Enhanced Model for Tugboat Scheduling Problem Considering Multiple Tugboat Assignment: Reviewing Literature and Proposing Model

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***Abstract*— Ports that handle container ships play a vital role in facilitating global logistics and supply chain operations. These ports offer essential services for managing container vessels. When a container ship arrives at a port, it typically needs the support of tugboats to assist with critical maneuvers. These maneuvers include docking the ship at its berth, repositioning or shifting the vessel within the port area, and undocking or departing from the berth. The tugboat operations are crucial for ensuring the safe and efficient movement of these large container ships during their time at the port. Effective scheduling of tugboats to serve vessels is essential to ensure the safe and efficient movement of container vessels in a port. This research discusses the problem of tugboat scheduling or Tugboat Scheduling Problem (Tug-SP). This study focusses on reviewing literature aiming to identify variables for optimizing tugboat operations, this study also proposed horsepower capacity constraint application to the model application for future research. Proposing future research could also focus on studying more dynamic problems, solving larger and complicated cases, designing a more efficient solution method, using appropriate and developed algorithms. Apart from that, other factors such as the uncertainty such as ship arrival times or under certain situation can also be considered to be included in the consideration variables in minimizing total tugboat services time or to reduce operations cost, especially for large and busy container ports.**

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

I. Introduction

Ports become goods distribution centers that connect the needs of producers (senders) with consumers (recipients) whose core services are ship and cargo handling. Ports play an important role in facilitating trade, especially international trade worldwide. Global trade has undergone a remarkable expansion since the 1950s, accounting for an increasingly larger portion of worldwide economic output. In 2007, international trade exceeded 50% of the global Gross Domestic Product (GDP) for the first time ever, a substantial increase from the conventional range of 20% to 25% that it occupied during the initial 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]. With the rapid growth of trade and the increasing volume of ship traffic, the use of tugboats at Port in carrying out business processes has become a crucial need. Tugboats play an important role in facilitating safe and efficient port operations. Tugboat is a small ship that helps large ships that will dock at the port or unmooring at sea by pulling or pushing the ship to the port so that the ship does not damage the dock when anchored 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.

Tugboats have the following main functions such as [2]:

1. Pulling or pushing large ships that have difficulty docking at the dock. Examples: tankers, cruise ships, aircraft carriers, etc. Nor ships that do not have their own propulsion. Example: barge. As well as moving offshore buildings. Examples: semi-submersible, jack-up barge.
2. Assist in the implementation of mooring and unmooring of tankers. Tankers often have difficulties when mooring and unmooring on the high seas. Therefore, the role of the tugboat as a guide in this process is needed.
3. Monitor weather conditions. Tugboats are often used to monitor the weather around ports.
4. Overcoming oil spills. With the water pump on the tugboat, when a port or ship fire occurs, the tugboat can help put out the fire together with the firefighting ship. Tugboats are also often used when oil spills occur which are caused by ship fires, ships sinking, by pulling oil filter nets.

Tugboat operations demand meticulous planning due to the limited availability of tugboats and the constrained capacity of each tugboat to service vessels. Since the costs associated with renting tugboats and their fuel consumption are substantial, it is crucially important to optimize the scheduling of the available fleet of tugboats. Effective scheduling ensures that vessel service requirements are met while minimizing the time and expenses incurred during tugboat operations. Accurate tugboat scheduling planning can support the creation of efficient port activities and prevent delays in the loading/unloading of containers from ships.

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

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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 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.

II. Methodology

A. *Systematic Literature Review Overview*

As described in literature [7], a systematic review is a methodological approach and process aimed at identifying and critically evaluating pertinent research studies. It involves systematically and objectively collecting and analyzing data from the identified relevant research in a rigorous and unbiased manner. The systematic review is a distinct research method that enables a comprehensive synthesis and appraisal of existing evidence on a specific topic or research question. [7], [8]. The primary objective of conducting a systematic review is to comprehensively identify and synthesize all empirical evidence that satisfies predetermined inclusion criteria, with the intent of addressing a specific research question or hypothesis. By adhering to explicit and systematic methodological approaches in the evaluation and examination of relevant articles and available evidence, the potential for bias is mitigated. Consequently, systematic reviews yield reliable findings upon which well-founded conclusions can be drawn and informed decisions can be made. [6]. A systematic literature review was chosen to analyze the issues in Tugboat Scheduling Problem (Tug-SP).

In conducting a systematic literature review related to in tugboat scheduling problem, the primary focus includes identifying models, including objectives, decision variables, and constraints, evaluating the used of algorithms and scheduling approaches by examining the strengths and weaknesses of the variable that several paper used. The analysis also involves examining research trends on in tugboat scheduling problem and recommending future research requiring further exploration in the field of tugboat scheduling problem.

B. *Research Questions for Mapping Reviewing Scope*

When constructing the literature review, it is crucial to clearly define the research questions in order to facilitate a structured and impartial analysis. For this particular study, the research questions that will guide the process are presented in Table I.

TABLE I. Research Question

No	Research Question	Purpose
1.	What primary goals or optimization criteria are commonly examined and discussed in previous research studies focusing on the problem of scheduling tugboat operations?	The aims are twofold: First, to pinpoint and critically examine the core functional objectives that are frequently tackled in existing literature exploring the tugboat scheduling problem. Second, to identify prominent, high-impact research journals that have published works pertaining to this specific subject area.
2.	What key factors, objectives or optimization criteria are frequently analyzed and examined in research publications focused on addressing the tugboat scheduling problem?	The goal is to thoroughly review and evaluate the criteria that are commonly discussed and examined in existing research related to this topic, with the purpose of identifying the key factors and considerations pertinent to the tugboat scheduling problem.
3.	What are the solution methods and algorithmic approaches that researchers predominantly employ and rely upon when conducting studies focused on addressing the tugboat scheduling problem?	The objectives are to determine the solution algorithms and methodologies that are most prevalently adopted by researchers investigating the tugboat scheduling problem, as well as to assess the strengths, limitations, and relative effectiveness of the different applied techniques and approaches for tackling this issue.
4.	What specific research domains or areas of focus offer opportunities for additional examination	The goals are to pinpoint the specific research areas related to the tugboat scheduling problem that remain underexplored and have untapped potential for further

No	Research Question	Purpose
	and deeper exploration when it comes to the tugboat scheduling problem?	investigation. Additionally, to establish potential avenues and recommendations that can guide the focus of future research efforts in this field of study.

C. Comprehensive Study

A comprehensive is exhaustive, methodical overview of the existing research and literature published on a specific research question or topic area. A comprehensive study flow and progression in the literature on Tugboat Scheduling problem (Tug-SP) involving databases searched - operations research, engineering, maritime databases, research of the background on tugboat operations and key scheduling decisions required, overview of real-world constraints and objectives, structured keyword search strategy covering problem variables, Screening criteria - relevance to tug scheduling literature, reflects a systematic and transparent approach in collecting and filtering information. By implementing a structured flow in the comprehensive study, research on Tugboat Scheduling Problem (Tug-SP) can provides better context and tracing of progression literature synthesis, provides highlights gaps and opportunities more clearly in the tugboat scheduling literature.

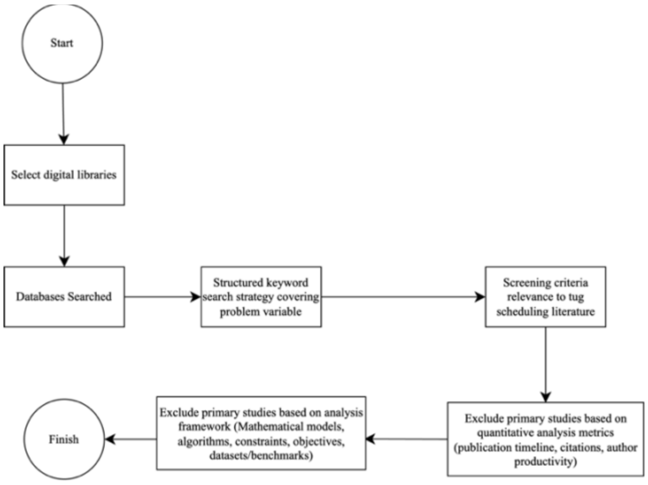

Fig. 1. Flow of Comprehensive Study

D. Study Selection

In the stage of study selection during the systematic literature review on Tugboat Scheduling Problem (Tug-SP), the choice of journal sources from digital publisher such as MDPI (https://www.mdpi.com), IEEE Explore (http://ieeexplore.ieee.org/), and ScienceDirect (http://www.sciencedirect.com/) provides a robust framework for comprehensively exploring literature related to Tugboat Scheduling Problem. The use of the keyword "Tugboat Operation" writer explored on 20 January of 2024 yielded 10 journals from MDPI, 27 conferences and journals from IEEE, and 1099 journals from science direct indicating substantial research interest among scholars in this topic. The selection of the keyword "Tugboat Scheduling," resulting in 3 journals from MDPI, 18 journals from IEEE, 332 journals from ScienceDirect, also reflects the availability of sufficient literature to support the examination in this subsection. By adopting a comprehensive approach that spans across diverse platforms and strategically employs keywords, this systematic literature review is poised to provide an exhaustive understanding of the evolving landscape of research in the realm of Tugboat Scheduling Problem. The synthesis of various perspectives and methodologies inherent in the selected studies is expected to contribute to a nuanced and holistic analysis of the current state of knowledge in this field. As the review embarks on the synthesis and analysis phase, it is poised to unravel not only the current trends and findings but also potential gaps and avenues for future exploration within Tugboat Scheduling Problem (Tug-SP).

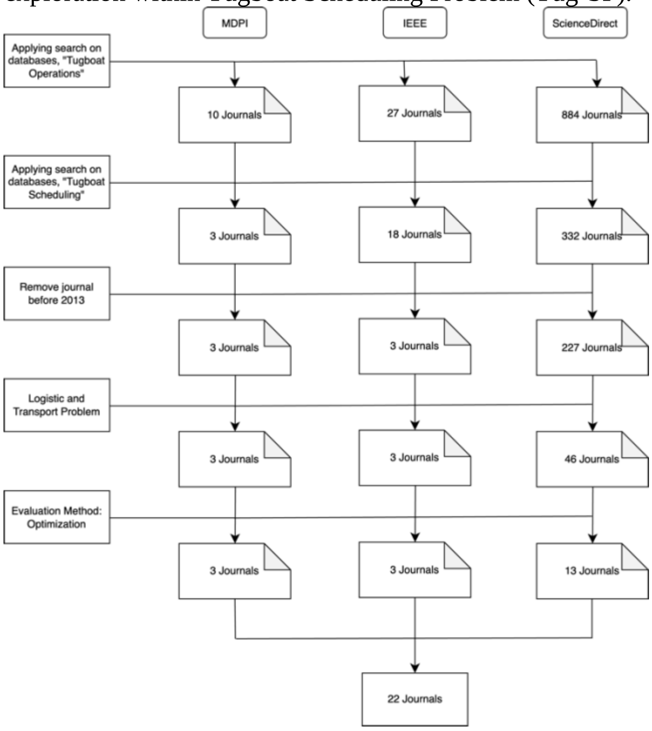

Fig. 2. Systematic Mapping

III. RESULT AND DISCUSSION

A. Objective Function for Tugboat Scheduling Problem Publication

Table II illustrates the variations in objective functions in the literature concerning tugboat scheduling. The primary focus in Table II is on minimize tugboat operation time and operation cost and with 11 studies addressing this aspect. However, other objective functions, such as minimizing travel time, maximum delay of vessel, penalty cost of delay, fuel cost, completion time, and tugboat idling distance, are also noteworthy. This analysis reflects a diverse distribution of research and identifying the focus, can help us in understanding trends and priorities in Tugboat Scheduling Problem.

TABLE II. OBJECTIVE FUNCTION FOR TUGBOAT SCHEDULING PROBLEM PUBLICATION

No	Objective Function	Number of Publication	Referenced Journal
1.	Minimize Tugboat Operations Cost	4	[9], [10], [5], [11]
2.	Minimize Tugboat Service/Operation Time	3	[4], [12], [13]
3.	Minimize Tugboat Travel Time	1	[3]
4.	Minimize Maximum Delay of Vessel	1	[9]

No	Objective Function	Number of Publication	Referenced Journal
5.	Minimize Penalty Cost of Delay	1	[3]
6.	Minimize Tugboat Fuel Cost	1	[5]
7.	Minimize Completion Time	1	[5]
8.	Minimize Ship Waiting Time	1	[5]
9.	Reduce the number of vessel requests that cannot be fulfilled or serviced satisfactorily.	1	[9]
10.	Minimize Tugboat Idling Distance	1	[14]

B. Most Discussed Criteria in Tugboat Scheduling Problem Publication

1. Constraints

Tugboat scheduling is an enormously complex logistics task with a multitude of constraints that arise from operational efficiencies, regulations and uncertainty. Common constraints encoded in mathematical models across the tugboat scheduling problem literature include time windows for individual jobs and ships, fleet size limitations, assignment/tug-ship pairing restrictions based on capability matching, route continuity, refueling requirements, and mandated crew working hour thresholds per maritime labor laws. More advanced formulations also account for stochastic constraints modeling uncertain service times at berths as well as unreliable asset availability arising from unplanned maintenance downtimes. Furthermore, some recent papers have begun exploring multi-modal environmental constraints minimizing mission impacts. Overall the richness of the constrain space coupled with the combinatorial exploded the solution pace, necessitating a variety of mathematical, algorithmic and computational advancements to progress state-of-the-art in actionable tugboat scheduling tools. The constraint that several paper is show on Table III. below.

TABLE III. CONSTRAINTS

No	Type of Constraint	Number of Publication	Referenced Journal
1.	Tugboat Required	6	[4], [10], [11], [12], [14], [15]
2.	Horsepower Requirement	5	[9], [4], [13], [12], [14]
3.	Tugging Start Time	4	[4], [10], [12], [14]
4.	Tugboat Travel Time	4	[9], [10], [13], [12]
5.	Tugboat Qualification	3	[4], [13]
6.	Ship Departure Time	3	[5], [10], [12]
7.	Tugboat Departure Time	3	[3], [5], [12]
8.	Multiple Berthing Bases	3	[9], [18], [16]
9.	Ship Tonnage	2	[16], [17]
10.	Time Window of Ship	1	[9]
11.	Tugboat Syncronization	1	[5]
12.	Tugboat Operation Time	1	[14]
14.	Cost per Unit Distance Traveled by Tugboat	1	[12]
15.	Distance	1	[12]
16.	Planning Horizon	1	[13]
17.	Berth Capacity	1	[13]
18.	Tidal Window	1	[13]

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2. Future Research

Intricate tugboat scheduling problem space are immense. While extensive studies exist addressing deterministic cases, integrative solutions embedding uncertainty are imperative as dynamics and non-stationarity increase in port environments with surging traffic, new technologies and regulations. Additionally, augmenting optimization with predictive analytics leveraging AI merits deeper exploration beyond current superficial usage for estimation tasks. There has also been inadequate attention to holistic supply chain integration spanning landside transportation and yard handling processes that affect inter-terminal coordination. Furthermore, while emissions considerations have grown recently from an optimization lens, research explicitly assessing different policy and fleet migration pathways applying sustainability principles remains open. As maritime transportation and technologies transform, immense prospects exist in collectively integrating modern mathematical programming with simulation, machine learning predictions (ML), IoT infrastructure and environmental analytics into novel digital native methodologies that can reliably improve tugboat scheduling amidst intensifying port congestion and competitiveness dynamics.

TABLE IV. FUTURE RESERCH

No	Future Research	Number of Publication	Referenced Journal
1.	Algorithm Improvement	9	[4] , [5], [10], [12], [13], [16], [21], [23], [25]
2.	Model Improvement	8	[9], [12], [13] [14], [22], [21], [23], [24]
3.	Berth Assignment/Allocation	8	[4], [9], [14], [16], [21], [23], [26]
4.	Dynamic Scheduling Problem (High Computional Complexity)	3	[10], [19], [20]
5.	Green Tugboat Scheduling	2	[9], [12]
6.	Uncertainty (Natural Hazard, Man-Made Hazard, Port Congertion)	2	[5], [26]
7.	Uncertainty (Services Request are not completely known, Delay of Ships)	2	[5], [16]
8.	Uncertainty (Stochastic Tugboat Service Duration)	1	[5]
9.	Tugboat Requirement	1	[21]
10.	Integrating Artificial Intelligence with Human Intelligence	1	[14]
11.	Longer Planning Horizon	1	[16]

No	Future Research	Number of Publication	Referenced Journal
12.	Vessel Traffic Scheduling	1	[9]

C. Most Used Solving Algorithm

The extensive literature on tugboat scheduling documents a range of sophisticated optimization algorithms tailored to solve formulated mathematical problems. While exact methods like integer and mixed integer programming were applied on basic models initially, explosive combinatorial complexity steered focus toward efficient metaheuristics. Key stochastic solvers explored include genetic algorithms, and discrete event approaches. Additionally, given uncertainty, approximate dynamic programming has gained prominence demonstrating robust feasible solutions. For large scale instances, decomposition procedures breaking integrated problems into hierarchical phases have provided promising iterative resolution pathways. Overall, a rich toolbox of mathematical, imitated algorithmic, communicative and technological solvers now exists as viable options, applicable based on problem scale, instance types and availability of data resources.

TABLE V. SOLVING ALGORITHM

No	Solving Algorithm	Number of Publication	Referenced Journal
1.	Mixed Integer Programming (MIP)	6	[3], [13], [16], [21], [25], [27]
2.	Improved Genetic Algorithm Reversal Operation (GA-RE)	4	[5], [14], [24], [27]
3.	Mixed-Integer Linear Programming (MILP)	4	[9], [12], [13], [23]
4.	Lagrangian Relaxation	3	[9], [22], [21]
5.	Evolutionary Algorithm	1	[28]
7.	Neighborhood Search Algorithm	1	[13]
8.	Grey Wolf Optimization Algorithm	1	[12]
9.	Branch-and-Cut Algorithm	1	[3]
10.	Simulated Annealing-based Ant Colony Algorithm	1	[20]

D. Possibility Research in Tugboat Scheduling Problem

While the contemporary literature on the tugboat scheduling problem has established rigorous metaheuristics, stochastic programming, and multi-objective techniques to progress pure mathematical optimization, several promising directions exist for future explorations. The dynamic tugboat scheduling problem presents immense challenges from exponentially high computational complexity, multitude of uncertainties, and the need for greener renewed operations. Significant research opportunities exist in developing adaptive scheduling systems leveraging advances in predictive analytics, robust optimizations, and multi-agent simulations to address these issues. For instance, harnessing AI to predict near-term service requests, port congestion conditions, and asset availability could enable better informed proactive planning amidst stochastic dynamics. Additionally, algorithmic improvements incorporating rolling planning horizons and feedback loops would make scheduling policies more leading, resilient, and responsive. Furthermore, integrating such intelligent automation with human expertise through explainable interfaces and for settlements of corner cases can augment explanations and transparency. Another understudied area warranting attention is formulating sustainability considerations like renewable energy transitions and circular economy practices directly into green tug scheduling frameworks applying life cycle principles to improve environmental and social indicators. In summary, substantial headroom remains in advancing theory, tools, and next-gen capabilities taking the dynamic scheduling problem into a new era of intelligent, resilient and sustainable tugboat operations.

1. Finding Gaps

Gap is the missing pieces in a research literature, the area that literature has research has not yet been explored or is under-explored. While tugboat scheduling has received substantial attention for several decades, systematic analyses to consciously map literature gaps are limited. Upon reviewing solution approaches at different time periods, some potential gaps emerge. For instance, classical mathematical formulations largely utilize simplified assumptions around deterministic parameters and costs-centric single objectives. However, contemporary literature is evolving stochastic and robust programming leveraging this limitation. Similarly, early literature inadequately addresses integrated scheduling across multiple terminals at a regional level compared to within terminal optimizations. Additionally, connections to emerging technologies remain underexplored other than basic simulation usages for evaluation. Specifically, the harnessing of optimization ML integration for predictive analytics and utilizing Internet-of-Things sensor streams have significant innovation possibilities. Analyzing chronological research themes and solution sophistications thus provides a structured methodology to critically identify such literature gaps and formulate impactful research questions that can push new frontiers focusing on realism, uncertainty management and integrated problem formulations.

IV. 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.

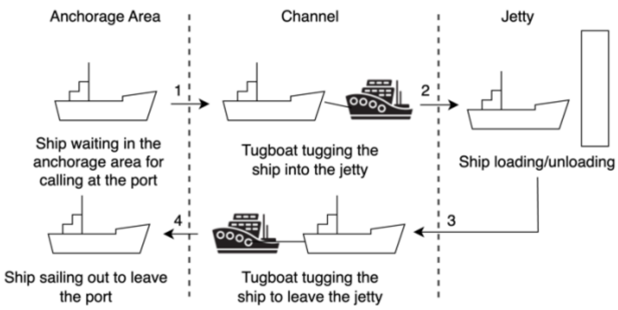

Fig. 3 Tugboat Operation Process Flow

In order to formulate the mathematical model, certain constraints and assumptions were employed, specifically:

1. 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.
2. 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.
3. This study considers the relative importance of the customer (ship) based on 3 points criteria, which are tally tonnage, lateness, and discharge rate.
4. This study uses historical data from the port located at Southeast Asia.

A. *Objective Function*

The objective function of tugboat scheduling problem [4] is to minimize the total weighted service time of tugging operation which have the optimal process time of 20 minutes. 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 (ε_j), tugging start time of ship j by tugboat g at the kth 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).

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

B. *Proposing Constraint*

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.

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

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

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.

V. CONCLUSION

In conclusion, this systematic review studied the extensive literature landscape around formulations, algorithms, and implementations addressing the Tug-SP over the past few decades. Initial papers focused on service time and cost efficiencies using exact solvers for basic constraints. Advances in metaheuristics enabled incorporating uncertainties and larger problem scales. Latest works embed remains an open challenge with many complexities. While maturing metaheuristics address basic deterministic cases efficiently, substantial gaps persist in managing multivariate uncertainty from port congestion, climate risks, variable vessel traffic, and service time stochasticity. Advancing robust optimization and aggregating predictive analytics into systems could enable adaptive policies.

In summary, amongst model, algorithmic, predictive, participative and sustainability dimensions lie fertile grounds for high-impact inquisition that can progress the state-of-art in dynamic scheduling. Execution would necessitate interdisciplinary synthesizing of maritime, logistics and technology into an integrated digital native framework. The payoffs in terms of efficiency, responsiveness, resilience and renewal would be invaluable for next-gen ecological tug operations.

This systematic review has comprehensively analyzed the existing literature on the tugboat scheduling problem, identifying key functional objectives, solution methodologies, and potential research gaps. While prior studies have made valuable contributions, there remains an opportunity to further enhance optimization models by explicitly incorporating horsepower constraints. As highlighted, ensuring adequate tugboat horsepower is critical for safely and effectively handling ships based on their tonnage and maneuverability needs. However, relying solely on horsepower thresholds is an oversimplification that fails to account for other pertinent maritime factors influencing tugboat capabilities. Consequently, future research should focus on developing holistic scheduling models that integrate horsepower requirements with other operational constraints like spatial separations, propeller wash considerations, and environmental conditions. Achieving this balanced and multi-faceted approach through techniques like multi-objective optimization or constraint programming could yield more practical and robust tugboat schedules. Ultimately, advancements in this domain can lead to significant efficiency gains, time savings, and enhanced safety for vital maritime support operations governed by the tugboat scheduling problem across global ports and waterways.

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