Simulating oil port facilities expansion to meet changing trade demands

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Abstract

Originally described by Schriber in *An Introduction to Simulation Using GPSS/H* (1974), the "African Tanker Problem" deals with a port that loads tankers with crude oil for overwater shipment, with facilities for loading three tankers simultaneously. In the real world, this fictional port would be quite small — particularly in the context of the unremitting expansion of oil markets since the problem's publication. A port in the US state of Texas, the Port of Corpus Christi (PCC), illustrates this well. As the first US port to handle the export of crude oil following the country's lifting of an embargo in 2015, its trade volume in crude over the latter half of that decade underwent a massive expansion and re-orientation toward exports. This shift in traffic presents an opportunity to expand on the original problem's queueing fundamentals to address changing resource needs from a baseline.

We use oil tanker arrival and product volume data from PCC, as well as relevant global tanker fleet data, to construct a simplified representation of the Gulf port's 2016 oil activity in ARENA. After establishing baseline expectations for waiting times, transport times, and dock utilization using this model, we updated it with 2021 traffic data to identify how the port's resources should change in the intervening years. Our model informed recommendations for the installation of new docks and additional transport, and ultimately identified comparable new resource needs to that proposed in public documentation from PCC.

1. Background and Problem Description

The African tanker problem as detailed in Law [1] outlines a small queueing scenario involving a number of oil tanker ships sharing transport and processing resources at a hypothetical African port. Our goal with this project was to expand the scenario to more closely resemble the commercial activities of a real-world oil port, and solve a business problem pertaining to its operational efficiency. The port we chose, the Port of Corpus Christi on the Gulf Coast of Texas, provides a wealth of data to flesh out our scenario and build a realistic simulation problem.

PRODUCT	PCC IMPORTS 2016	PCC EXPORTS 2016	PCC IMPORTS 2021	PCC EXPORTS 2016
Crude oil	15,608,098 (barrels of oil)	18,993,758	10,290,892	85,768,178
Refined petroleum	15,412,587	30,223,444	11,739,408	37,842,575

Table 1: *Upon legalization, US crude oil exports quickly swamped all other business in the Port of Corpus Christi by volume of product [4] [5]. This table illustrates how the proportion changed in the first six years. This data was used to determine product distributions in our model.*

The Port of Corpus Christi is one of the largest oil shipping hubs in the United States. It was the first facility to handle crude oil export in 2015 after the country lifted a 40-year ban on the practice [2], and continues to expand with additional oil docks and inland access points.

Our framing of the problem was inspired by a 2012 planning document published by the port outlining contemporary plans to expand its facilities in response to new business. At that time, the port operated 12 public docks and 15 docks owned by private companies. The document stated that "eight additional public docks to moor vessels and barges [...] will be added" [3].

The proposed expansion was discussed just a few years before the 2015 commencement of oil exports fundamentally changed the port's business, as illustrated in Table 1.

Our scenario makes use of this rapid change to address the question: **given the port's contemporary resources and shipping data after one year of exporting crude oil (2016), how would it need to expand or change its operations to handle business commensurate with data on its 2021 trade activities?**

We were tasked with using simulation to first assess the port's 2016 resource usage, in order to establish a baseline of expectations, and then to determine how other resources would need to change to maintain or improve tanker waiting times in 2021. The resources under consideration in the original tanker problem included harbor transport (tugboats) and docks. These are the resources we assessed for queueing time and utilization. Our scenario assumes that a budget for up to eight additional public docks with proportional new transport equipment is under consideration, as outlined in the 2012 proposal. In addition, our model takes account of different classes of oil tankers with different capacities and specific docks needed to facilitate them. We addressed the following questions:

1. What is the baseline average waiting time for docks for each tanker class? For tugboats?
2. What is the average total system time for tankers of each class?
3. What is the utilization rate for docks accommodating each tanker class? For tugboats?
4. How many new docks are needed for each class of tanker given the increased 2021 traffic? Are any classes over-resourced?
5. Are additional tugboats needed to accommodate the new traffic?
6. Can system times be improved with the allowed new resources?
7. Does the increased business justify the full quota of new resources? Or are 2016 utilization rates low enough to justify only partial implementation?

History provides us with a couple clues to consider: in 2020, a public dock was added that was equipped to operate with Suezmax tankers [6], and in 2017, the port tested the country's first reception of a Very Large Crude Carrier (VLCC) [7]. As such, an increase in the size of ships the port can accommodate plays a part in its response to changing business. A minimum of two of the budgeted docks will necessarily be allocated to accommodate these new classes.

The problem's scope is limited to the port's public docks, but the shipping activities of the 15 private docks impact queues for the port's shared tugboats. The original African tanker problem added two constraints, a storm pattern and an additional UK client, that we've adapted as follows:

- The UK client has become a Brazilian company that, lacking its own private dock, makes use of the port's public docks to deliver crude oil exports to the US on a recurring timescale.
- Storms will be modeled in much the same way as outlined in the original problem, but with an arrival rate and duration that changes throughout the year and peaks during the Gulf's hurricane season.

Finally, the port operates 24/7 year round [8].

2. Preliminary Data Analysis

We made use of data published by PCC in combination with distributions outlined in Law's problem statement to model a tanker's time and route in the port. The number of baseline oil docks (12 public, 15 private) was obtained from the port's 2012 planning document [3]. Specific details about year-by-year numbers of docks available are not published, so this was assumed to hold until the first year of our simulation. The remaining analysis of arrival and service times was performed for both 2016 and 2021 data.

TANKER CLASS	% OF ARRIVALS	SERVICE TIME	DOCKS AVAILABLE
Small/Medium-Range	57%	16 - 20 hours	1, 2, 4, 5, 7, 9, 10, 12
Pana/Aframax tankers	43%	20 - 28 hours	3, 6, 8, 11

Table 2*: An index of tanker classes, their service times, and the public docks that they're able to use.*

The 2016 scenario

Port data provides the number of liquid cargo ships that visited the port in 2016, which was the basis for determining their overall arrival rate [9]. The arrival rate is modeled as a Poisson process, and a goodness-of-fit test was carried out using the port's available month-by-month liquid ship data [10]. This monthly breakdown was unavailable for the 2016 test, so the monthly data for the closest available year — 2018 — was adjusted by the ratio between the two years' total ships; 2016 had 86% of 2018's traffic.

Tanker arrival rate

$$\lambda = \frac{hours\ in\ a\ year}{2016\ ship\ total} = \frac{8760}{1278} = 6.9\ hours$$

$$H_0 = Tanker\ arrivals\ fit\ a\ Poisson(6.9)\ distribution$$

$$Unbiased\ distribution\ mean\ estimate:$$

$$\overline{X} = \frac{1}{12}\sum_{i=1}^{12} X_i = 107$$

X_i	99	89	114	106	108	103	100	108	112	116	113	110
$\frac{(X_i-\overline{X})^2}{\overline{X}}$	0.6	3.03	0.46	0.01	0.01	0.15	0.46	0.01	0.23	0.76	0.34	0.08

$$\alpha = 0.05;\ k = 12;\ s = 1$$

$$\chi_0^2 = 6.17 \leq \chi^2_{0,05,\,10} = 18.301$$

$$We\ fail\ to\ reject\ the\ null\ hypothesis\ at\ a\ confidence\ of\ 0.05.$$

Equation 1: *A χ^2 goodness-of-fit test provided good justification for modeling 2016 ship arrival rates as a Poisson process, with an overall interarrival rate λ = 6.9 hours.*

The 12 public docks are each outfitted to handle tankers of a certain class. The smallest class, Small/ Medium-Range tankers, typically carry refined petroleum products [11], so the proportion of the total arrivals comprised of this class was determined by the proportion of the port's total liquid trade taken up by refined petroleum. Raw data for this is given in Table 1. In 2016, the port's public docks were only equipped for up to Aframax and Panamax size crude carriers [3], which therefore represent the entirety of the crude oil portion of the traffic in our 2016 simulation. The two are modeled as one tanker type for simplicity.

Tanker assignments

DISC(0.57, "Refined", 1.0, "PanaAframax")

Lacking data about loading times at the port, we adopted the original problem statement's service time distributions [1] and assigned each to a corresponding real-life tanker class. The 2016 simulation made use of Law's two smallest distributions, while 2021 accounts for two additional sizes. The docks that each class of tanker is able to use are listed alongside the time distributions in Table 2. All vessels are docked on a first come first serve basis.

Additionally, the port's 15 privately owned docks serve arbitrary oil tankers, with service times that are uniformly distributed across the span of possible times across all categories: *Unif(16, 28)*. Tankers bound for private docks have the same arrival rate distribution of *Poisson(6.9)* as ships bound for public docks, and are generated separately.

While the operations of the private docks are completely independent of the public docks under consideration, tugboats (transport) for berthing of oil vessels at a dock are shared between all docks and suffer constraints from the combined traffic.

The port uses five tugboats, which operate in line with the original African tanker problem. From Law's description, "tankers of all types require the services of a tugboat to move from the harbor into a berth and later to move out of a berth into the harbor. When the tugboat is available, hooking a tanker up takes an hour (whether in preparation for berthing or unberthing)" [1]. The tugboats now service the port's 27 total docks, which are clustered in four different travel nodes; their distances are described in Figure 1, and approximated from a map of the port [3]. Tugboats travel at a speed of 15 knots (17.3 miles per hour) when unloaded, and 5 knots (5.7 mph) when pulling a tanker, based on real-world estimates [12]. Five tugboats were chosen as a baseline to match the four dock clusters and entrance/exit node.

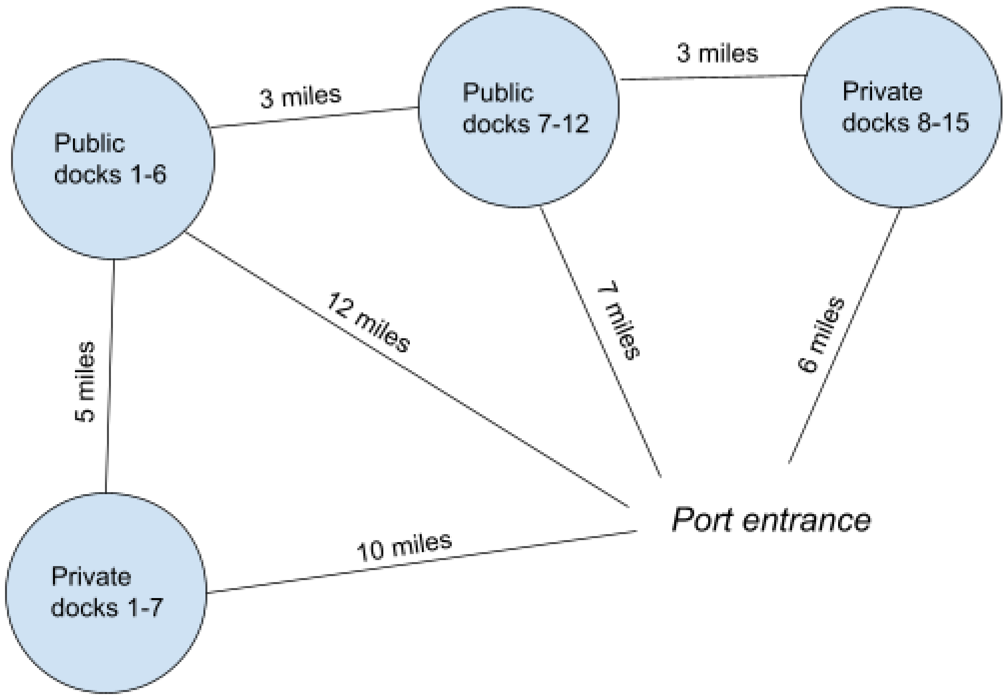

Figure 1: *Diagram illustrating the rough distances between the 27 docks.*

The nearest available tugboat is requested to the most recently queued tanker at either a dock or the port entrance. When not in use, they travel to a designated home dock. One assumption of this model is that each tug boat has an independent "home" dock at one of the nodes (i.e., no node has more than one tug boat that will return there by default). Travel between dock clusters lacking a direct connection are defined as the sum of intervening edges, e.g. travel from *"Private docks 1-7"* to *"Private docks 8-15"* = *5 + 3 + 3 = 11 miles*.

The additional Brazilian company requires five Pana/Aframax tankers. After unloading their oil they travel to Rio de Janeiro, fill up, and embark on a return trip. The total time between visits is estimated to be 336 ± 48 hours, or *Unif(288, 384)*. For the purposes of the simulation, these additional ships are in the queue for their first service at $t = 0$.

Storms are modeled based on average weather patterns in the Gulf of Mexico [13]. Each month of the year has different distributions for storm arrival rate and duration. Historical data on the number of monthly precipitation days was used to bound a uniform distribution for the arrival rate. More severe storms cause longer delays to the port's service, and duration distributions are based on the amount of precipitation in each month. Tugboats will not start a new activity when a storm is in progress, but finish an activity already in progress. The docks operate during storms.

MONTHS	ARRIVAL RATE	DURATION
January - March	*Unif(120, 144)* - approx. 5-6 precipitation days per month	*Triangular(1, 1.5, 5)*
April	*Unif(102, 120)* - approx. 6-7	*Triangular(1, 2, 8)*
May	*Unif(65, 72)* - approx. 10-11	*Triangular(1, 1.5, 8)*
June - September	*Unif(31, 36)* - approx. 20-23	*Triangular(1, 4, 11)*
October	*Unif(55, 65)* - approx. 11-13	*Triangular(1, 1.5, 8)*
November - December	*Unif(120, 144)* - approx. 5-6	*Triangular(1, 1.5, 5)*

Table 3 *Storm arrival rates and durations by month of the year, given by distributions in hours.*

The 2021 scenario

Most of the above description applies to the simulation based on 2021 data, with new tanker arrival rates and two additional tanker classes.

Tankers arrive with a new, faster arrival rate determined by the overall total of ships with liquid cargo that visited the port in 2021 [9]. Now in addition to Small/Medium-Range and Pana/Aframax tankers, the port's new dock budget includes some that are equipped to service Suezmax and VLCC class tankers. As stated in the previous section, reliable service time data associated with loading/unloading activities broken out by tanker class was unavailable, and so Law's problem statement was used as reasonable ballpark distributions. Conveniently, the ratio between Law's average service times for the second and third tanker types is similar to the ratio of the Pana/Aframax and Suezmax average carrying capacity [11]. It stands to reason that a tanker's service time is proportional to the amount of oil it is carrying at any given time, so the direct substitution of Law's tanker Type 3 for Suezmax tankers was considered a reasonable one. Derivation of a service time distribution for the VLCC tankers involved slightly more effort, given that Law does not describe a fourth class of tanker. A reasonable approximation was obtained by scaling the Suezmax variance and mean service time by the ratio of carrying capacities between the Suezmax and VLCC tankers.

The baseline 2021 simulation dedicated just one dock to each of the two classes in order to allow them service, with original dock allocations otherwise remaining unchanged. The proportion of each category visiting the port is based on the proportion taken up by each in the global fleet of oil tankers [14]. The split between small refined carriers and crude carriers is still determined by the proportion of each product in the port's trade in 2021, with raw data detailed in Table 1.

VLCC Service Times

Ratio of VLCC-Suezmax Capacity:

$$a \approx 1.64$$

Mean VLCC Service Time:

$$\mu = a * Mean\, Suez\, Service\, Time = 1.64 * \frac{(40+32)}{2} \approx 59\, hours$$

Variance of Suezmax Service Time:

$$Var(X) = \frac{(40-32)^2}{12} = 5.3\, hours$$

Variance of VLCC Service Time:

$$Var(Y) = Var(aX) = a^2 Var(X) = 14.2\, hours$$

Uniform Half Width:

$$\frac{(b-1)}{2} = \frac{\sqrt{12Var(Y)}}{2} = 13.0\, hours$$

Range of VLCC Service Time:

$$59 \pm 6.5 \sim UNIF(52.5,\ 65.5)$$

Tanker arrival rates

$$\lambda = \frac{2021\, ship\, total}{hours\, in\, a\, year} = \frac{1885}{8760} = 4.6$$

$$\sim Poisson(4.6)$$

Tanker assignments

44% Refined Petroleum

56% Crude oil

Crude carrier size:

Total tankers in fleet: 2210

Pana/Aframax: 746, 33.4%

Suezmax: 571, 25.8%

VLCC: 810, 36.7%

Crude tanker size: Disc(0.334, "PAMax", 0.592, "Suez", 1.0, "VLCC")

Overall tanker distribution: Disc(0.44, “Small”, 0.627, “PAMax”, 0.771, “Suez”, 1.0, “VLCC”)

Equation 2: *To determine a service time distribution for a fourth class of tanker, the capacities of the different classes were used to determine a proportional difference between the service times defined by Law. Tanker arrival rates are once again modeled as a Poisson process based on the statistical test performed for 2016, with a faster arrival rate based on 2021's ship total. Class assignments are based on proportions of petroleum products in the port's 2021 trade [5], and by the proportion of each crude carrier class in the global tanker fleet [14].*

TANKER CLASS	% OF ARRIVALS	SERVICE TIME	DOCKS AVAILABLE	CARRYING CAPACITY
Small/Medium-Range	44%	16 - 20 hours	1, 2, 4, 5, 7, 9, 10, 12, additional to be determined	22,197 - 406,945 barrels
Pana/Aframax	18.7%	20 - 28 hours	3, 6, 8, 11, additional to be determined	443,940 - 887,880
Suezmax	14.4%	32 - 40 hours	13, additional to be determined	887,880 - 1,331,820
VLCC	22.9%	52.5 - 65.5 hours	14, additional to be determined	1,331,820 - 2,367,680

Table 4: *Updated tanker distributions based on the port's 2021 data.*

The port's 15 privately owned docks once again have uniformly distributed service times that encompass the possible times across categories: *Unif(16, 65.5)*. Private tankers have the same arrival rate distribution as ships bound for public docks and are generated separately.

Our analysis will determine how many new docks and how much additional transport is needed to adjust to the new demand, so the same five tugboats were the assumed starting point. The port's updated layout accounting for up to eight new docks is detailed in the Appendix.

4. ARENA Implementation

We implemented our models with discrete event simulation in ARENA. The main components are a transporter routing network between a set of dock stations, tanker generation and classification, and a dynamic storm generator.

Assignments and routing

Our simulation separately generates three types of ships: public tankers, private tankers, and Brazilian tankers. Public tankers are further assigned a tanker class and accompanying service time based on the distributions described in Section 3. Brazilian tankers are generated only once, with five total entities appearing at t=0.

All ships need to be routed to an appropriate dock based on three conditions: public or private, tanker class, and dock location.

Private tankers simply reserve the first available dock in the set of private docks with no restrictions on class. They are only designed to serve as a constraint on transport queues.

Public tankers first reserve an available dock that is equipped for their class (e.g. a Pana/Aframax dock), and then reserve transport to the station that matches their dock's location in the two public clusters.

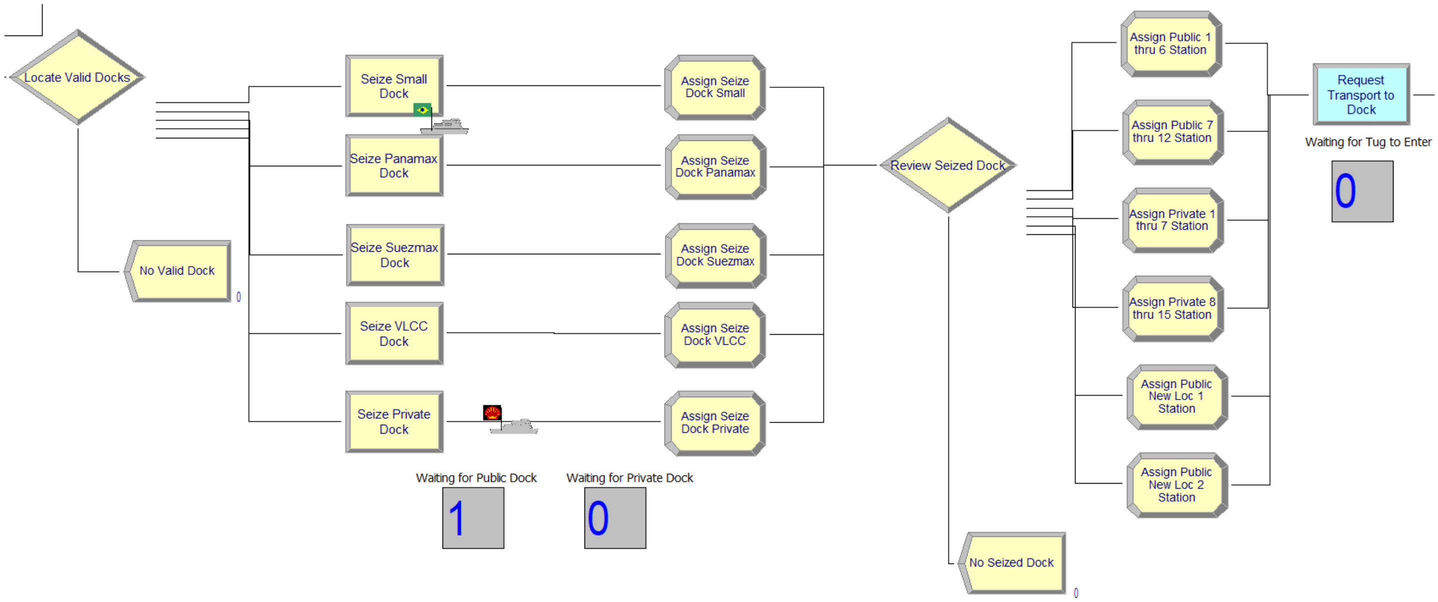

***Figure 2**: Our ARENA implementation made use of a two-step check to first assign each tanker a dock appropriate for its class, and then a station destination to match its dock's location.*

This two-step check approach is then repeated when the tankers prepare to exit to ensure they free the correct resources. Tugboats are freed after dropping the tanker off, and reserved again when it's ready to exit.

Brazilian tankers

While in the port, the Brazilian tankers are handled the same as other Pana/Aframax class tankers. Rather than heading to a dispose block, however, the Brazilian tankers are routed through a branch that first gathers statistics, and then holds them for the random time described in Section 3. Afterwards, they loop back to the port's entrance station.

Simulating changing weather

The storm function is handled with two types of fake customers, generated in a separate section of the simulation. The first entity is a simple month tracker, used to index the current storm distributions.

Storm entities arrive according to the distributions described in Section 3. Upon creation they trigger a Halt block for each of the tugboats individually to ensure they are all successfully stopped. When all tugs are stopped, the storm is delayed according to the current month's duration distribution. It then resumes each tug's activity and is disposed. This process is pictured in the Appendix.

5. 2016 Simulation Analysis

The 2016 simulation was used to determine what queue times and resource utilization rates to expect when the port's resources are in line with its trade volume for a given year. 2016 was selected as a baseline year because it followed the port's first full year of dealing in crude oil exports, and is arguably the first like comparison with the post-boom activity of 2021. The simulation was assessed with averages from 250 1-year replications.

System times, waiting times, and incompletes

Overall, an average of 1270 total tankers arrived for service at the public docks, comprised of 546 Pana/Aframax (crude) and 725 Small/Medium-Range tankers. The crude classes spent on average 37 hours in the port, while small tankers spent 29. This is somewhat above the global median time in port of 25 hours for liquid petroleum ships circa 2021 [15].

Transfer times for the crude and small tankers averaged 7.5 and 8 hours, respectively. Law's original problem statement estimated an hour of hookup time for tugboats for berthing and unberthing. We interpreted this conservatively to indicate an hour each for: hookup time upon port entry, getting set up at the dock, hookup for the return, and release at the exit. This provides a constant input of 4 hours to each ship category's total transfer time. The remainder constitutes travel time through the harbor.

These numbers are fixed — without more specific data about PCC's transfer times, our best estimates are the assumptions defined in Law's problem statement and general data about tugboat speeds.

Waiting times, however, do reveal an opportunity for improvement, particularly with regard to rebalancing docks between classes. Wait times for the crude and small tankers averaged 6.1 and 3.1 hours, respectively.

For small tankers, the bulk of this was waiting for tugboats. Across all tanker classes, waiting for a tug to the dock averaged 0.6 hours, and waiting to head to the exit averaged 0.55 and 0.68 hours for the two public dock clusters. Waiting to reserve a dock was no issue for small tankers, averaging 0.01 hours.

On the other hand, Pana/Aframax tankers had to wait an average of 3 hours to reserve a dock, in addition to the abovementioned transport wait time averages. Small tankers were given eight docks in this simulation, compared with crude tankers' four. Upgrading a small dock to fit a larger ship or setting aside a portion of the funding for new docks suited to these classes is one opportunity to improve operations.

Traffic did not cause a major issue with incompletes. On average, 4.7 total ships were left unfinished on the public docks, or 0.4% of the total.

Resource utilization

Public dock utilization rates, given in Table 5, illustrate the disparity in resource access between the two classes.

Consistent with the distribution of waiting times, the five tugboats had a healthy overall utilization of 72%. On average, 3.2 of the tugboats were active at a given time.

DOCKS	CLASS	UP-TIME
1	Small	67.3%
2	Small	54.5%
3	Aframax	75.4%
4	Small	39.4%
5	Small	24.7%
6	Aframax	65.9%
7	Small	13.1%
8	Aframax	53.6%
9	Small	5.9%
10	Small	2.3%
11	Aframax	39.7%
12	Small	0.1%

Table 5: *Dock utilization rates by tanker class.*

Other constraints - Brazilian company and storms

The five Brazilian tankers were never disposed, and left to wait for their away time distribution before returning to the port. They averaged 38 hours in the port each visit, very close to the 37 hour average for generic public ships of the same size. The five ships were serviced 119 times total, on average, representing about 8.6% of the total public dock tanker traffic and 17.9% of Pana/Aframax dock traffic. While after initial generation the five ships arrived at the port in a single group, they gradually desynced as their random refill trips incurred differing delays. By late in the year the Brazilian ships blended in with the main public tanker traffic.

The port weathered 144 storms over the course of the year, with an average duration of 4.42 hours. This meant that tugboats were halted for about 636.5 hours out of the year, or 7.3%. The storm's impact is reflected in the simulation's tugboat utilization data. While the number of tugboats scheduled at a given time averaged 4.6, the number actually busy only averaged 3.2. It's possible that this gap arose from tugboats reserved for a transport task needing to sit halted at the dock for the duration of every storm.

5. 2021 New Traffic Analysis

For the initial 2021 simulation, one dock for each new tanker size (i.e., Suezmax and VLCC) was added, strictly in order to accommodate the new categories prior to determining the best course of action. This left six additional new docks to be allocated. No additional docks were built for the existing tanker sizes, and no additional tug boats were pushed into service. This initial iteration was anticipated to be inadequate; its purpose was to ensure additional resources were added on the basis of observed demand.

A review of 100 one-year replications indicated that only the Suezmax and VLCC tankers were bogged

TANKER CLASS	NUMBER IN	NUMBER OUT	% DISPOSED
Small	837.7 ± 5.8	834.9 ± 5.7	99.7%
Pana/Aframax	358.8 ± 3.4	357.3 ± 3.4	99.5%
Suezmax	273.8 ± 3.4	195.5 ± 0.3	71.4%
VLCC	435.6 ± 4.1	129.4 ± 0.2	29.7%
Private	1898.8 ± 8.2	1886.9 ± 8.2	99.4%

Table 6: *Proportion of tankers successfully completed in the different classes in the preliminary 2021 simulation.*

down with extraordinary wait times. This is evidenced by a comparison of the number of entities created vs. the number of entities disposed for each tanker type. Unlike in the 2016 simulation, incomplete service was a real problem for the two new tanker classes, as indicated in Table 6.

The capacity problems for the two tankers in question are further evidenced by the estimated half-widths in the estimation of the true entities in and out in a given year. For small, Pana/Aframax, and private tankers, the half widths for entities out is effectively equivalent to that for entities in. For our new tanker types, however, the variation on the number of entities exiting our simulation is minimal, indicating that we have reached the finite limit that can be processed in a fixed time period.

While tugboat usage wasn't investigated in detail at this stage, it's worth noting that the localization of capacity issues to just two tanker types strongly indicated that no resource shared amongst all tanker types (i.e., tugboats) was driving the low disposal percentages for Suezmax and VLCC.

Because the key problem was immediately clear, we proceeded with testing port improvements before doing detailed analysis on transporters and utilization rates of other classes' docks.

6. Port Improvements, Analysis

In order to proceed with assessing the best allocation of port improvements, we first iterated on dock allocations for the two new tanker classes.

Assessing impact of improvements

For this step in the analysis we looked at the utilization rates of the docks relevant to the two most backed up classes and at the tankers' disposal rates, stopping when they were both in line with baseline expectations.

MODEL #	SUEZMAX DOCKS	VLCC DOCKS
2021-1	13	14
2021-2	13, 15	14, 16
2021-3	13, 15, 17	14, 16, 18
2021-4	13, 15, 17	14, 16, 18, 19, 20
2021-5	13, 15	14, 16, 17, 18, 19, 20

Table 7: *Improvements made to the 2021 scenario first included expanding dock access for the two new tanker classes. We used five iterations to find a point of balance that left no massive dock over-utilizations for any class.*

Both indicators steadily improved with the addition of the new docks, and a balanced point was found with three Suezmax and five VLCC docks. This solution uses the full quota of new dock budget. Figures 3 and 4 illustrate the model improvements over each iteration.

While the utilization rates of all docks appear to be in check for both models 2021-4 and 2021-5, two problems were established in the review of the data:

1) Model 2021-5 results in disproportionately high average wait times for Suezmax tankers, mostly driven by wait times for dock seizure. This was surprising, given the reasonable utilization rates for these docks. Huge variation amongst the replications was observed across the 100 replications (14.9 minimum vs. 81.0 hours maximum). This model simply didn't appear built to handle situations in which a group of these ships arrived

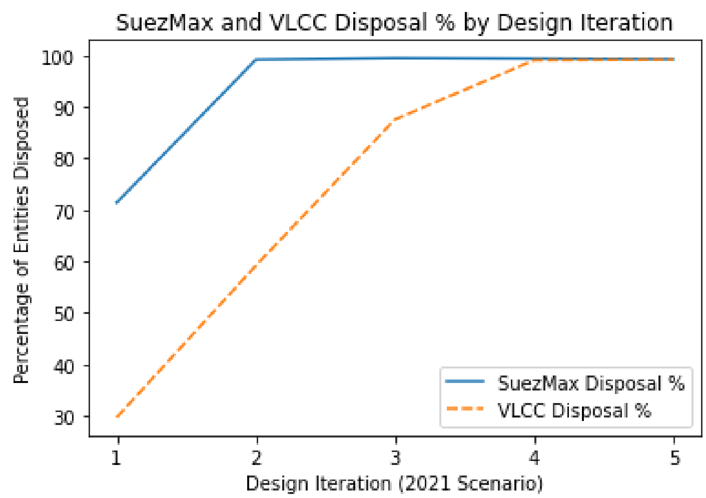

Figure 3: *Successful completion of Suezmax and VLCC tankers steadily improved with the introduction of additional docks.*

around the same time. Suezmax is the tanker class that arrives with the lowest frequency, so dock utilization should still appear reasonable, because such heavy-usage instances would be balanced by periods of without use. Reverting to Model 2021-4 was deemed prudent, as this reduced Suezmax wait times by a factor of three, as illustrated in Figure 5.

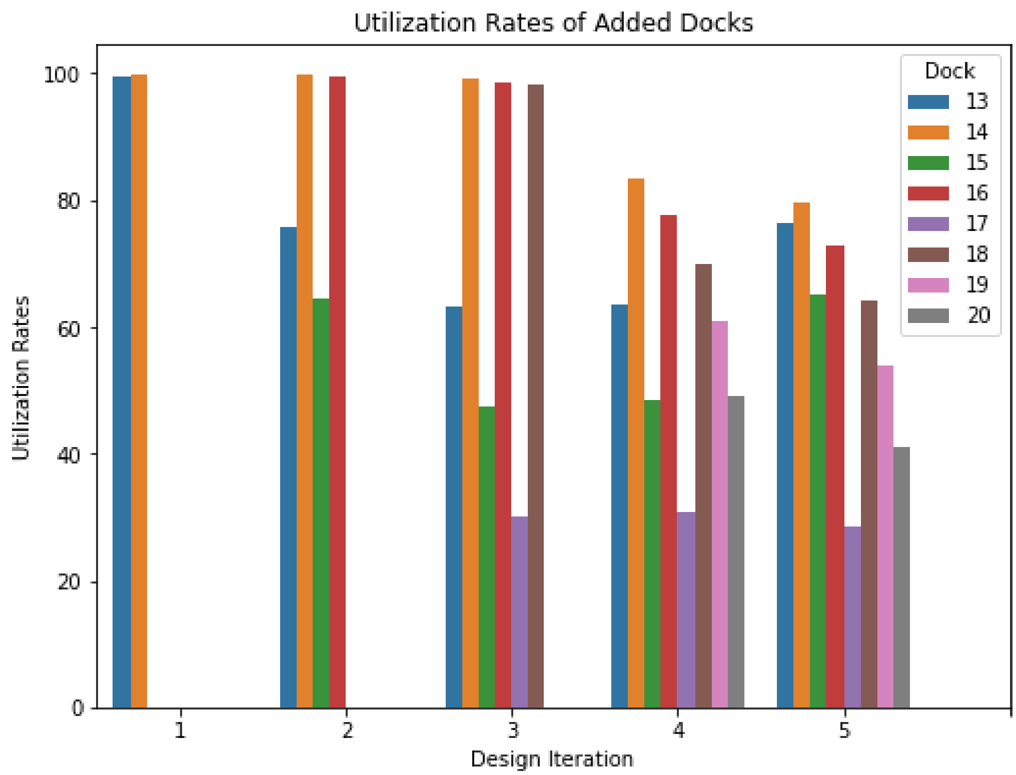

Figure 4*: An illustration of how utilization is distributed amongst the new docks for all models 2021-1 through 2021-5. These iterations allocated all new docks to the two new tanker classes.*

2) Both Models 2021-4 and 2021-5 show tug utilization at approximately 96.4%. A review of wait times for tug usage show 1-2 hours is common at each station, which isn't terrible. However, this sort of high usage is probably not sustainable for the real world. Eventually the boats would need to be taken in for maintenance; at present, our model does not dedicate time for such activities, so they could only feasibly take place when tugs are non-operational (during rainstorms).

Two subsequent models were run increasing the tug quantity by one (2021-6) and two (2021-7). These utilized the dock allocation from Model 2021-4, which showed superior Suezmax performance. Tug utilization was reduced to 88.2% and 80.7% for models 2021-6 and -7, respectively.

Not only did queue times for the tugs themselves decrease, but a secondary benefit is realized in the queue times for dock seizures as well. Because tankers are pulled out to harbor with greater frequency, the docks become available more often for subsequent ships to seize them. The impact on these queues was as significant as on the direct tug queues (about 1 hour apiece from models 2021-4 to -6 and 30 minutes each for models 2021-6 to -7), as shown in Figure 6.

System times and waiting times

We assessed our final model with averages from 250 1-year replications. An average of 1906 total tankers arrived at the public docks, comprised of 359 Pana/Aframax, 273 Suezmax, 434 VLCC, and 839 Small/Medium-Range tankers. System and waiting times are given in Table 8.

Since the port's new resources were levied to tackle the influx of large tanker traffic, the question remained whether there were any negative impacts on the pre-existing two classes to address. As noted in Section 5, transfer times are constant and service times are reliant upon the size of the tanker itself. The relative success of our baseline and final models is therefore measured in wait times. This is borne out by Table 8, which indicates that the changes in total system time and wait time for the two classes present in both simulations are nearly identical. Both classes saw slight improvement, sharing the benefits of two additional tugboats, and additional docks aren't needed to beat baseline expectations.

Our 2016 analysis noted a discrepancy between the wait time for docks in particular between small and Pana/Aframax tankers. The discrepancy has lessened; while small tankers still experience negligible dock waits (0.02 hours), the Pana/Aframax tankers now wait just 1.05 hours on average to seize a dock (down from 3 hours in 2016). The problem was resolved as consequence of 2021's crude tanker traffic being offset to the two larger classes.

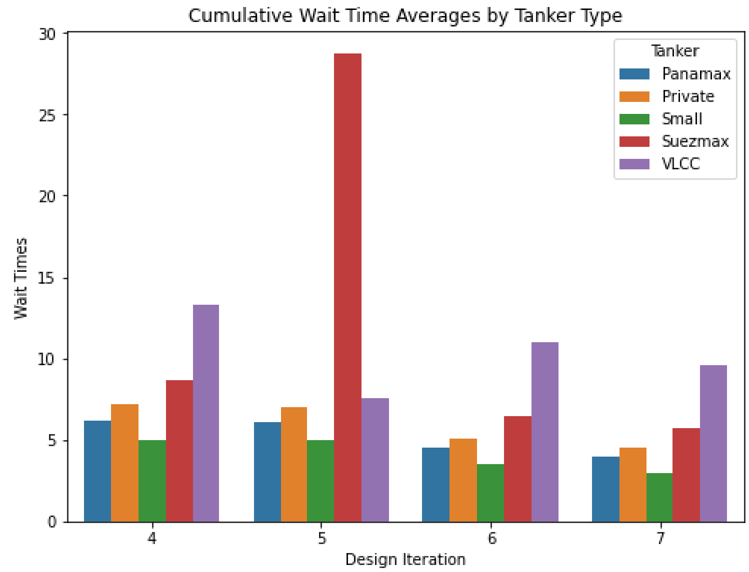

Figure 5: *Suezmax class tankers suffered anomalous wait times when one of their docks was reallocated for VLCC class. The dock arrangement in iteration 4 was instead used to analyze the impact of additional tugboats.*

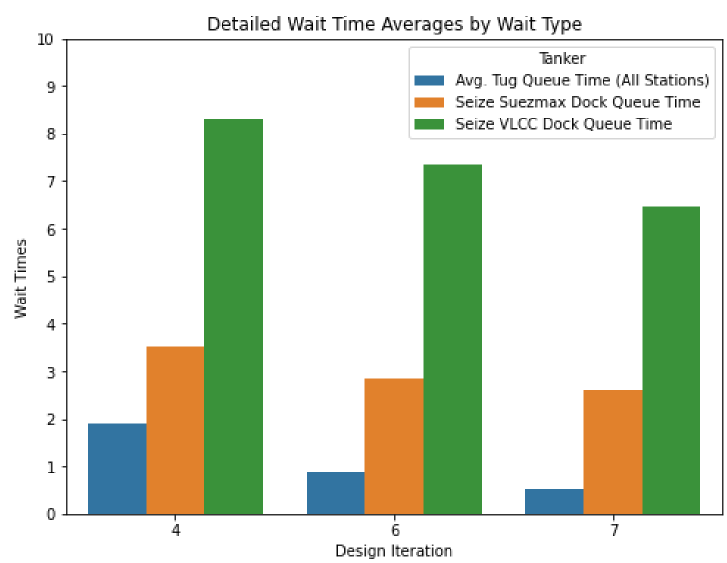

Figure 6: *The addition of two tugboats had a cascading effect on the port's wait times, improving not only queues for transport but resource queues as well.*

CLASS	TOTAL	2016 Δ	WAIT	2016 Δ
Small	28.9	-0.3	2.9	-0.3
Aframax	35.6	-1.9	3.9	-2.1
Suezmax	50.4	N/A	5.6	N/A
VLCC	77.1	N/A	9.8	N/A

Table 8*: Final total and waiting times for all classes in the post-improvement 2021 model.*

Final assessment

In view of waiting times and the balance of resource utilization, Model 2021-7 offers the best performance. The eight new docks and two additional tugboats servicing two new public dock locations align with the original budget laid out for the project. However, there exist some opportunities to recoup funds and further improve operational efficiency.

In particular, final utilization rates for the full set of public docks are given in Supplemental Table 1 in the Appendix. As was already the case in the 2016 simulation, Small/Medium-Range class tankers are over-resourced compared to the larger classes. Docks 10 and 12 in particular are reserved for less than 5% of the simulation.

One option is to repurpose these underutilized docks towards the higher volume tanker types, rather than constructing entirely new docks.

For various reasons, this may be infeasible due to the size differences between the two configurations. In this case, we propose selling one or both of these docks for private use to defray costs for the required expansions, as at present they don’t provide much value.

7. Opportunities for Further Work

In the data collection phase of this project, we explored a variety of opportunities to add complexity and realism to the simulation. Studies with a broader scope could incorporate several key features of the port to reflect its real oil trade operations with more detail:

- Import/export ratios and product storage: on-dock storage has limits, and is kept in balance with tanker traffic by direct pipeline supply. An additional constraint on tanker waiting times could be implemented via an inventory check against the tanker's capacity and whether it is importing and exporting. This would add an inventory modeling challenge to the queueing scenario. The data for this is available in the port's import-export volume for previous years and in public releases detailing expansions to oil storage capacity. The assessment of resource allocation could then be expanded to include additional oil silos if need be.
- Inland shipping: the full picture of PCC's oil trade also includes visits from both highway tankers and three railways.
- Changing weather: while we kept our weather patterns the same between 2016 and 2021 for lack of specific regional data, a key concern for over-water shipping in the future is increasing intensity of tropical storms.

- Multiple oil products: we allude to this in the way we allocate our tanker classes, but a more realistic simulation would need to account for the different equipment and storage needed to handle refined vs. crude oil products, and the differing traffic between the two categories.

8. Conclusion

Following discrete event simulation of multiple pre- and post-improvement traffic scenarios, our analysis indicates that the Port of Corpus Christi's budget proposal for public dock expansion adequately prepares it to meet the changing demand needs of a US oil export boom. In particular, their best course of action is to devote all of their eight new docks to larger tanker classes, based on the preponderance of these ships in the global fleet, with three equipped for Suezmax and five for VLCC tankers. Additionally, investment in two additional tugboats ensures reasonable wait times in the harbor and a reasonable rate of use.

We further suggest selling three docks dedicated to Small/Medium-Range tankers to private entities due to underutilization. This is one possible approach to bringing dock utilization rates more in line with traffic across classes, freeing up funding for larger-class docks.

Following these changes, wait times in the dock were on par with or improved over their 2016 equivalents, and wait times for the new tanker classes scaled proportionally to their necessarily longer service times.

These findings align well with the plan outlined by PCC for eight total new docks and indicate that our model, while simplified, does closely depict this real world business challenge of one of largest ports in the United States.

9. References

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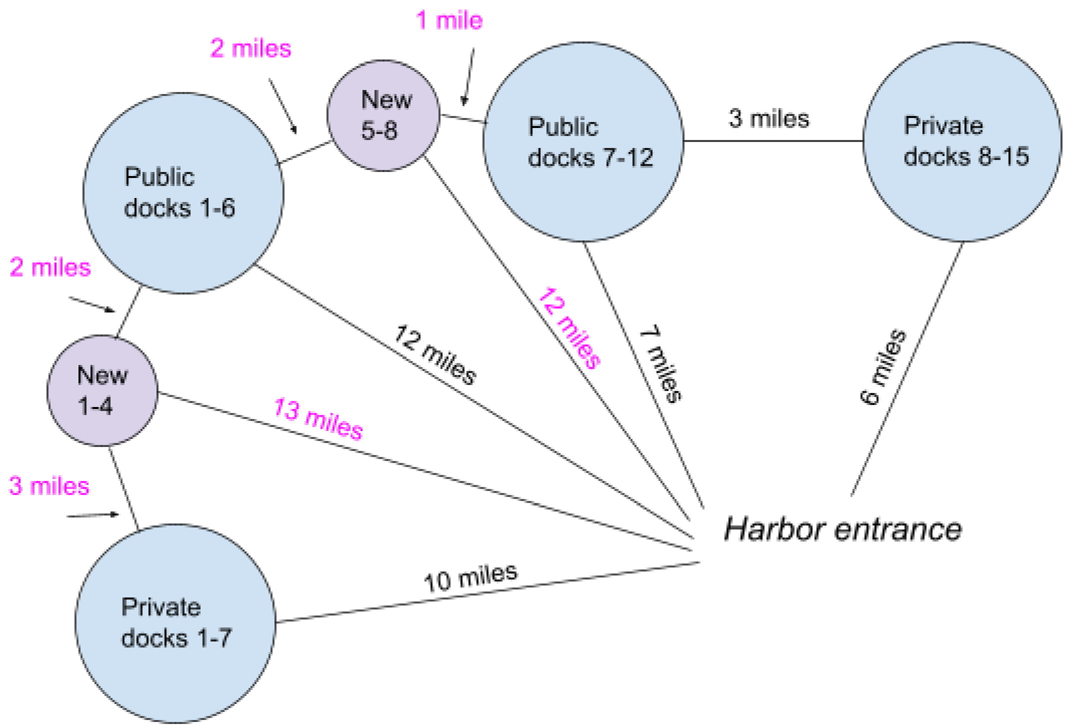
Appendix

Additional figures and statistics.

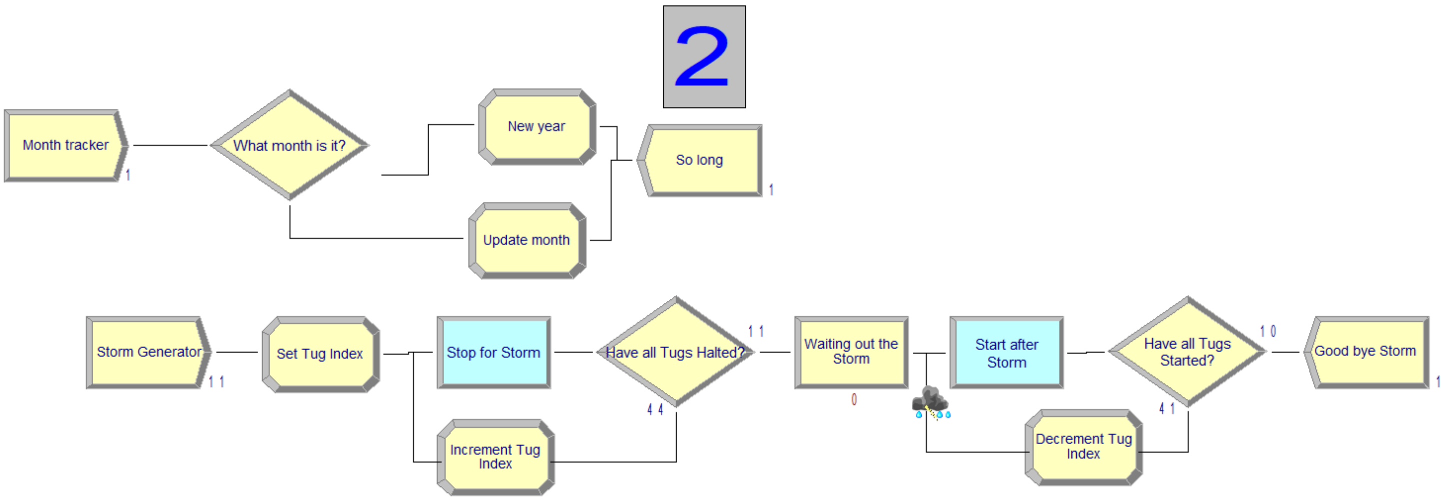
Supplemental Figure 1: Updated dock map with the locations for up to eight new docks following an assessment of necessary resource upgrades for 2021 data.



Supplemental Figure 2: Dock resources in ARENA needed to be classified both by which class of tanker they serviced - including private tankers - and also by which node cluster they were located in for transportation purposes. This screenshot shows our resource sets from the pre-upgrade 2021 simulation.

Docks Small	Resource	Manual List	8 rows
Docks Panamax	Resource	Manual List	4 rows
Docks Suezmax	Resource	Manual List	1 rows
Private Docks	Resource	Manual List	15 rows
Public Docks 1 to 6	Resource	Manual List	6 rows
Public Docks 7 to 12	Resource	Manual List	6 rows
Private Docks 1 to 7	Resource	Manual List	7 rows
Private Docks 8 to 15	Resource	Manual List	8 rows
Docks VLCC	Resource	Manual List	1 rows

Supplemental Figure 3: The storm generator relied on two types of fake customers. A storm entity first halted all tugboats before delaying according to a monthly distribution. The month tracker incremented the month index, resetting it to 1 every January.



Supplemental Table 1: Dock utilization rates by tanker class in the final, post-upgrades 2021 simulation.

DOCKS	CLASS	UP-TIME	DOCKS	CLASS	UP-TIME
1	Small	70.4%	11	Aframax	20.0%
2	Small	59.1%	12	Small	1.5%
3	Aframax	64.7%	13	Suezmax	62.1%
4	Small	45.5%	14	VLCC	82.0%
5	Small	31.0%	15	Suezmax	45.1%
6	Aframax	49.9%	16	VLCC	76.1%
7	Small	17.9%	17	Suezmax	28.1%
8	Aframax	34.0%	18	VLCC	67.3%
9	Small	8.9%	19	VLCC	57.1%
10	Small	3.9%	20	VLCC	44.7%