          | 100   | 1954            | 0.80% | 9436            |
| 9        | 9          | 40    | 159             | 0.90% | 618             |
| 10       | 9          | 60    | 736             | 0.40% | 3938            |
| 11       | 9          | 80    | 1281            | 0.30% | 11138           |
| 12       | 9          | 100   | 1835            | 0.70% | 17785           |
| 13       | 12         | 40    | 67              | 0.10% | 945             |
| 14       | 12         | 60    | 607             | 0.10% | 17316           |
| 15       | 12         | 80    | 2419            | 0.10% | 34925           |
| 16       | 12         | 100   | 3450            | 0.90% | 63959           |

A: Objective value
Figure 3. The performance of the MILP model.
5. Conclusions

Container ships are not allowed to fully maneuver near the basin of a container port due to shallow waters and their powerful inertial force that may crash berths during their berthing time. They are pushed (direct contact) or pulled (by means of a tow line) by powerful tugboats through crowded and narrow fairways and tugboat resources are quite limited [6]. In this study, a MILP model was first developed for the tugboat scheduling problem with the objective function of minimizing the total processing cost for container ships. By using the solver CPLEX to solve the built MILP model in a case study of the Singapore Port, the efficiency of the MILP model was validated. Some future studies are presented here. It is worthwhile to study the green tugboat scheduling concerning the global emission of greenhouse gases. In terms of operations research and optimization problems, the green tugboat scheduling can be as follows: tugboat routing, port multi-service congestion, tugboat, and gantry crane scheduling, and dynamic tugboat fuel consumption modeling.

Acknowledgements

The author sincerely thanks Prof. L. Kang, who proposed the idea of the study and helped me improve the paper significantly.

References

[1] Kang L, Meng Q and Liu Q 2018 Fundamental diagram of ship traffic in the Singapore Strait Ocean Eng. 147, 340-354
[2] Kang L, Lu Z, Meng Q, Gao S and Wang F 2019 Maritime simulator based determination of minimum DCPA and TCPA in head-on ship-to-ship collision avoidance in confined waters Transportmetric A 15(2) 1124-44
[3] Kang L, Meng Q, Zhou C and Gao S 2019 How do ships pass through L-shaped turnings in the Singapore Strait Ocean Eng. 182 329-42
[4] Xu Q, Mao J and Jin Z 2012 Simulated annealing-based ant colony algorithm for tugboat scheduling optimization Math. Probl. Eng. 2426978, 1-22
[5] Zhen L, Wang K, Wang S and Qu X 2018 Tug scheduling for hinterland barge transport: A branch-and-price approach Eur. J. Oper. Res. 265(1), 119-32
[6] Kang L, Meng Q and Tan K C 2020 Tugboat scheduling under ship arrival and tugging process time uncertainty Transport. Res. E 144 102125
[7] Wang S, Kaku I, Chen G and Zhu M 2012 Research on the modeling of tugboat assignment problem in container terminal Adv. Mater. Res. 433 1957-61
[8] Chang D, Hu X and Bian Z 2012 A research on port tug dynamic scheduling model and algorithm Advanced Mater. Res. 524 832-35
[9] Kang L, Gao S and Meng Q 2020 Capacity analysis of ship-tugging operations in a large container port. Asian Transport Stud. 6 100011