Optimisation of bulk carrier loading and discharge

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June 2013

Abstract

This report summarises progress made towards the problem submitted by Rusal Aughinish at the 93rd European Study Group with Industry. Rusal Aughinish is a company that refines alumina from bauxite. The problem presented to the study group was to review the percentage of time that the company's inner berth was occupied and how to minimise this percentage. A number of different approaches were taken with this aim in mind. Firstly, data supplied by Rusal Aughinish was analysed. This analysis found that there is an optimal loading rate (with respect to eliminating demurrage costs) and suggested bands of optimal ship sizes. Further to these studies, two models of Rusal Aughinish's shipping process were developed by the group: a simulation model and an analytical model. Both models were found to replicate the shipping process reasonably well and were, hence, used to study alumina output, berth occupancy and demurrage costs.

1 Introduction

Rusal Aughinish is Europe's largest alumina plant. It is located on Aughinish Island which is on the southside of the river Shannon Estuary, approximately 35 km west of Limerick city, Ireland. Alumina (or Aluminium Oxide) is a white sandy type material. It is refined from bauxite, a reddish brown ore which is imported from Guinea in West Africa and Brazil. The refinery process is known as the Bayer process. Once alumina is refined in Aughinish, it is exported to smelters worldwide [1].

In order to satisfy its large shipping needs, Rusal Aughinish maintains and operates its own jetty (see Figure 1). As well as exporting alumina and importing bauxite, the company also uses the jetty to import caustic soda, acid and fuel oil. Caustic soda is used in the refining process to dissolve bauxite, acid is used for cleaning, while the fuel oil is used to satisfy its energy needs. For each ship that arrives at Aughinish, the company are allowed a certain amount of time to load or unload the ship. This time is known as *laytime* and is determined by the contract agreed between the shipping company and Rusal Aughinish. If Rusal Aughinish use more than this time then they must pay the shipping company a compensation known as *demurrage*.

Another thing that is of concern to Rusal Aughinish is berth occupancy. Berth occupancy is the amount of time that ships are berthed on the jetty in Aughinish (usually expressed as a percentage of total time). As Figure 1 shows, there are two berths to Aughinish's jetty, an inner and outer berth. The outer berth is used almost exclusively for importing bauxite[1]. The inner berth is used solely for alumina, caustic, acid and fuel oil ships. Table 1 gives the percentage of the different types of ships docked in the inner berth for 2010 - 2012.

Both berths are limited to having one ship docked on them at a time. As a result, some ships may have to wait in the Shannon Estuary before docking. Tidal patterns complicate the process of docking. Ships may only dock at Aughinish at

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[1]This was only the case in recent years. Previously the other cargo ship types used the outer berth, although bauxite ships have always been the primary user of the outer berth.

Figure 1: Rusal Aughinish's jetty.

	2010	2011	2012
Alumina	73%	76%	79%
Caustic	18%	18%	16%
Fuel Oil	7%	5%	2%
Acid	2%	1%	2%

Table 1: Percentage of the different types of ships docked in the inner berth for 2010 - 2012.

certain times when the tide is suitable. Further discussion on this complication is provided in Section 1.1.1. In recent years the inner berth occupancy at Aughinish has steadily increased (see Table 2). Rusal Aughinish want to minimise berth occupancy whilst maintaining alumina production (and hence export) rates. Minimising berth occupancy allows the company more time to carry out necessary maintenance work on the jetty and also helps minimise demurrage costs.

	2010	2011	2012
Berth occupancy	65%	73%	77%

Table 2: Berth occupancy for 2010 - 2012.

The two main factors affecting berth occupancy in Aughinish are ship size (in tonnage) and loading rates. Having bigger ships means that the time spent per ship on the berth is greater as it takes longer to load or unload the ship. However, smaller ships cannot carry as much of a load which means more ships are needed in order to maintain production rates. Loading rates also affect berth occupancy as a higher loading rate means that ships are available to leave the berth earlier. Due to a number of reasons however, the (un)loading of ships may be curtailed or delayed. Examples of events that may delay the (un)loading of ships are weather and mechanical failure. A more detailed description of the entire shipping process is provided in Section 1.1.

As a result of these delays, two types of loading rates are referred to in this report: *operational* and *effective* loading rates. Operational loading rates are based only on the time that it actually takes to load the ship, i.e., when delays are excluded. In contrast, effective loading rates are based on the total time a ship spends on the berth, i.e., the time it takes to load the ship, including delays. Operational loading rates are always greater than or equal to effective loading rates.

In June 2013, Rusal Aughinish brought a problem, associated with its shipping process, to the 93rd European Study Group with Industry. This study group was hosted by MACSI at the University of Limerick, Ireland, 23rd June - 28th June 2013 and this report summarises the work undertaken by the group. The aim of the study group was to examine Rusal Aughinish's

1. optimal ship sizes,

2. optimal loading rates,

with respect to

(a) Inner berth occupancy,

(b) Total alumina output,

(c) Demurrage costs.

As mentioned above there are two berths in the jetty at Aughinish, an inner and outer berth. For the study group, the above aims were only analysed with respect to the inner berth. As a result, an analysis of outer berth activities was not included. Henceforth, in this report, all berth activities refer to inner berth activities. In order to address the aims above, Rusal Aughinish provided data on its shipping process for the years 2010, 2011 and 2012. This data included details of all the ships that docked at Aughinish during these years. In particular, it included information on the size of ship, time of arrival, delays, demurrage costs and loading rates associated with each ship.

A number of different approaches, taken by the Study Group, are described in this report to address the aims above. Firstly, the data is used to analyse the laytime (and hence demurrage costs) of ships arriving into the inner berth of Aughinish. This analysis looks at the optimal loading rate that ensures that laytime is always met. Secondly, a visual representation of the shipping process is provided over a period of three months. This informs the development of an Excel algorithm that helps identify the optimal ship sizes. The third approach taken by the study group and described in this report is the development of a simulation model. The model is a queueing model that attempts to replicate the actual shipping process at Aughinish. Queueing models are widely used in operations research and are used to model queues or waiting lines stochastically [2]. The queue in this context are the ships waiting to berth at Aughinish's jetty. The model developed here is novel in that takes into account the unique aspects of Rusal Aughinish's shipping process. The model is informed by statistical analysis, carried out by the group, of the aforementioned data. In order to validate the model, simulations are compared with actual data from 2012. Once validated, the model is used to examine the effects of increasing loading rates and the effects associated with some of the loading related delays.

The final approach taken during the Study Group was the development of an analytical stochastic process model. When compared with the simulation model, this model is a simplified model. However, in contrast to the simulation model,

it has an analytical framework. This analytical model is used to examine optimal ship sizes, the effects of increasing loading rates and the effects of loading related delays. Again, due to the unique nature of the company's shipping process, the model presented is novel.

This report is laid out as follows: firstly, in Section 1.1 a detailed description of Rusal Aughinish's shipping process is given. Secondly, in Sections 2 and 3 the data is used to analyse laytime and optimal shipping sizes respectively. Following this, in Section 4, the detailed simulation model is presented. The analytical stochastic model is described in Section 5. Finally, in Section 6, a summary and ideas for future works are discussed.

1.1 Description of shipping process

Each year Rusal Aughinish operate to a shipping schedule. This schedule is subject to change depending on cost and shipping agency requirements. The ships firstly arrive at Scattery Island, an island at the mouth of the Shannon Estuary that is approximately 40km west of Aughinish. At this point, a shipping pilot boards the ship to take it to Aughinish. Once the pilot boards the ship, the clock for laytime begins. The ship does not leave Scattery Island unless the tides are suitable and the inner berth at the Rusal Aughinish's jetty is free. See Section 1.1.1 for a more detailed discussion on when a tide is suitable for a ship to berth at Aughinish. When the ship leaves Scattery, it takes roughly three hours to arrive at Rusal Aughinish's jetty. Upon arrival, a pre-loading inspection takes place by an independent (to both Rusal Aughinish and the shipping agency) surveyor. If a ship fails an inspection the shipping company must deal with the issue. Depending on the nature of the issue, this may occur onsite in Aughinish or the ship may have to be brought to Foynes[2], where there is a port. There are many different reasons why a ship might fail this inspection, for example mechanical failure. Delays caused by inspection are not included in demurrage costs. Loading commences once a ship is cleared by the independent surveyor. Loading however may be

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[2]Foynes is a port village approximately 5km from Aughinish.

curtailed or stopped for a number of different reasons. These may be categorised as either shore or weather related issues. Examples of shore related issues are Rusal Aughinish's conveyor belt breaking down or the unavailability of docking servicemen. An example of a weather related issue is high winds. If it's very windy then the machinery on the jetty becomes inoperable. Another example of a weather delay is heavy rainfall. When loading, if alumina comes into contact with rain then the quality of the product may be affected. As a result, heavy rainfall ensures loading ceases for a period until it passes. Once a ship is loaded, a post-load inspection takes place to ensure everything is in order[3]. When this is finished, the ship is ready to leave Aughinish. However, it cannot do so unless the tide is suitable. Again, see Section 1.1.1 for a more detailed discussion on when the tide is suitable. Once a ship leaves the berth at Aughinish, the clock for laytime stops.

1.1.1 Tides

As mentioned already, Rusal Aughinish's jetty is located is on the south side of the Shannon Estuary approximately 35km downstream from Limerick City. This part of the river is tidal. Rusal Aughinish need to ensure that there isn't a strong down stream tide (i.e., going from east to west in Figure 1) when a ship is berthing. As a result, ships coming into and out of the jetty can only do so in the time between one hour after low tide and one hour before high tide. Further information on the Shannon Estuary's tidal pattern can be found in [3]. Throughout this report, tidal cycles are assumed to last 12.5 hours, i.e., high (low) tide occurs every 12.5 hours. In reality, the time between high (low) tides differs slightly from day to day.

2 Laytime

In this section the laytime formulae used to calculate demurrage costs are examined. In 2012 there were four different formulae used in determining the laytime

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[3]Post-load inspections may begin before ships are fully loaded.

allowed for alumina ships. Of interest is when can these allowed laytimes be met. The time taken to load a ship is

$$loadtime = \frac{\text{Ship Tonnage}}{\text{Effective Loading rate}}. \qquad (1)$$

Figure 2 displays a plot of the maximum ship tonnage that can be filled within the laytime allowed for different loading rates for four different laytime formulae. It shows that, when formula (1) is used, an effective loading rate of 500 tons/hr
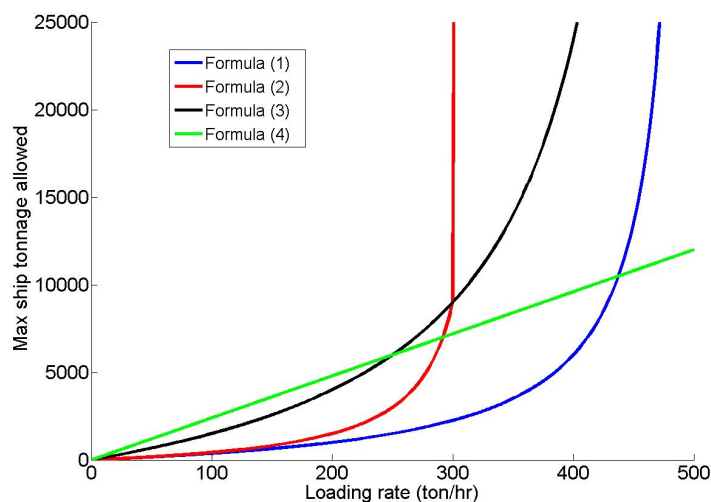

Figure 2: The maximum ship tonnage that can be filled within the laytime allowed for different loading rates for four different laytime formulae.

ensures that the laytime is met for any ship size. Similarly, it also shows that effective loading rates of 300 and 400 tons/hr ensures that the laytime is met, for every ship size, when formulae (2) and (3) are used, respectively. When formula (4) is used, Figure 2 illustrates there is no maximum loading rate that ensures that laytime will be met for any ship size. However the maximum size ship that uses formula (4) is 9000 tons. At this tonnage an effective loading rate of 375 ton/hr is sufficient to meet the laytime. Overall, this analysis shows that an effective loading rate of 500 tons/hr would allow any size ship to be loaded within the allowed

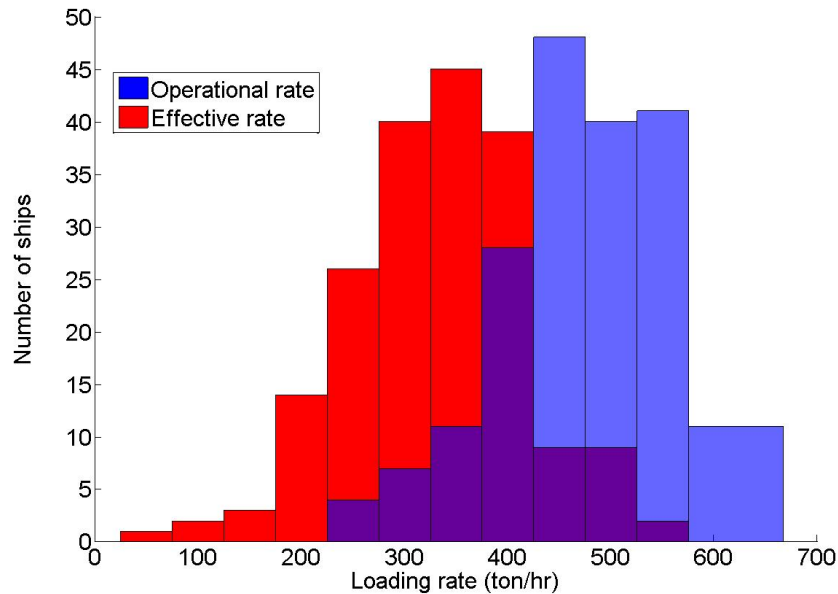laytime regardless which formula was used. Shown in Figure 3 is a histogram

Figure 3: Histograms of the loading rates in tons/hr for the year 2012

of the effective loading rates (red) for alumina ships in tons per hour that was achieved in the year 2012. The average effective loading rate for 2012 was 332.4 tons/hr. This average is well below the desired level to guarantee that the laytime allowed can be met. Only 1.58% of the alumina ships in 2012 were loaded at a rate equal to or exceeding the 500 tons/hr needed to meet the laytime. In order to negate the effects of delays, Figure 3 also displays the operational loading rates (blue) of alumina in 2012. These effects shows a significant shift to the right of the histogram. The mean operational loading rate is 469.61 tons/hr. While this is still below the desired level of 500 ton/hr, the percentage of alumina ships which are loaded at a rate equal to or exceeding the 500 tons/hr rate increases to 38.42%. This shows the effects of delays on exceeding laytimes (and hence demurrage costs) and the benefit of increasing Rusal Aughinish's effective loading rates.

3 Optimal ship size

In this section the data supplied by Rusal Aughinish is used to examine optimal ship sizes. Much information can be gained by a visual presentation of the available data. Representing the data in bar format with lengths assigned for the different time components from arrival at the inner dock to departure (see Figure 4) provides a very clear picture of the time spent on each. It is immediately clear which processes and delays are taking the most time. By incorporating the tide times it is also possible to see how much time is spent waiting until the next tidal cycle. The snapshot of the first part of 2011 indicates that demurrage was paid almost exclusively due to missing the tide (except in cases where there was major equipment failure or bad weather delays).

This information provides the basis for a tool that enables a consideration of the time spent on ships of different sizes and hence which sizes are optimal (in some sense) for minimum time wastage in port. Given this information it is possible to predict quite well the time in port for ships of given sizes and loading rates compared to the tidal cycle. Since most ships begin their time at dock at the beginning of the tidal cycle, given average clearance approval times and minor delays, the ships that will be filled just before the low tide (which will hence be ready to depart immediately after they are loaded) can be obtained. This will give "optimal" performance for the dock since less time will be spent waiting. Hence more alumina can be exported in a fixed time.

An `Excel` algorithm can be used to identify the optimal ship sizes that minimize waiting time before departure given different loading rates. The algorithm takes an estimated initial start time (set at 3 hours but easily modified), adds the time required to fill a ship of a particular capacity at the nominated loading rate, and then computes the time to the next tidal window. It can be modified to provide estimates of the most efficient distribution of ships to maximize export and minimize dock occupancy.

Figure 5 shows components of time spent in each part of the process for two different loading rates. Time before loading begins appears as blue and consists of
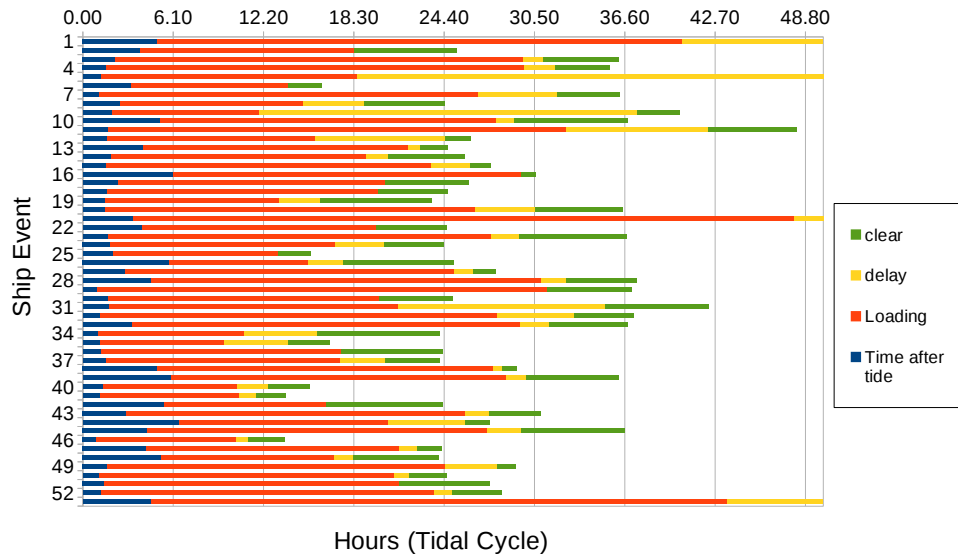
11

Figure 4: Data for the first 52 ships (3 months) of 2011. Bars consist of components for clearance to load, delay, loading time and waiting for clearance for departure.

waiting time (this could be waiting for approval or any initial delays). Any other delays (even if they occur later) could be included here (or added as a separate category). Loading time is shown in red and includes actual loading of the ship at the specified rate. The green component of the bar indicates the time from completion of loading until the ship can leave. This may include approval time, but is mainly waiting for the next tidal window.

The figure shows that the "optimal" sizes for a loading rate of 750 ton/hr are around 7000, 12000 and 17000 tons as these will have the shortest waiting times (those with the shortest green component in the figure), while for a loading rate of 650 ton/hr the best sizes are 6000, 14000 and 23000 respectively. In other words, for the loading times and delays programmed, these will provide the op-
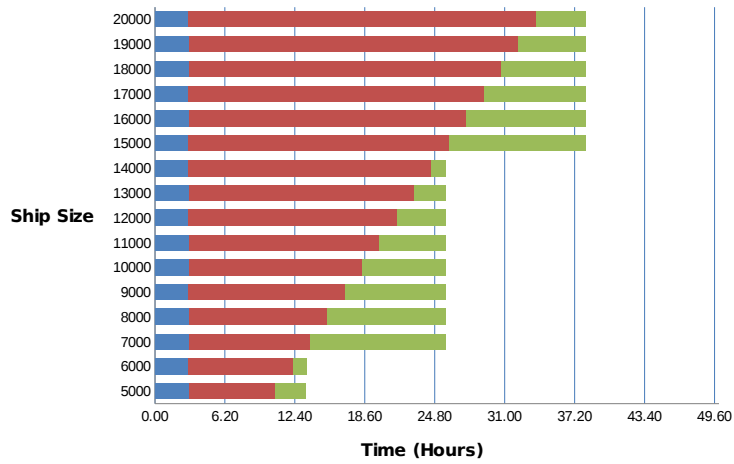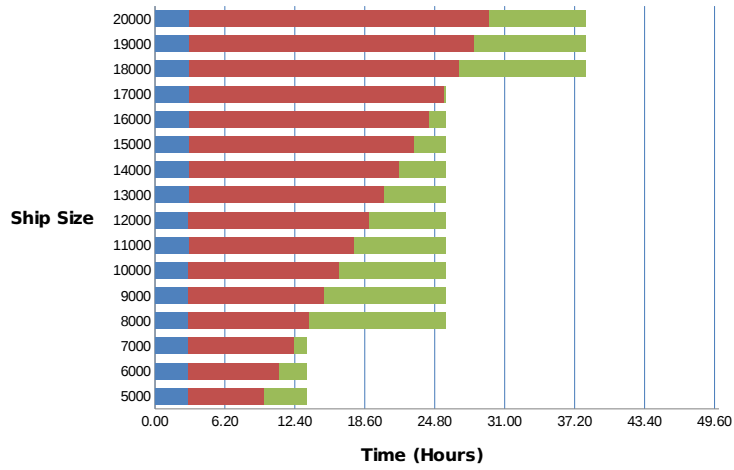
Figure 5: Time at berth for ships of each size assuming a 1 hour clearance, 2 hour delay and a loading rate of 750 ton/hr (top) and 650 ton/hr (bottom). The green indicates waiting time to the next departure window. This should be as small as possible to maximize efficiency.

timal capacity through the port (and minimize time in dock). These figures are demonstrative only and all variables can be changed to provide optima for various load rates, waiting times and clearance. It can be made more accurate by including real tide times (those shown are approximate only). With some tuning for real waiting times the algorithm can be used to calculate the expected completion time for a single incoming ship or to investigate a number of "what-if" scenarios of loading rate and ships sizes.

The same algorithm can be easily modified to estimate the throughput of the inner dock given a list of ships of different sizes and loading rates. These could be realistic data entries or imagined data, but might provide significant reductions in waiting time if used correctly.

4 Simulation model

In this section the simulation model is described, tested and used to analyse Rusal Aughinish's shipping process. The model attempts to replicate the arrivals and departures of ships, as described in Section 1.1, into the inner berth. Algorithm 1 provides the pseudo-code for the simulation model. Tables 3 and 4 explain the notation used in the algorithm. Table 3 gives the event times associated with ship i while Table 4 gives the different activities of ship i. In both tables, $*$ represents events/activities that are determined stochastically. As mentioned in the introduction, random events in the simulation are determined via frequency tables derived from the data supplied by Rusal Aughinish to the Study Group on its shipping process for 2010 - 2012.

a_i^*	Arrive at Scattery Island
b_i	Depart Scattery Island
c_i	Arrive at Aughinish berth
d_i	Start unloading
e_i	Finish unloading
f_i	Finish inspection
g_i	Depart Aughinish berth

Table 3: Event Times for Ship i

Waiting time at Scattery	$b_i - a_i^*$
Voyage up river	$T \equiv c_i - b_i$ (Constant)
Tie up/survey etc.	$(d_i - c_i)^*$
Loading ship	$(e_i - d_i)^*$
Inspection duration	$(f_i - e_i)^*$
Start next tide window	w_t
Tide Window Open (TideOK)	$w_{t-1} \leq e_i \leq w_{t-1} + TW$
Depart Aughinish	$f_i = \begin{cases} e_i & \textbf{if} \quad TideOK \\ w_t & \textbf{otherwise} \end{cases}$
Time to clear berth	S (Constant)

Table 4: Ship Activities

Data: Historical Data for 2010-2012 to generate ship characteristics
Result: Dynamics of activity at berth and Scattery Island
SpecifyParameters(); InputDataFiles();
for $i = 1 \rightarrow \textit{TotalQueueSize}$ **do**

    if $a_{i+1} + 3 > g_i$ **then**

        if *TideOK* **then**

            $b_{i+1} = a_{i+1}$;

            $c_{i+1} = a_{i+1} + 3$;

        end

        else

            $b_{i+1} = a_{i+1} + w_t - 3$;

            $c_{i+1} = a_{i+1} + w_t$;

        end

    end

    else

        if *TideOK* **then**

            $c_{i+1} = e_i - T + S$;

            $b_{i+1} = c_{i+1} - 3$;

        end

        else

            $c_{i+1} = w_t - T + S$;

            $b_{i+1} = c_{i+1} - 3$;

        end

    end

    InspectShipPreload();

    LoadShipWithRandomDelays();

    InspectShipPostload();

    if *TideOK* **then**

        $g_i = f_i$;

    end

    else

        $g_i = f_i + w_t$;

    end

end

Algorithm 1: Queueing Model - Simulation Pseudocode

To run the simulation model it takes, as inputs, a fixed number of alumina, caustic, acid and fuel oil ships. Inter-arrival times between ships of the same cargo arriving at Scattery Island, in the simulation model, are determined randomly by frequency tables derived from the data provided. Once a ship arrives at Scattery the queue counter increases by one. The ship doesn't leave Scattery Island unless the tides are suitable and the inner berth at the Rusal Aughinish's jetty is free. Once it is suitable to leave Scattery, it is assumed to take three hours for a ship to reach Aughinish and the queue counter decreases by one again. Once berthed, the pre-loading inspection takes place. The simulation model assumes that the different ships fail this inspection with fixed probabilities. In the model, it is assumed that once a ship fails, a delay is added to the berth time of the ship. This delay is determined randomly from a uniform distribution generating a delay between one and five hours. A ship having to leave the berth and go to Foynes, as a result of failing an inspection, is not explicitly modelled here. Loading commences once a ship is cleared. The loading time of each ship is determined by the size of the ship and Rusal Aughinish's loading rate with random delays added in. The size of a given ship is determined randomly by frequency tables. The loading rate is a parameter of the model. In Section 4.2, this parameter is varied. There are three types of delays modelled: shore–related, ship–related and other delays[4]. The sizes of each of three random delays are given by frequency tables, again, derived from the data supplied. Ship–related delays are not included in demurrage costs. Once loading is finished, a post-load inspection of the ship takes taken. This is assumed by the simulation model to take 30 minutes. Following the post-load inspection, the ship is free to leave as long as the tide is suitable. When the ship leaves Rusal Aughinish's inner berth, the clock for $Berth\_time$ stops and the demurrage cost is calculated as follows:

$$\max(0, Laytime - Berth\_time) * demurrage\_rate. \tag{2}$$

As described in Section 2 there were four different formulae used to calculate

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[4]Other delays include weather delays.

laytime allowed for the ships docked in Aughinish in 2012. For the simulation model one single formula, suggested to the group by Rusal Aughinish, was used. The model also assumes that the demurrage rate is constant; the value of which was again suggested to the group by the company. In reality, demurrage rates vary from ship to ship and this is thus, a simplification of the model. The simulation model also assumes, that once every 12 weeks, the inner berth must be free for five days in order for maintenance to occur.

4.1 Model testing

In order to test whether or not the model replicates Rusal Aughinish's actual shipping process the results of the model are firstly compared with historical data. Figure 6 compares the actual queue size for 2012 versus one simulated. In order to generate this figure, it was assumed, that the operational loading rate at Aughinish was 650 ton/hr and the percentage of alumina, acid, fuel oil and caustic ships was 81%, 2%, 1%, and 17% respectively. Figure 6 shows that both plots are qualitatively similar; at most times there is one ship in queue, less frequently there is two ships in it and less frequently again there are three ships. Only on rare occasions are there four ships in the queue, while there are never more than four ships.

Figure 7 shows the ship sizes for each ship docked in 2012 as well as for one simulation of the model. In comparison to Figure 6 the two plots are qualitatively similar in that there appears to be two major bands of ship sizes, one between 5000 and 10000 tons and another for between 13000 and 14000 tons. For both actual and simulated plots, there are few ships that are above 20000 tons. Note: both Figures 6 and 7 are examples of one simulation of the model. As a result, the group did not try and match the plots exactly but rather the qualitative features.

Table 5 displays the alumina output (as a ratio of the 2012 level) and berth occupancy for 2010 - 2012 and for the mean of 500 simulations. The alumina output is similar for both the actual years and for the mean of the simulations. For berth occupancy, the model simulated a mean rate of 65%. This is the same as that
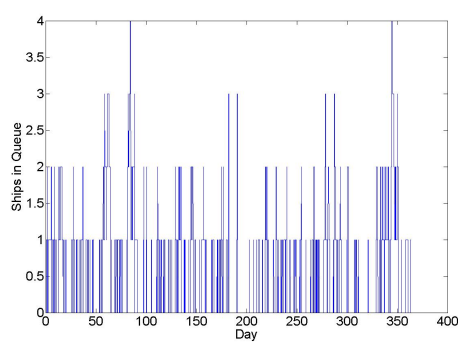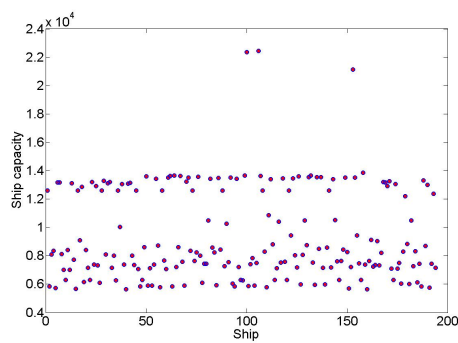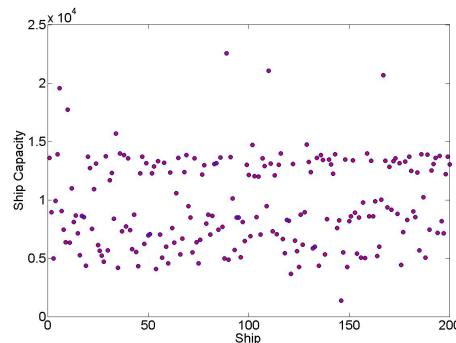
(a) Actual (2012)
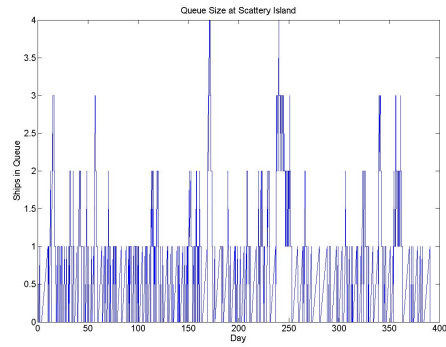
(b) Simulated

Figure 6: Queue size at Scattery Island for ships waiting to dock on inner berth.

(a) Actual (2012)

(b) Simulated

Figure 7: Size of alumina ships docking on the inner berth.

for 2010 but lower than those for 2011 and 2012. However, Figure 8 shows the berth occupancies for each of the 500 simulations which suggests that the range of berth occupancies over the simulations is 45% to 80% when a operational loading of 650 ton/hr is assumed. This range covers the berth occupancies of both 2011 and 2012. Overall, Figures 6 and 7 and Table 5 show that the simulation model captures the different aspects of Rusal Aughinish reasonably well.

19

	2010	2011	2012	Mean of simulations
Alumina output	0.96	1.02	1	1.02
Berth occupancy	65%	73%	77%	65%

Table 5: Alumina output (divided by the 2012 level) and berth occupancy for 2010 - 2012 and for the mean of 500 simulations.

4.2 Analysis

The simulation model is now used to test the effects of varying some of the parameters of the model. As in the previous section, the results assume that the percentage of alumina, acid, fuel oil and caustic ships is 81%, 2%, 1%, and 17% respectively. Figure 8 shows the effects of increasing the operational loading rate on alumina output and berth occupancy for 500 simulations. Figure 8a displays the effects on alumina output. It shows that increasing the operational loading rate has little or no effect on the mean alumina output. The reason for this, is that the model assumes a fixed number of alumina ships while the distribution of these ships is also fixed. Figure 8b shows that the mean berth occupancy decreases as operational loading rates increase. This is intuitive because the less time Rusal Aughinish spend loading ships means that ships are available to leave the berth earlier.

Figure 9 displays the effects of changing shore–related delays by a factor in the interval $[0, 2]$. As mentioned earlier, shore–related delays are captured in the model stochastically via frequency tables. Thus, in this analysis, when the shore–related delays are changed by a factor f, each value in the distribution is multiplied by f. In comparison to Figure 8a, Figure 9a shows that changing the amount of shore–related delays has no effect on the alumina output. The reason for this, is again, the fact that the model assumes a fixed number of alumina ships and the distribution of ship size is fixed. Figure 9b shows that as the amount of shore–related delays increase, so does berth occupancy. This result is intuitive as the longer a ship is delayed, the more time it will spend on the berth.
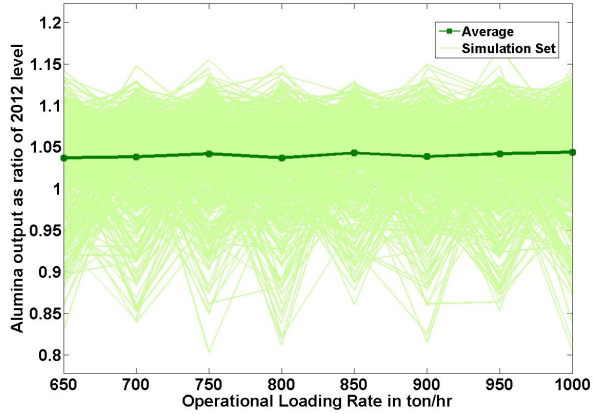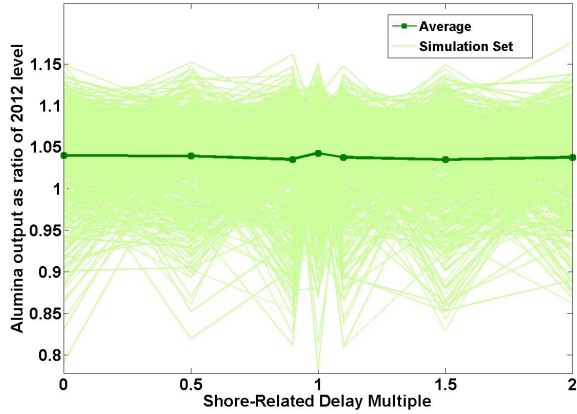
(a) Alumina output
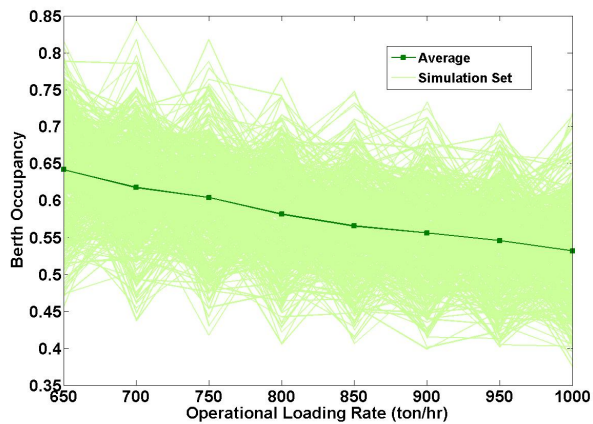
(b) Berth Occupancy

Figure 8: Effects of increasing operational loading rates for 500 simulations.

To conclude this section, it is important to note, that while these analyses examine the effects of operational loading rates and shore–related delays, there are many other applications of the simulation model. For example, the model could be also used to investigate the effects of changing the ship size distribution and the effects of increasing the probability of a ship failing the pre-load inspection.

21

(a) Alumina output
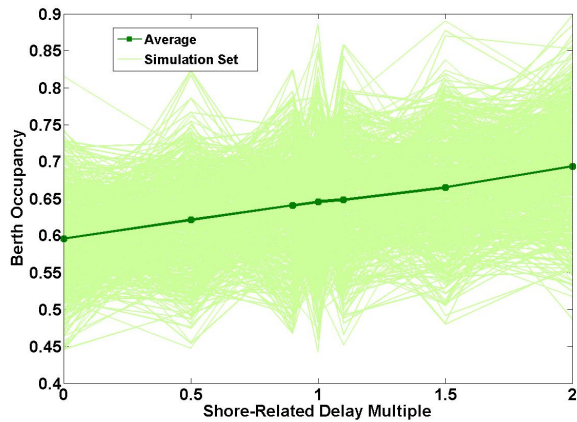
(b) Berth Occupancy

Figure 9: Effects of increasing/decreasing shore–related delays for 500 simulations.

5 Stochastic model

In this section, the analytical model is constructed. It is used to predict the performance characteristics of the inner berth by varying input parameters. The model focuses on the expected shipment of alumina per day, and gain insights into how alumina output depends on the (distribution of) ship sizes, the mean operational

loading rate, the inspection times and delay distributions.

The model developed is a stochastic process, embedded at the times the tidal window is open for departures and arrivals of ships at the inner berth. In this way, tidal windows are taken into account. The time that a ship is served at the berth is known as effective processing time. This time depends on the ship size and the mean operational loading rate, both of which are varied in order to understand how they influence the performance of the berth. Also, the model is used to investigate the influence of delays.

In this analysis, the model is, firstly, described and notation introduced. Then it is shown how to analyse the model. After this, the input parameters are discussed, while finally effects on expected shipment of alumina per day are examined for changes in the various parameters. Note that, in this model, only alumina ships are focused on and all other types of ships are left out of the model. This is a simplification in comparison to the model described in Section 4. Other ships could be included along similar lines.

5.1 Model and notation

Alumina ships arriving at the inner berth are modelled as a stochastic process in the following way. Based on the tidal periods, there are windows in time in which ships can depart from and arrive at the inner berth. Denote these consecutive windows by $t_1, t_2, \ldots$. Let T_{tidal} be the duration of a tidal period, of which T_{open} is the duration that ships can arrive at and depart from the inner berth (both in hours). So, the time between the beginning of t_i and that of t_{i+1} is T_{tidal} hours. See Section 1.1.1 for more details on the actual tidal patterns at Aughinish.

The process is embedded at consecutive tidal windows, where consideration is given to whether or not a ship is present at the start and end of the period, and, if both hold, whether this is the same ship or a new one. Denote the state of the system at window t_i by X_{t_i}, where each of the five possible states are encoded as

follows:

$$X_{t_i} = \begin{cases} 00 & \text{no ship present at beginning and end,} \\ 01 & \text{no ship present at beginning, ship present at end,} \\ 10 & \text{ship present at beginning, no ship present at end,} \\ 11 & \text{ship present at beginning, and another ship present at end,} \\ 1 & \text{same ship present at beginning and end,} \end{cases}$$

where all cases are referring to tidal window t_i. It is assumed that when a ship departs from the inner berth, a new ship arrives during the same window with an (independent and identically distributed, i.i.d.) probability a. It is also assumed that this is the (i.i.d.) probability that a ship docks during a window in which no ship was present at the inner berth at the beginning of the window.

For an arriving ship, the time from which it docks at the inner berth, until it is ready to leave (loading completed), is referred to as the *effective processing time* (EPT, [4]), denoted by the random variable S. It consists of two parts. The first part is the operational loading time of the ship S_l, when loading under ideal circumstances. Denoting by s the size (capacity) of the ship in tons, and by r the mean operational loading rate (in tons per hour), then

$$S_l = \frac{s}{r}.$$

The second part of S is the non-loading service time S_{nl}: the sum of all other durations until the ship is ready to leave. This includes inspection times and all delays (i.e., due to break downs and operational, ship, and weather delays). It is the duration the ship is processed at the dock, excluding the clean processing time. Note that the time until the tide is such that the ship can depart, is *not* included, as this duration is already incorporated in the model (by only allowing ships to arrive and depart from the berth during tidal windows).

The distribution of S_{nl} is estimated using historical data. One can either use

an empirical distribution, or fit an appropriate distribution to the data (see Section 5.3). In this analysis

$$S \overset{d}{=} S_l + S_{nl},$$

where $\overset{d}{=}$ stands for equality in distribution.

Now, the transition probabilities of the process are as follows:

- If $X_{t_i} = 00$ or $X_{t_i} = 10$, then $X_{t_{i+1}} = \begin{cases} 01 & \text{with probability } a, \\ 00 & \text{otherwise.} \end{cases}$

- If $X_{t_i} = 01$ or $X_{t_i} = 11$, then $X_{t_{i+k}} = \begin{cases} 11 & \text{with probability } a, \\ 10 & \text{otherwise,} \end{cases}$

  where $k = \max\left\{\left\lceil \frac{S - T_{open}}{T_{tidal}} \right\rceil, 1\right\}$, and $X_{t_{i+1}}, \ldots, X_{t_{i+k-1}} = 1$.

For the first case, note that the berth is empty until the start of the next period. Then, with probability a a new ship arrives, moving the process to state 01, and to 00 otherwise. In the second case, a new ship arrives at the berth during t_i. Its effective processing time is S, and based on this, the time in which period the ship leaves again is determined. It is assumed that a ship arrives at the beginning of a time period. Then, the time until the end of period t_{i+k} is $k\, T_{tidal} + T_{open}$. Hence, the ship leaves after $k = 1$ time period if

$$S \leq T_{tidal} + T_{open},$$

and in period t_{i+k} (for $k \geq 2$) if

$$(k - 1) \cdot T_{tidal} + T_{open} < S \leq k \cdot T_{tidal} + T_{open},$$

i.e., if $k = \lceil (S - T_{open})/T_{tidal} \rceil$. The ship stays docked during this time, therefore $X_{t_{i+1}}, \ldots, X_{t_{i+k-1}} = 1$. When the ship leaves, a new ship arrives again with probability a, moving the process to state 11, and to state 10 otherwise.

5.2 Analysis

The steady–state behavior of the system is considered in this analysis. Suppose a ship docks during tidal window t_i. The effective service time S determines the distribution of the number of tidal windows, say k, until it departs again. It then leaves during window t_{i+k}. Denoting by p_k as the probability that a ship leaves after k periods gives

$$
\begin{aligned}
p_1 &= \mathbb{P}[S \le T_{tidal} + T_{open}], \\
p_k &= \mathbb{P}[(k-1) \cdot T_{tidal} + T_{open} < S \le k \cdot T_{tidal} + T_{open}], \qquad k = 2, 3, \ldots.
\end{aligned}
$$

Figure 10 shows an example of the p_k. Note that it is assumed that a ship cannot be served within a single tidal window (i.e., $p_0 = 0$).
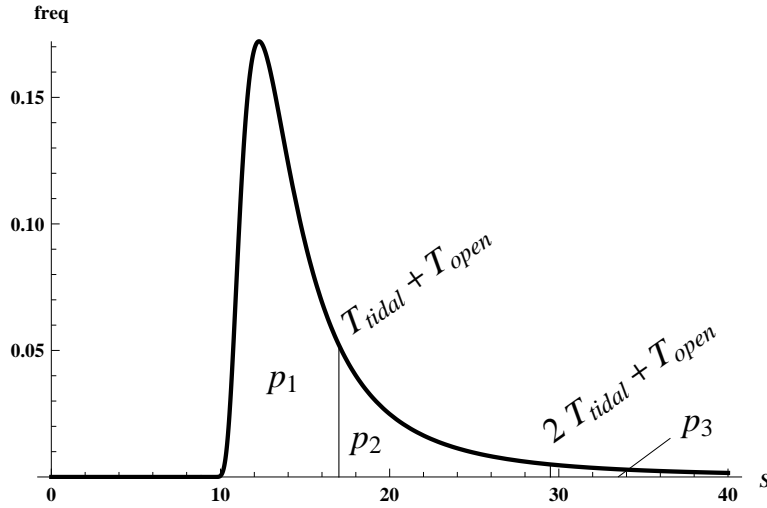

Figure 10: Example of the distribution of p_k, the probability that a ship leaves after k tidal periods, based on the distribution of S.

Recall that if a ship departs during, or if there is no ship present at the start of the window, a new ship arrives with (i.i.d.) probability a. Therefore, the expected number of windows until the next ship docks follows a geometric distribution, with mean $(1 - a)/a$. This is the expected number of tidal periods from the one

26

in which the ship is leaving, until a new ship docks at the berth.

Let the random variable N be the number of tidal periods from the one in which a ship docks until the one in which the next ship does so. Note that N depends on the effective service time distribution S (and hence on the ship size s, the mean operational loading rate r, and the non-loading service time distribution S_{nl}) and on the arrival probability a. Its mean is given by $\mathbb{E}[N] = \sum_{k=1}^{\infty} k \cdot p_k + \frac{1-a}{a}$.

From this, the alumina shipment per day (24 hours, in tons), say A, is calculated; the expectation of which is given by

$$\mathbb{E}[A] = \frac{1}{\mathbb{E}[N]} \cdot s \cdot \frac{24}{T_{tidal}}, \tag{3}$$

when the ship size is a fixed s. When the ship sizes follows a given distribution, where q_s is the probability of a ship being of size s, for $s \in \mathcal{Q}$, this becomes

$$\mathbb{E}[A] = \sum_{s \in \mathcal{Q}} q_s \cdot \frac{1}{\mathbb{E}[N(s)]} \cdot s \cdot \frac{24}{T_{tidal}}, \tag{4}$$

where N is now a function of s.

5.3   Input

For input parameters for the results in the next section, the following values are used. Firstly, it is assumed that a tidal period lasts $T_{tidal} = 12.5$ hours, of which $T_{open} = 4.5$ hours ships are able to dock at and depart from the inner berth.

When a ship leaves, the probability that another ship is available and is docked during the same period, a, is estimated using the historical data for 2010–2012. Out of 490 departures during these three years, a new ship is docked within the same tidal period in 272 cases, hence $a = 272/490 = 0.555$.

Historical data from 2010–2012 for alumina ships is used to estimate the non-loading service time S_{nl}. Ships that fail inspection are not included in the delay times data. For each of the alumina ships, the time between the ship being docked

27

(gangway out) until loading is completed is calculated. From this, the operational loading time is excluded in order to find the empirical distribution of S_{nl}, as shown in Figure 11. Figure 11 displays a Fréchet distribution [5], with shape parameter α, scale parameter β, and location parameter $m = 0$, for which the probability density function $f(x)$ is given by

$$f(x) = \frac{\alpha}{\beta} \left(\frac{x}{\beta} \right)^{-1-\alpha} e^{-\left(\frac{x}{\beta} \right)^{-\alpha}}, \qquad x > 0.$$

Hence,

$$p_1 = \int_0^{(T_{tidal}+T_{open}-s/r)^+} f(x)\mathrm{d}x, \quad p_k = \int_{((k-1)\cdot T_{tidal}+T_{open}-s/r)^+}^{(k\cdot T_{tidal}+T_{open}-s/r)^+} f(x)\mathrm{d}x, \qquad k = 2, 3, \ldots,$$

denoting $(x)^+ = \max(0, x)$. The best fit to the data is found for $\alpha = 1.8408$, $\beta = 4.4635$, see again Figure 11. Hence, $\mathbb{E}[S] = 8.6543 + s/r$.
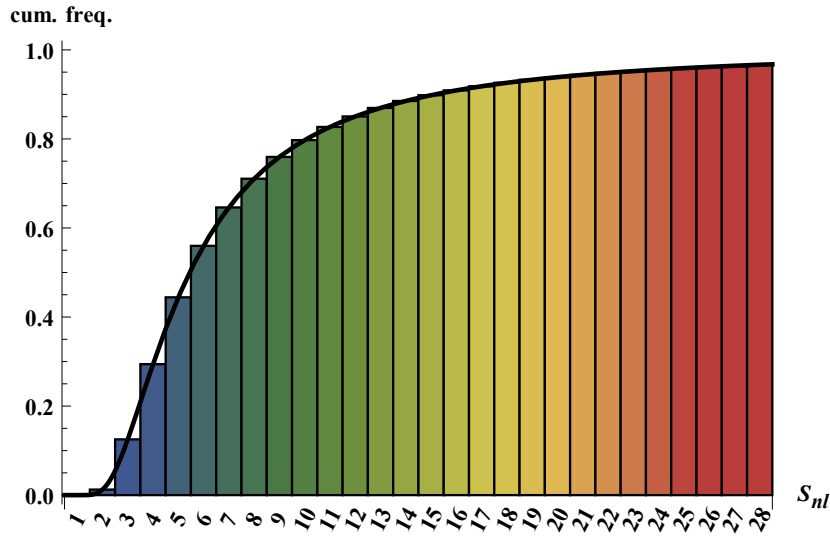

Figure 11: Empirical distribution of the non-loading service time S_{nl}, and a Fréchet(1.8408, 4.4635, 0) distribution fitted to it (right-side of bins indicated).

The distribution of the sizes (capacities) of the alumina ships loaded in 2010–

2012 is given in Figure 12. Mean sizes are used for each bin in the analysis.
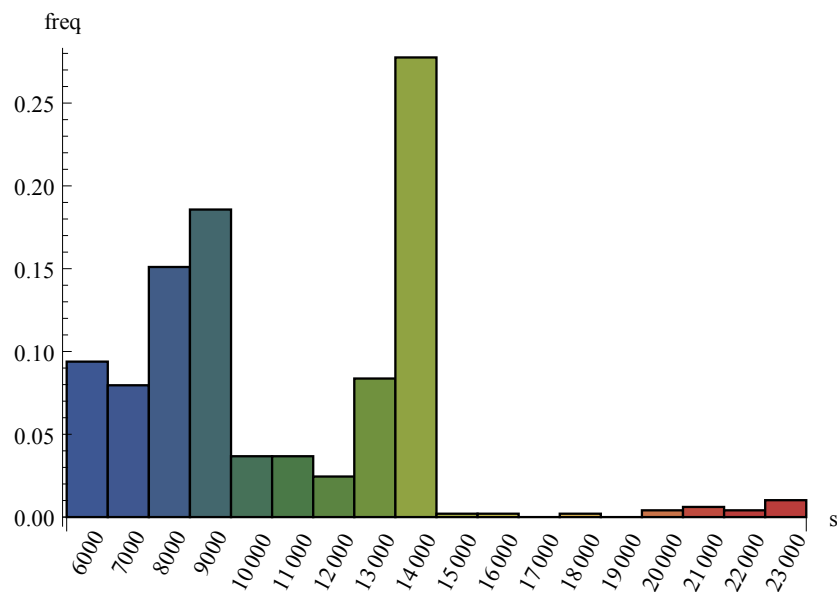

Figure 12: Ship size distribution of alumina ships, over 2010–2012 (right-side of bins indicated).

5.4 Results

In order to gain insights into how the expected shipment of alumina per day $\mathbb{E}[A]$ depends on the ship size s, the mean operational loading rate r and the non-loading service time S_{nl} are varied.
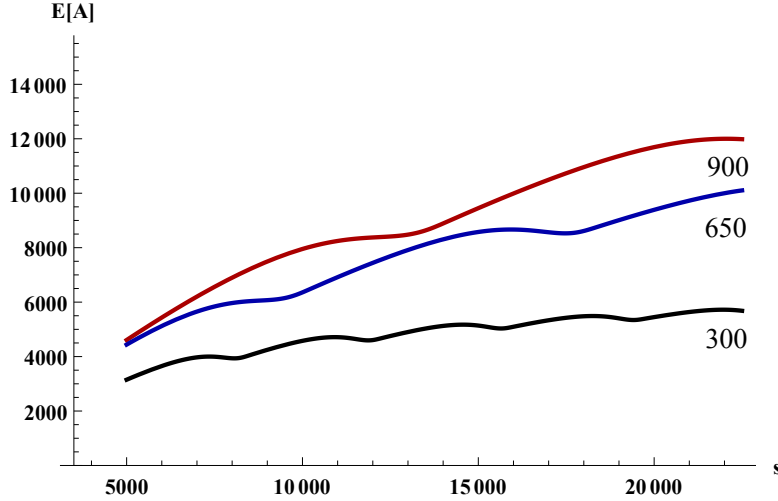
Figure 13: Expected alumina shipment per day $\mathbb{E}[A]$, for a fixed ship size s (ranging from 5,250 to 22,500), plotted for three mean operational loading rates $r \in \{300, 650, 900\}$, both for $a = 0.555$.

Firstly, the ship size s to be set to fixed values, between 5,250 and 22,500, and the mean operational loading rate r is varied. The expected shipment of alumina per day $\mathbb{E}[A]$ for this is calculated using (3) and is given in Figure 13 for $a = 0.555$. The graph clearly shows the influence of the tidal cycles. Some ship sizes fit well with the opening of tidal windows, whereas others do not. For some ship sizes there is little won by increasing the loading rate, whereas for others it might mean a significant increase in the alumina shipment. Interestingly, for the current situation where $r = 650$, the local maxima are found around $s = 7,000$, $s = 14,000$, and $s = 22,000$, which coincide with the maxima in the current ship size distribution (see Figure 12). This result is consistent with those presented in Section 3 which also suggests there is also optimal bands of ships sizes. In particular, when the loading rate is fixed at 650 ton/hr, that analysis shows that ship sizes of $s = 6,000$, $s = 14,000$, and $s = 23,000$ are desirable.

The impact of the non-loading service time S_{nl} is considered in Figure 14. It shows the improvement in the alumina shipment when the mean of S_{nl} is varied, taking values in $\{6, 8, 10\}$ for $a = 0.555$. For each case, a Fréchet distribution

30

with $\beta = 4.4635$, and vary α, such that its mean ($\beta\Gamma\left(1 - \frac{1}{\alpha}\right)$) equals $\mathbb{E}[S_{nl}]$ is used, where $\Gamma(.)$ represents the Gamma function. Again, for some ship sizes, a huge improvement can be seen by lowering $\mathbb{E}[S_{nl}]$, whereas for other ship sizes the improvement is small or even negligible. In this case it would be even more important to correctly tailor the size of ships that are ordered. Recall that historical data revealed a mean of 8.6543 for S_{nl}.
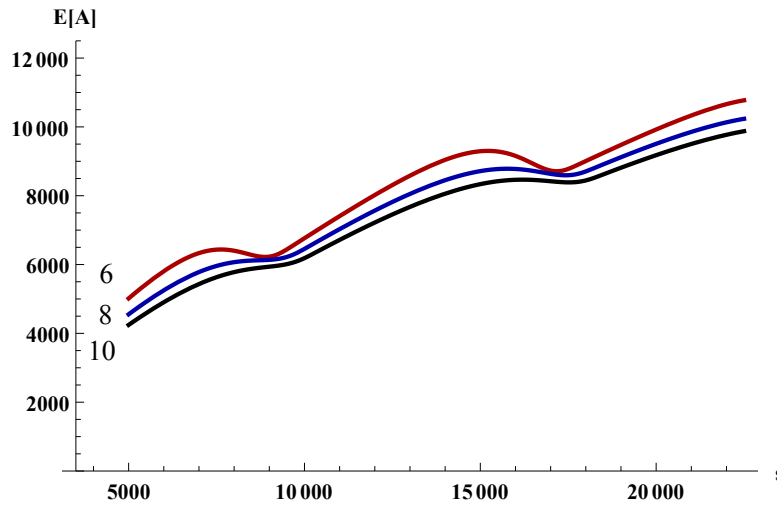

Figure 14: Expected alumina shipment per day $\mathbb{E}[A]$, for a fixed ship size s (ranging from 5,250 to 22,500), when $r = 650$, plotted for four mean non-loading service times $\mathbb{E}[S_{nl}] \in \{6, 8, 10\}$, for $a = 0.555$.
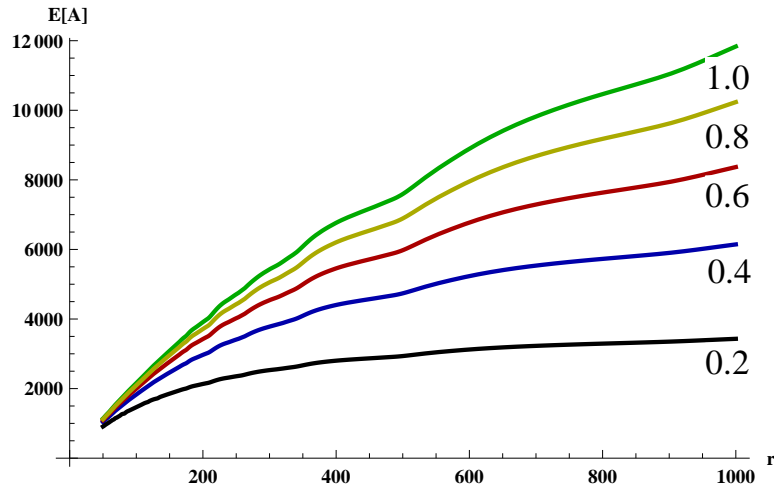
Figure 15: Expected alumina shipment per day $\mathbb{E}[A]$, using the current ship size distribution (cf. Figure 12), varying the mean operational loading rate r, plotted for $a \in \{0.2, 0.4, 0.6, 0.8, 1.0\}$.

Finally, in order to further investigate the effect of increasing the mean operational loading rate r the current ship size distribution (see Figure 12) and equation (4) are used to plot the alumina shipment $\mathbb{E}[A]$ versus r, as shown in Figure 15. The plot features five values of a, where in each case $\mathbb{E}[A]$ increases with r. However, the plot also shows that the increase becomes slower for larger r, until $\mathbb{E}[A]$ approaches its limiting value, which is found for $S = S_{nl}$ (as S_l tends to zero in this case).

6 Summary

This report details the work completed at the 93rd European Study Group with Industry on a problem brought by Rusal Aughinish in relation to its shipping process. The aims of the study group were to examine

1. optimal ship sizes,

2. optimal loading rates,

32

with respect to

a Inner berth occupancy,

b Total alumina output,

c Demurrage costs.

Four different analyses were detailed in this report which are now summarised. Firstly in Section 2, the four different laytime formulae used in 2012 were examined. This analysis found that an effective loading rate of 500 ton/hr would ensure that the all laytimes would be met. Section 3 then investigated optimal ship sizes using an `Excel` algorithm that estimates the time it takes a ship to go through the shipping process (taking into account all delays and tidal constraints) at Aughinish. This analysis found that, for a given loading rate, there are optimal bands of shipping size and that increasing loading rates decreases berth occupancy.

In Section 4, a simulation model of Rusal Aughinish's shipping process was presented. The model was firstly shown to replicate the qualitative features of the historical data. The model was then used to show that increasing operational loading rates decreases berth occupancy. The model was also used to illustrate that increasing shore–related delays results in no change in alumina output but does increase berth occupancy. The model also examined the effect of operational loading rates and shore–related delays on demurrage costs.

In the final analysis section of the report (Section 5), another model of Rusal Aughinish's shipping process was presented. In contrast to the model developed in Section 4, it doesn't model as many of the actual features seen at Aughinish but it was constructed using an analytical framework. When tested, this analytical model showed that, in agreement with Section 3, there are bands of optimal ship sizes. In particular, when a loading rate of 650 ton/hr was assumed, Section 3 and 5 suggest that ship sizes of 6000/7000, 14000, and 22000/23000 tons are optimal in terms of minimising waiting times for the tide and alumina output, respectively. The model developed in Section 5 also showed that increasing delays on the inner berth would decrease the expected daily amount of alumina output.

As well as this, the model was used to illustrate that increasing operational loading rates would increase the expected daily amount of alumina output, however, this increase becomes small when the operational loading rate becomes large.

6.1 Future work

While both the simulation model (Section 4) and the analytical model (Section 5) were shown to capture the different aspects of Rusal Aughinish's shipping process, there are a number of areas where both models could be made more realistic. These are listed below and are thus seen as areas for potential future work. They are

1. for both models

   (a) In Section 4.1 results from the simulation model are compared with actual data. While that analysis shows the actual and simulated data to be qualitatively similar, more scientific measures of comparison would help improve model validation, for example, statistical comparisons of distributions. Currently the analytical model contains no model validation.

   (b) As described in Section 4, demurrage rates are (unrealistically) assumed constant in the simulation model. The amount of demurrage paid, as predicted by the simulation model, would improve if variable demurrage rates were included. Currently the analytical model does not take into account demurrage rates.

   (c) Both models assume that the inter-arrival times of ships at Scattery Island follow a random distribution. In reality, Rusal Aughinish are given a rough schedule of the ships arriving at the start of each year. While this schedule is rarely kept to, both models would improve if the schedule was taken into account.

(d) As described in Section 1.1.1, both models assume, unrealistically, that a tidal cycle lasts for 12.5 hours. Including actual tidal timetables for the Shannon Estuary would again help improve accuracy.

2. for the analytical model only

(a) The analytical model currently only models alumina ships. Thus, an obvious area of future work is extending this for caustic, fuel oil and acid ships.

(b) As described in Section 5.1, the analytical model, models the distributions of all loading delays as one. This model would improve if these delays were broken down into different types, e.g., ship–related and shore–related delays.

Acknowledgments

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