

# Enhanced Model for Tugboat Scheduling Problem Considering Multiple Tugboat Assignment to Minimize Total Tugging Operation Time

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**Abstract**— Ports that handle massive container ships play a pivotal role in global logistics and supply chain operations. These ports provide essential services for managing and accommodating the large container vessels. When a container ship arrives at a port, it requires the assistance of powerful tugboats to aid in critical maneuvering. These tugboat operations are crucial for safely docking the ship at its designated berth, repositioning or shifting the vessel within the port area, and undocking or allowing the ship to depart from the berth. The efficient scheduling of tugboats to serve these vessels is essential to ensure the safe and smooth movement of container ships during their time at the port. This research examines the tugboat scheduling problem (Tug-SP), focusing on reviewing literature to identify variables for optimizing tugboat operations. It proposes incorporating horsepower capacity constraints and conducts numerical experiments to demonstrate the practical significance of the developed models using historical port data from a major maritime hub in Southeast Asia. The findings revealed no substantial discrepancy between the projected scenarios and the historical data. Future research could explore more dynamic problems, solve larger and more complicated cases, design more efficient solution methods, and use appropriate algorithms. Additionally, other factors such as uncertainty in ship arrival times or specific situations could be considered as variables to minimize total tugboat service time or reduce operational costs, especially for large and busy container ports.

**Keywords**— *Container Port, Tugboat Scheduling Problem, Logistics, Supply chain.*

## I. INTRODUCTION

Ports have evolved into central hubs for the distribution of goods, bridging the gap between producers (senders) and consumers (recipients), with their core services revolving around handling ships and cargoes. Ports play a pivotal role in facilitating trade, particularly international trade on a global scale. Global trade has undergone a remarkable expansion since the 1950s, accounting for an increasingly larger share of worldwide economic output. In 2007, international trade surpassed 50% of the global Gross Domestic Product (GDP) for the first time in history, a substantial increase from the conventional range of 20% to 25% that it occupied during the first half of the 20th century. In the 19th century, the proportion of world trade to global economic output was even lower, hovering around just 10% [1]. As trade continues to expand rapidly and ship traffic volumes surge, the utilization

of tugboats at ports has become an indispensable necessity for carrying out business operations. Tugboats play a vital role in facilitating safe and efficient port operations. A tugboat is a small vessel that assists larger ships in docking at the port or unmooring at sea by pulling or pushing the ship towards the port. This prevents the larger ship from damaging the dock when anchoring at the port [2]. Tugboats are needed to help ships berthing operations to or from the jetty/pier and have an important influence on the ship's turnaround time.

Tugboat operations require meticulous planning due to the limited number of available tugboats and the constrained capacity of each tugboat to service vessels. Since the costs of renting tugboats and their fuel consumption are substantial, optimizing the scheduling of the available tugboat fleet is of utmost importance. Effective scheduling ensures that vessel service requirements are met while minimizing the time and expenses incurred during tugboat operations. Accurate tugboat scheduling planning can facilitate efficient port activities and prevent delays in the loading/unloading of containers from ships.

## II. RELATED STUDIES

Several previous studies have addressed the steps taken for the scheduling of tugboat operation activities. The studied explored by [3] the tugboat scheduling problem in the context of barge operations. Their approach involved assigning one or more barges (grouped into batches) to a single tugboat and determining the departure time for each tugboat. It's worth noting that in their study, each tugboat was assigned only one task within the given time horizon. The problem was formulated as a mixed-integer programming model and solved using a branch-and-price method. The objective was to minimize the penalty costs arising from delays in the tugboat's travel time. The research [4] explores an intriguing tugboat scheduling problem that accounts for uncertainties in both the arrival times of container ships and the duration of tugboat operations at large container ports. A mixed-integer linear programming model is formulated to address the proposed tugboat scheduling problem. To handle large-scale instances of the problem effectively, the study designs an ad-hoc algorithm to generate tugging chains. This algorithmic approach enables the efficient resolution of complex, large-scale tugboat scheduling scenarios., this study research aim to minimize service time of tugging operations. The study [5] develops a mixed-integer programming model for the

tugboat scheduling problem, taking into account several practical constraints. These constraints include the dynamic arrival and departure of ships, tugboat qualifications, synchronization requirements, and flexible options for tugboats to return to their base. The objective is to minimize the tugboat operation costs incurred within the planning period. The model draws inspiration from a genetic algorithm framework that employs three-dimensional coding. The primary goals are to minimize the operating costs associated with tugboat operations and reduce the waiting time for ships in the anchorage area [5].

Studies based on literature reviews have also been conducted to offer a comprehensive overview of research areas that are scattered and interdisciplinary. These types of reviews serve as a means to synthesize research findings systematically, transparently, and reproducibly across various disciplines and domains. They help consolidate the existing knowledge and identify potential gaps or opportunities for further exploration within a specific field or topic [6]. However, that research did not specifically focus on the proposing model and constraint, such as the objective function, considered variables, solving algorithms, and other technical designs. Therefore, in this study, we concentrate on examining several literature sources related to optimizing scheduling tugboat operations and develop model constraint for more effective tugboat operation based on real situations especially in large and busy port. The main aim of this research is to determine factors that could be incorporated when planning and scheduling the operations of tugboats. There has been minimal prior research conducted specifically on optimizing tugboat scheduling, which has sparked our curiosity and motivated us to investigate the possibility of developing new models for these types of maritime activities. After recognizing the opportunity for further study in this area, we suggest pursuing future research that takes into account various elements to improve scheduling processes for tugboat operations. To test the developed model, we use real case sample data and solve it using Mixed Integer Linear Programming (MILP) using port traffic historical data obtained from one of busiest port and maritime hubs in Southeast Asia.

### 1. Related Studies for Model Development

The bustling harbor was a choreographed dance of vessels large and small, with tugboats playing an indispensable role in maneuvering the larger ships safely into their berths. However, ensuring an efficient schedule for deploying these powerful little workhorses was a complex challenge. Researchers delved into a myriad of studies, each offering insights to build a comprehensive model. Queueing theory provided a framework for analyzing the patterns of vessel arrivals and tugboat service times. Principles of combinatorial optimization enabled exploring the vast number of possible tugboat assignment scenarios to find optimal solutions. Simulation models allowed testing different policies under varying conditions like weather and traffic volumes. Techniques from operational research, like integer programming and constraint programming, offered powerful tools to capture the intricate constraints and objectives. By synthesizing these diverse studies, researchers aimed to develop a robust optimization model that could dynamically match tugboat assignments with the dynamic ebb and flow of shipping traffic, ensuring smooth maritime operations.

Several studies have conducted of tugboat scheduling problem (Tug-SP). Studies undertaken by [3] discusses Tugboat scheduling model with homogeneous barges, same destination and the same required delivery time, and tug speed are identical aiming to minimize the sum of a tug's cost related to its travel distance (time) and the penalty costs related to the delayed delivery times of barges. The developed model takes into account several variables such as delays of barge arrival, capacity limitation of each tug, and departure time of the tug. Studies [3] proposed a mixed integer programming and developed an branch and price approach algorithm to solve the problem. The algorithm has proven to solve the computational time ratio of the B&P algorithm without the acceleration technique and the algorithm with the acceleration technique is 2.93. Moreover, this time ratio increases when the scale of the instances grows. The results imply that the acceleration technique is highly effective and that considerable computational time can be saved.

Studies undertaken by [9] discusses Tugboat scheduling model considering combined turning and mooring moves of incoming vessels and combined unmooring and turning moves of outgoing vessels with aiming allocate sufficient tugboat horsepower to each vessel while minimizing the tugboat operating cost and the vessels' berthing and departure delays. The developed model takes into account several variables such as berth plans of vessels, the tug points of vessels for different move types, and the horsepower requirements of the tug points. Studies [9] proposed a integer programming and developed an novel iterative solution which combines Lagrangian relaxation and Benders decomposition to solve the problem. The iterative has proven to decreased vessel service rejection and total tardiness cost which represent the #R generated by LRBD increases from 1.2 to 2.6 and the #R value generated by BM1 increases from 1.2 to 4.2.

Studies undertaken by [4] Tugboat scheduling problem by considering uncertainty of ship arrival times and tugging process times, aiming to minimizing the total weighted service time of tugging operations and the expected value of recovery cost under uncertainty. The A mixed-integer linear programming model developed takes into account. Studies [4] invoking CPLEX to solve the developed models and giving the result decreased of tugging process time for these 50 ships is 2,250 min, the average tugging process time for each chain is 281.25 min, and the standard deviation (SD) of the tugging process times of 8 chains is 120.748 min. Moreover, the average number of towing times is 6.25 and the standard deviation of towing times is 2.68.

Studies undertaken by [10] Tugboat scheduling model considers different types of berth operations and heterogeneous tugboats and aiming to minimize the total travel cost of the tugboats. The studies formulate the Tug-SP using a mixed-integer linear programming (MILP) model and develop tailored branch-and-cut algorithm to solve the the Tug-SP efficiently. The algorithm has proven to solve and giving result of average lower bound is enhanced by 45.34%.

Studies undertaken by [29] Tugboat scheduling problem considering dynamic arrival and departure of ships, qualification of tugboats, synchronization, and a flexible returning way to base and aiming to minimize the tugboat operation costs generated within the planning period. The studies formulate mixed-integer programming model combined with scheduling rule. Then a algorithm is provided to obtain the optimal solution of Tugboat Assignment Problem, which shows the computation time of the algorithm in this study increases rapidly with the increasing of problem scale but only fit for small scale problems.

Moreover, this studies proposing model minimizing the total weighted service time of tugging operations considering tugboat horsepower capacity by invoking multiple assignment of tugboat and do some numerical studies to proven to solve the problem.

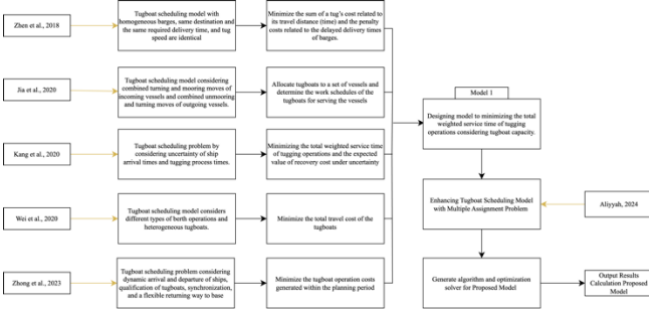


Fig. 3. Model Development of Tugboat Scheduling

### III. METHOD AND MODEL DEVELOPMENT

#### A. Proposing Model for Tugboat Scheduling Problem

Tugboat assignment is a have a important effect in the turnaround time of ships [31]. There are typically two main types of assignment approach found in the literature, single assignment and multi assignment [32]. The single assignment problem is a type of optimization problem in which the goal is to assign a set of tasks or jobs to a set of resources or agents, subject to the constraint that each task can be assigned to only one resource. This problem arises in various contexts, such as machine scheduling, workforce allocation, and transportation logistics. In the context of tugboat scheduling, the single assignment problem involves assigning a set of tugboats to a set of tasks, such as towing vessels or assisting in docking operations, with the constraint that each task can be assigned to only one tugboat. The objective is typically to minimize the total cost or time required to complete all tasks while ensuring efficient utilization of the tugboat fleet.

However, in some cases, it may be beneficial to allow multiple assignments, leading to the multiple assignment problem. The weakness of the multiple assignment problem is that it introduces additional complexity and potential conflicts, as tasks may need to be shared or prioritized among different tugboats. This can lead to scheduling conflicts, resource contention, and potential inefficiencies [27].

Nevertheless, the multiple assignment problem can be useful in certain scenarios, such as when tasks have varying priorities or deadlines, and it is necessary to allocate multiple tugboats to ensure timely completion of high-priority tasks. Some tasks require collaboration or coordination among multiple tugboats, such as in the case of particularly large or complex vessel movements. Tugboats have different capabilities or specializations, and certain tasks may require a combination of tugboats with specific capabilities. In these cases, allowing multiple assignments can improve the overall efficiency and effectiveness of the tugboat scheduling process, albeit at the cost of increased complexity in the optimization problem.

Based on the findings from reviewing existing literature, we recommend creating a new constraint model that is critical for scheduling tugboat for port efficiency. The development of this model will be structured around the typical tugging process flow found at ports located at Southeast Asia. The various steps involved in this standard tugging process flow are visually depicted in Fig. 3 below. As the author sought to

identify a timely and impactful topic for their upcoming research paper, a recently published study [4] on the tugboat scheduling problem caught our attention. The tugboat scheduling problem is a complex logistical challenge faced by many ports and harbors around the world. Tugboats play a crucial role in assisting large commercial ships with docking, undocking, and maneuvering within the confines of a port. However, the scheduling and coordination of these tugboats can be a significant operational headache. Factors such as the varying size and power requirements of different ships, the tidal and weather conditions, the availability of tugboats, and the need to minimize wait times and fuel consumption all contribute to the difficulty of this problem. Inefficient tugboat scheduling can lead to delays, increased costs, and environmental impacts. As a result, developing optimized tugboat scheduling models and algorithms has been an active area of research in the field of transportation and logistics management. An in-depth examination of the problem background, current approaches, and opportunities for improvement could provide valuable insights for port operators seeking to enhance the efficiency and reliability of their tugboat operations.

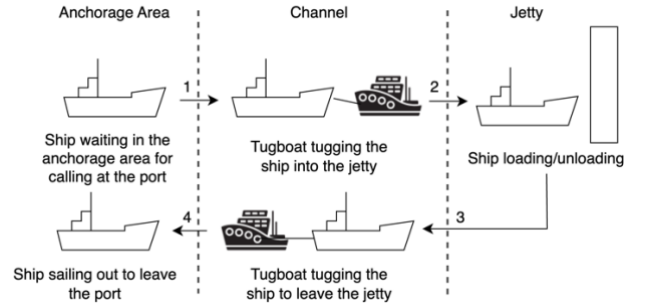


Fig. 1 Tugboat Operation Process Flow

#### B. Basic Model of Tugboat Scheduling Problem

The objective function of tugboat scheduling problem is adopt by model proposed by [4] is to minimize the total weighted service time of tugging operation determined by Equation (1). The service/process time minimization will be performed on each segment, which takes into account several factors, which is the weighted importance of the of customer ship  $j$  ( $\epsilon_j$ ), tugging start time of ship  $j$  by tugboat  $g$  at the  $k$ th position of the baseline schedule ( $t_{gj}^k$ ), the multiple of tugging process time also considered since the jobs of the tugging operation ( $c_{gj}^k$ ) is difference because is includes the loading/unloading ( $L_j$ ) time of ships (anchorage-to-jetty trip and the jetty-to-anchorage operation model), and estimated arrival time of ship  $j$  ( $A_j$ ). The basic model are shown in equation (1)– (11) .

$$\min \sum_g \sum_j \sum_k \epsilon_j \cdot (t_{gj}^k + 2 \cdot c_{gj}^k + L_j \cdot x_{gj}^k - A_j \cdot x_{gj}^k) \quad (1)$$

$$\sum_g \sum_k x_{gj}^k = 1, \forall j \in J \quad (2)$$

$$\sum_j x_{gj}^k \leq 1, \forall g \in G, \forall k \in K \quad (3)$$

$$\sum_j x_{gj}^{k-1} - \sum_j x_{gj}^k \geq 0, \forall g \in G, \forall k \in \{2, \dots, m\} \quad (4)$$

$$A_j + M \cdot (x_{gj}^k - 1) \leq t_{gj}^k \leq A_j + \tau_j, \forall g \in G, \forall j \in J, \forall k \in K \quad (5)$$

$$C_j + M \cdot (x_{gj}^k - 1) \leq c_{gj}^k \leq C_j + \tau_j, \forall g \in G, \forall j \in J, \forall k \in K \quad (6)$$

$$t_{gj}^k - \sum_j (t_{gj}^{k-1} + 2 \cdot c_{gj}^{k-1} + L_j) - \Delta C \geq M \cdot (x_{gj}^k - 1), \forall g \quad (7)$$

$$\forall g, \forall j \in J, \forall k \in \{2, \dots, m\}$$

$$\sum_g \sum_k (m_g - w_j) \cdot x_{gj}^k \geq 0, \forall j \in J \quad (8)$$

$$x_{gj}^k \in \{0, 1\}, \forall g \in G, \forall j \in J, \forall k \in K \quad (9)$$

$$t_{gj}^k \geq 0, \forall g \in G, \forall j \in J, \forall k \in K \quad (10)$$

$$c_{gj}^k \geq 0, \forall g \in G, \forall j \in J, \forall k \in K \quad (11)$$

Equations (2) specifies that every vessel must be allocated exclusively to a single tugboat over the given time period. Equation (3) Implies that the capacity of each tugboat is restricted to servicing a single vessel concurrently. Equation (4) Establishes a tangible representation of the chronological order in which each tugboat carries out its assigned towing operations, spanning from its initial job to its final task. Equation (5) It determines the initial *baseline schedule* ( $t_{gj}^k$ ) when tugboat  $k$  begins towing ship  $j$ . If  $x_{gj}^k$  equals zero, indicating no assignment,  $t_{gj}^k$  is set to zero. However, when assigned,  $t_{gj}^k$  must commence after ship  $j$  arrival  $A_j$ , but within the maximum tardiness window of  $A_j + \tau_j$ . This requires tugging to start after the ship's anchorage and limits excessive wait times to  $\tau_j$  minutes. Equation (6) It calculates the duration  $c_{gj}^k$  of the tugging operation performed by tugboat  $k$  for ship  $j$ . If  $x_{gj}^k$  equals zero, indicating no assignment, then  $c_{gj}^k$  is set precisely to zero. However, when  $x_{gj}^k$  is non-zero,  $c_{gj}^k$  must fall within the bounded range from  $C_j$  to  $C_j + \pi_j$ . Equation (7) stipulates that a tugboat can only be assigned to an incoming ship  $j$  after finalizing its preceding towing operation for ship  $j'$ . Moreover, the tugboat must return to the anchorage and undergo the predetermined idle sailing period  $\Delta C$ , accounting for setup and staff rest, prior to initiating the new job for ship  $j$ . Failure to adhere to this sequence will result in  $x_{gj}^k$  being set to zero, precluding the assignment, thereby enforcing a U-turn restriction. Equation (8) imposes the horsepower limitation on tugboat assignments, ensuring that the tonnage of each ship  $j$  does not surpass the horsepower capacity of its assigned tugboat  $g$ . The subsequent constraints, equation (9) through (11), delineate the permissible value ranges for the decision variables under typical operational conditions.

### C. Proposing Constraint Model for Tugboat Scheduling Problem

When developing a mathematical model to optimize tugboat scheduling and assignments, one crucial constraint must be incorporated. This constraint dictates that the tonnage or weight of any ship requiring tug assistance cannot surpass the maximum horsepower rating of the tugboat assigned to that vessel. Violating this constraint could lead to scenarios where an underpowered tug attempts to maneuver a ship exceeding its horsepower capabilities. By enforcing this tonnage-horsepower constraint within the model's mathematical formulation, solutions will only consider feasible tugboat-ship pairings where the tug's horsepower sufficiently accommodates the ship's tonnage requirements. This constraint ensures that scheduled tugboat assignments align

with the practical horsepower limits necessary for safe and effective ship handling operations.

Several studies in the literature have highlighted the importance of incorporating horsepower constraints when developing tugboat scheduling models. A key operational requirement is ensuring that the combined horsepower of the assigned tugboats is sufficient to handle the bollard pull and maneuvering needs of the ships they are tasked with assisting. Distinct ship types and sizes have varying horsepower demands based on factors like vessel weight, dimensions, and propulsion systems. Consequently, optimization models need to account for these horsepower requirements and mandates when allocating tugboat resources. Imposing horsepower constraints guarantees that tugboats with inadequate horsepower are not scheduled for jobs exceeding their capabilities, thereby preventing potential safety hazards or disruptions from underpowered assistance. Effectively modeling these horsepower constraints leverages data on tugboat specifications as well as empirical calculations linking ship characteristics to requisite horsepower needs. We develop model constraints based on the eq. (2) which is the jobs/tugging operations can only happen if that the tonnage of ship  $j$  not exceed the horsepower of tugboat  $g$ . However, we proposing the model that consider if the horsepower of tugboat  $g$  ( $m_g$ ) is small than the tonnage of ship  $j$  ( $w_j$ ), then one tugboat will be added to satisfied requirement ( $m_g + m_{g+1}$ ), then if ( $m_g + m_{g+1}$ ) is still doesn't satisfied the horsepower requirement or the customer (ship  $j$ ) are too heavy to handle, then one more tugboat will be added ( $m_g + m_{g+1} + m_{g+2}$ ) to satisfied requirement. Otherwise, if the  $m_g + m_{g+1} + m_{g+2}$  still do not satisfied requirement of the customer, so the jobs/tugging operations will not happen.

$$\sum_g \sum_k (m_g - w_j) \cdot x_{gj}^k \geq 0, \forall j \in J \quad (2)$$

$$x_{gj}^k = \begin{cases} 1 & \text{if } m_g \geq w_j; g \in G; \text{ then } m_g; x_{gj}^k = 1; j \in J \\ 1 & \text{if } m_g < w_j; g \in G; \text{ then } m_g + m_{g+1}; x_{gj}^k = 1; j \in J \\ 1 & \text{if } m_g + m_{g+1} < w_j; g \in G; \text{ then } m_g + m_{g+1} + m_{g+2}; x_{gj}^k = 1; j \in J \\ 0 & \text{otherwise, } m_g + m_{g+1} + m_{g+2} \leq w_j; g \in G; \text{ then } x_{gj}^k = 0 \end{cases} \quad (3)$$

The optimization algorithms embedded in the model also enable port authorities to minimize operations time, all while maintaining the highest levels of safety and on-time performance. As global trade volumes continue to surge, and ships grow ever larger, the ability to dynamically allocate tugboat horsepower in an optimal manner will only become more essential. The insights and best practices demonstrated in this study provide a valuable roadmap for seaports seeking to future-proof their tugboat scheduling processes and adapt to the evolving demands of the maritime industry. Ongoing refinement and deployment of this modeling approach can yield significant operational and environmental benefits for ports worldwide.

## IV. DISCUSSION AND RESULT

### A. Constraint and Assumptions

Having formulated the model, we proceeded to an evaluation phase where the developed optimization approach was benchmarked against practical scenarios encountered at the port. The mixed-integer linear programming (MILP) model was implemented using the CPLEX solver. The model's

performance was assessed by applying the following restricting criteria and underlying premises:

1. The port authority has established a key performance indicator (KPI) of 20 minutes for the tugging process
2. Do not consider the rescheduling of the tugging operations due the occurrence of not fulfilling of the horsepower requirement satisfied or the unexpected incidents such as equipment reliability and weather or sea conditions.
3. An acceptable and workable schedule for tugboat operations needs to satisfy additional specific criteria, This includes ensuring that a minimum assigned number of tugboats are available to service a given quantity of ships, while also having adequate capacity to handle the combined weight or total tonnage of those vessel.
4. This study considers the relative importance of the customer (ship) based on 3 points criteria, which are tally tonnage, lateness, and discharge rate.
5. This study uses historical data from the port located at Southeast Asia.

By utilizing sample data from a major port in Southeast Asia, we can leverage real-world scenarios and operational parameters to validate and refine their models.

### B. Parameter Setting and Scenario

As part of the model validation process, a small-scale tugging operations dataset was utilized for testing purposes. The Excel solver, employing the simplex method, was used to identify the optimal sequencing of tugboat tasks based on our mixed-integer linear programming (MILP) model. The parametric inputs and scenario configurations applied during this testing phase are outlined in Table I.

TABLE I. PARAMETER SETTING

Description	Unit
Number of tugboats available	Unit
Number of Ship	Unit
Tugboat capacity and characteristics (horsepower)	HP
The estimated times of arrival (ETA)	Minute
Time Windows (The estimated tugging process time of ship)	Minute
Tugging Start Time	Minute
The loading/unloading time of ship	Minute
Tugging Process Time KPI	Minute

TABLE II. SCENARIO 1 & 2

Ship	Tug	$t_{gj}^k(\omega_s)^+$	$c_{gj}^k(\omega_s)^+$	$t_{gj}^k(\omega_s)^-$	$c_{gj}^k(\omega_s)^-$
1	1	324,3	82,01416667	239,7	-998,43333334
2	1	980,95	40,03916666	725,05	-487,43333333
3	1	426,65	36,58916667	315,35	-445,43333333
4	4	302,45	53,16833334	223,55	-647,26666667
5	1	416,3	47,55249999	307,7	-578,89999999
6	2	468,05	77,54833333	345,95	-944,06666666
7	4	570,4	67,045	421,6	-816,2
8	4	1223,6	89,60416667	904,4	-1090,83333333
Average		589,0875	25	435,4125	-751,07083333

Ship	Tug	Result Total Tugging Process Time Scenario 1	Result Total Tugging Process Time Scenario 2
1	1	1987,64662	-787,7852001
2	1	2270,735543	1903,407935
3	1	1003,743959	465,3939918
4	4	11427,74927	6508,138483
5	1	975,32834	174,7634001
6	2	1416,674672	242,1996801
7	4	54384,75646	48368,04338
8	4	16165,14375	4506,817499
Average		10562,50043	7672,622397

In Scenario 1, the focus was on the tugboat process times, which included the time required for tugging, maneuvering, and positioning the vessels. The researchers observed that as the process times increased, the total tugging operation time also increased correspondingly. This was an expected outcome, as longer process times naturally resulted in higher overall operation durations.

In Scenario 2, the researchers examined the impact of varying the tugboat operation start times. They found that as the start times were shifted earlier, the total tugging operation time decreased significantly. This is because starting the tugboat operations sooner allowed for better utilization of the available tugboats and reduced waiting times for vessels requiring assistance.

However, the researchers also noted that excessively early start times could lead to inefficiencies, as tugboats might have to wait idly for long periods before servicing the next vessel. Therefore, an optimal start time window existed, which balanced the benefits of early starts with the potential drawbacks of excessive waiting times.

In Scenario 2, the focus was on the tugboat process times, which included the time required for tugging, maneuvering, and positioning the vessels. The researchers observed that as the process times increased, the total tugging operation time also increased correspondingly. This was an expected outcome, as longer process times naturally resulted in higher overall operation durations.

Interestingly, the researchers found that the impact of process time variations was more pronounced for larger vessels requiring multiple tugboats. This was because the cumulative effect of longer process times was amplified when multiple tugboats were involved in servicing a single vessel.

Overall, the findings from these scenarios highlighted the importance of carefully considering both the start times and process times when optimizing tugboat scheduling. By identifying the optimal start time window and minimizing process times where possible, significant reductions in total tugging operation time could be achieved, leading to improved efficiency and cost savings for port operations.

## V. CONCLUSION

This research presented an enhanced mixed integer programming formulation for the tugboat scheduling problem, with the objective of minimizing the total tugboat operation time. A key distinguishing feature of the proposed model is its capability to assign multiple tugboats to service a single vessel, reflecting realistic operational practices that prior models failed to capture by restricting assignments to a single tugboat per vessel.

The enhanced formulation was validated on a test bed derived from real-world data obtained from a major seaport. Computational experiments demonstrated the superiority of the enhanced model in terms of reduced total tugboat operation time compared to the basic model that precluded multiple tugboat assignments. These improvements were particularly pronounced for large-scale problem instances involving many vessels and tugboats.

While the augmented model exhibits increased computational complexity relative to its basic counterpart, the performance remains viable for typical problem dimensions encountered in practice through the leveraging of a commercial optimization solver. The ability to optimally allocate multiple tugboats provides port operators with a powerful decision support tool to drive greater operational efficiency in tugboat scheduling.

Opportunities for further research include extending the model to additionally account for tugboat fuel consumption, incorporating stochastic elements such as weather conditions, and developing tailored solution algorithms to further enhance computational performance on very large problem instances. Collectively, this study underscores the importance of realistic modeling of tugboat assignment constraints to fully capitalize on optimization for improved scheduling in the maritime transportation domain.

#### ACKNOWLEDGMENT

This work is supported by Faculty of Industrial Engineering, Industrial and System Engineering Department, Telkom University.

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