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A Fluid Flow Simulation Model for Performance Analysis of Bulk Liquid Terminals

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***Abstract*—Bulk liquid terminals play a crucial role in enabling the timely discharge and loading of liquid from the tankers and also facilitating oil transport to the hinterland via pipelines and external trucks. However, the speed of operations (and demurrage costs in the likely event of vessel handling delays) depends on the capacities of all terminal resources including berth, loading arms, and storage tank farms. Today, there is a limited understanding of how the interactions among the resources affect the overall vessel sojourn time performance. Using an integrated fluid flow simulation model of a bulk liquid terminal, we are able to gain much insight into the discharge operations of a tanker, in particular, implications of storage tank capacity feedback on the loading arm utilization and vessel sojourn times.**

***Index Terms*—bulk liquid terminal, simulation, performance analysis**

I. INTRODUCTION

Currently, oil is still the fuel that keeps the economy running. In 2021, around 1.83 billion metric tons of crude oil were transported by sea ([VSM, 2022]). Three primary routes of oil transportation include Panama to China, from the Strait of Hormuz to Japan, and from West Africa to India. Crude oil tankers form an important vessel type and rank third in the global merchant fleet. Even when the role of oil will be diminished in the (hopefully near) future, the transport of liquid will remain an important part of overseas transport.

Bulk liquid terminals play a crucial role in enabling the timely discharge and loading of oil from the tankers and also facilitating oil transport to the hinterland via pipelines and external trucks. Crude oil tankers first berth at a liquid terminal jetty for discharging the oil. The crude oil is then transferred from the tankers to the storage tank farms via loading arms. Tankers face considerable uncertainty in the arrival times at the port. The time for tanker arrival at the jetty experiences high uncertainty due to factors such as unfavorable weather conditions, waiting for favorable tide levels, availability of pilot, and jetty availability. Since a jetty's capacity is finite, variability in the tanker arrival times can cause significant tanker waiting times. Further tanker discharge delays can emerge from shortage in unloading capacity as well as variability in unloading process times. For example, the availability of oil unloading infrastructure at the liquid bulk terminal such as the number and capacity of the loading arms, storage tank capacity, and oil outflow rate from the storage tanks affect the speed of oil discharge from the tankers. Tanker discharge delays can be excessively long. Long delays can result in high demurrage costs that could be borne by the shipping line or/and the port authority. Tanker discharge delays can be managed with the right sizing of equipment capacity such as loading arms and tank farm capacity. Hence, understanding the effect of the liquid bulk terminal design parameter settings on terminal performance and subsequent sizing of terminal resources holds significant relevance for the ports.

Studies in OR modeling and management literature on bulk liquid terminals have been mostly restricted to scheduling and routing of tankers from source port to destination ports, and pipe network design in a deterministic environment. There are limited research studies on performance analysis and design of a bulk liquid terminal that account for stochasticity in both vessel arrivals and unloading process times. While there are a few discrete-event simulation studies that investigate the effect of bulk liquid terminal parameters such as berth capacity on vessel sojourn time, models that analyze integrated terminal operational performance such as estimating the effect of storage tank capacity on tanker waiting times are limited. In this paper, we develop a fluid flow simulation model for the integrated operations of a bulk liquid terminal including tanker berthing, tanker discharge and transfer to the storage tanks, tank storage, and liquid discharge from the storage tanks via external trucks. We perform numerical analysis using realistic data from the field and existing literature.

To manage long tanker wait times, the terminal manager typically analyzes several capacity management scenarios. For example, plan to expand the tank storage capacity, add additional loading arms for unloading, or increase the capacity of the existing loading arms. Queuing models are effective in the evaluation of the performance gain with additional resources. Using a fluid flow simulation model with a network of queues, we discuss the interactions between loading arm capacity and storage tank farm capacity on vessel sojourn times. Analysis of the fluid flow queuing network model provides insights that can guide the port authorities in resource sizing decisions and reduce tanker delays at the port. In this paper, we refer to liquid tankers and vessels interchangeably.

The rest of this paper is organized as follows. In Section II, we discuss the background literature. We describe the bulk liquid terminal system along with the simulation model in Section III. We present our numerical insights in Section IV and include concluding remarks in Section V.

II. LITERATURE REVIEW

Since our focus lie in the intersection of liquid bulk terminal performance and queuing networks (fluid flow networks, in particular), we review literature in three domains: 1) Optimization models for bulk liquid terminals, 2) Queuing network models for container terminals, and 3) Fluid flow models for logistics.

Optimization for Bulk Liquid Terminals: [Rakke et al., 2011] study the routing and scheduling of a heterogeneous fleet of LNG ships with an objective to minimize the long-term delivery program costs. They develop an MIP formulation and a novel decomposition approach to solve the problem. Likewise [Diz et al., 2014] implement a DSS to schedule vessels for long-haul crude oil transportation for PETROBAS, a multinational energy company. [Van den Bossche et al., 2020] study a real-world truck scheduling problem at the landside of a bulk terminal where external trucks need to be scheduled to avoid both blocking the path within the terminal yard space as well as blocking the tank loading stations. [Rothfarb et al., 1970] study the optimal design of natural gas pipeline systems considering the selection of optimal pipe dimensions, gas-field locations, and optimal expansion choices. Likewise, [Brimberg et al., 2003] study an oil network design problem for the South Gabon oil field using a mixed-binary-integer linear program. The design problem considers different choices of pipe capacities, construction of tree-like network structure anchored to a single node (port), and also network expansion.

Analytical Models for Container Terminals: Another stream of research focuses on developing analytical models for performance analysis and design of container terminals. For example, [Roy et al., 2020] propose integrated queuing network models for rapid design evaluation and analysis of container terminals with automated vehicles at the seaside. They analyze several design parameters such as the type of automated vehicle and vehicle dwell-point on the performance of container unloading operations. [Roy and de Koster, 2018] analyze the performance of sea container terminals with both vessel loading and unloading operations. Using a queue of network of semi-open and open, they develop a new integrated stochastic model that captures the flow of variability among the seaside processes namely quayside, vehicle, and stackside processes. They obtain robust yard configurations with both loading and unloading operations. [Roy et al., 2022] analyze the interactions of external trucks and train arrivals at the landside of the container terminals using a stylized semi-open queuing network model with bulk arrivals (of containers on trains). This study particularly sheds insight on the role of the right vehicle choice (coupled vs. decoupled) on the congestion at the landside. These models offer the flexibility to analyze alternate terminal design variations and develop operational insights.

Fluid Flow Models in Logistics: [Belaqziz et al., 2018] model the congestion of trucks at the landside gates of a container terminal using a non-stationary $M(t)/E_k/c(t)$ queuing system and propose a queue length estimation model using the point-wise stationary fluid flow approximation. Fluid models are often used to analyze queues under heavy-traffic conditions. For instance, using a fluid model, [Whitt, 2006] develop simple first-order performance approximations for a $G/GI/s+GI$ queueing model, which has a general stationary arrival process with arrival rate, independent and identically distributed (IID) service times with a general distribution, s servers, and IID abandon times with a general distribution. [Lu et al., 2022] adopt a fluid queue model-based analytical approach to estimate vehicle travel time and design routing for vehicles in a congested urban environment. However, research on analyzing the performance of integrated bulk liquid terminals is extremely scarce.

III. SYSTEM DESCRIPTION AND SIMULATION MODEL

Our model considers a terminal setting with a single jetty, oils with different densities, and different storage tank capacities, and analyzes the terminal performance (tanker sojourn time in particular) by accounting for the stochastic interactions in the oil discharge processes.

Figure 1 illustrates the process flow of a tanker arriving at a liquid terminal for unloading, which forms the scope of our modeling exercise. The fluid flow simulation model corresponding to the system described in Figure 1 is illustrated in Figure 2. The readers will notice that we model both the vessel discharge process as well as the storage tank discharge process with external truck arrivals. The vessel arrivals are modeled using an arrival process. The inter-arrival times can follow any general distribution. Likewise, the external truck inter-arrival times can follow any general distribution. For ease of exposition, we only illustrate the arrivals of a single type of vessel. However, we extend this model to multiple liquid types. We develop the fluid flow model using Arena simulation software where the storage tanks are modeled using the storage tank modules. The inflow and outflow from the storage tanks

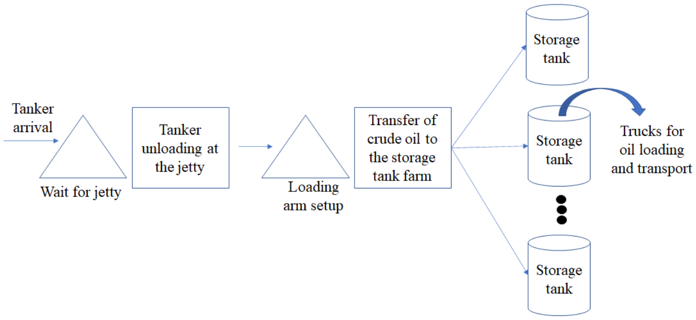

Fig. 1. Tanker unloading process at a bulk liquid terminal

are controlled using regulators. The regulator flow mimics the discharge speed of the loading arm. We capture the capacity feedback of the storage tanks on the loading arm utilization by seizing the loading arm and the beginning and releasing it only after fully discharging the tanker liquid to the storage tanks. The cleaning times are captured using delay blocks.

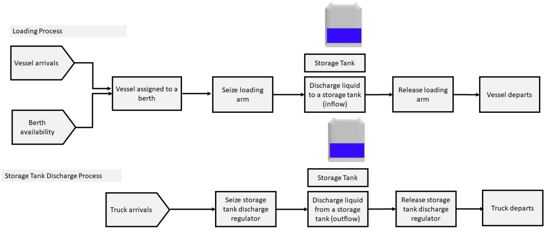

Fig. 2. Flowchart of the bulk liquid simulation model

IV. NUMERICAL RESULTS AND INSIGHTS

For analyzing the performance of a bulk-liquid terminal, we are interested in several performance measures. The simulation model for each scenario is run for 15 replications and 95% confidence intervals for the performance measures. For example, the average wait time of a vessel to access a berth, the sojourn time of a vessel to unload the liquid, the utilization of the loading arms, and vessel blocking delays due to limited storage tank farm capacity are of significant interest to the liquid port and terminal authorities. Note that there is a significant discussion among practitioners and academics alike on whether dedicated loading arms for separate liquids or a common loading arm should be involved for discharging different grades of oils/ liquid chemicals. Dedicated arms avoid the additional process of cleaning the loading arms post discharge albeit with a lower discharge capacity. On the other hand, common loading arms have a higher capacity but involve additional time with the pipe cleaning process also known as pigging process. During pigging operations, deposits are cleaned to separate products discharged using the same pipe one after another ([Esmaeilzadeh et al., 2009]). This trade-off presents an interesting line of analysis (for example, see [Dey and Gupte, 2015]). Another approach to reducing vessel sojourn times could be to use a common discharge pipe for multiple liquids; however, loading arm cleaning time involved with the pigging operations can be eliminated with bunching (grouping) tankers that are carrying the same liquid. If tankers carrying the same liquid are sequenced and discharge operations are performed one after another, then the loading arm can be used without additional cleaning processes. However, now, additional bunching time is involved in the process. We investigate this trade-off with our simulation experiments and study if bunching improves terminal performance. For our numerical experiments, we consider two liquids (white oil and fuel oil) with varying density levels. At low arrival rates, the two vessel types arrive at a rate of 0.05/day and 0.09/day, respectively. At a high arrival rate scenario, the vessels arrive at a rate of 0.06/day and 0.11/day, respectively. Storage tanks for each oil type have a capacity of 120,000 KL. The loading arm capacities for the two oils are 1400 m^3/hr and $2800 m^3/hr$. Table I shows the components of the vessel sojourn time which is composed of expected vessel bunching time, expected time to access a berth, and expected liquid discharge time.

TABLE I
PERFORMANCE MEASURES WITH TWO OIL TYPES, ALL TIMES ARE INDICATED IN HOURS

Arrival rate	Bunching size	E[Bunching time]	E[Berth wait time]	E[Discharge time]	Arm ute.(%)
0.05/day, 0.09/day	1	0.0	187.1	95.9	54.9
	2	177.2	255.5	101.9	58.5
	5	705.6	539.3	120.2	69.3
	10	1600.4	998.8	130.6	74.8
0.06/day, 0.11/day	1	0	187.1	95.9	73.3
	2	140.6	601.7	107.4	77.2
	5	567.8	1451.6	122.3	87.7
	10	1274.2	3587.1	132.9	95.2

From Table I, it is quite evident that bunching of vessels doesn't help with reducing vessel sojourn times i.e., the time reduced with additional pigging operations is far offset by the increase in the tanker bunching times. We observe this phenomenon for both low and high vessel arrival rates. However, it is interesting to observe that with vessel bunching, the utilization of the loading arm increases. For example, the arm utilization increases to 77.2% from 73.3% when the vessels are bunched in groups of two. Such an increase in loading arm utilization is not quite expected because, in typical open queues, batching customers doesn't increase server utilization. We argue that the tank capacity feedback mechanism is contributing to the increase in loading arm utilization. As common vessels are bunched together, the storage tanks are filled rapidly and it doesn't commensurate with the slow discharge rate of liquid from the tanks by external trucks. Hence, the storage tank's limited capacity blocks the loading arms and expands the vessel's sojourn times. In fact in this scenario, the tanks free up storage capacity during the cleaning process. Therefore, the loading arm cleaning times provide a window for discharging the liquid using external trucks and minimizing blocking delays. This insight underscores the value of integrated models for liquid terminals. In fact, under such a scenario, the pooling of pipes is unlikely to help in reducing the vessel sojourn times. On the contrary, dedicated unloading pipes (arms) are likely to reduce loading arm utilization and vessel sojourn times.

V. CONCLUSIONS AND FUTURE WORK

In this research, we develop a fluid flow simulation model for analyzing the performance of bulk liquid terminals. Using an integrated model, we show that analyzing subsystems in isolation may not be a good idea. In particular, capacity feedback from a downstream station (tank farms) in this case can affect the performance of upstream resources (loading arms). Such feedback loops are extremely crucial to estimate tanker sojourn times, which affects the demurrage costs. Using numerical experiments, we are able to develop insights that are important for port infrastructure and terminal capacity building. It is quite possible that just adding an additional berth may not mitigate tanker delays if the storage tank capacity is the bottleneck. The interactions between demand sources and resource supply should be carefully analyzed. This research can be extended to analyze the interactions among the resources including berth capacity, storage tank farm capacity, and loading arm discharge rates on vessel sojourn times.

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