Simulating the Impact of Various Quay Operational Protocols on Container Unloading and Loading Efficiency

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Abstract

This paper presents a simulation model for evaluating the impact of various quay operational protocols on the unloading and loading of containers at a container terminal. Two quay operational protocols were evaluated: 1) unload one container, load one container and then repeat the cycle and 2) unload all containers and then load all containers. In summary, Protocol1 was the more efficient quay operation. Also twelve chasses are necessary to maximize ship throughput, to minimize any delays in container unloading and loading and to minimize ship time at the terminal. Ship arrivals less than 1.5 days, even with twelve chasses, caused the simulation to become unstable. Ship throughput was similar for ship time between arrivals of 3 and 2.25 days for both protocols. Ship throughput varied considerably when the ship time between arrivals dropped to 1.5 days. As the time between arrivals of ships decreased ship delays increased and in most cases significantly when only six chasses were available. With six chasses for Protocol1 (Run2) the ship delay was 155 minutes and increased to 553 minutes (+256%) for Protocol2 (Run8). An increase in the number of chasses to twelve greatly reduced the ship delays for both protocols. There were no ship delays for Protocol1 (Run4) and Protocol2 (Run10) with 3 days between arrivals and twelve chasses. The ship delay was only 18 minutes for Protocol1 (Run5) and zero minutes for Protocol2 (Run11) with 2.25 days between arrivals and twelve chasses. With six chasses the time to unload and load a ship was greater for Portocol2 as compared with Protocol1. For Protocol1 (Run1) the total ship time was 1,248 minutes as compared to 1,923 minutes (+ 54%) for Protocol2 (Run7). Also with twelve chasses the time to unload and load a ship was greater for Protocol2 as compared with Protocol1. For Protocol1 (Run4) the total ship time was 1,227 minutes as compared to 1,653 minutes (+34%) for Protocol2 (Run10). Included in this paper are a description of the two quay protocols, the two quay ProcessModel simulation models and the simulation results.

Keywords: Container terminal, quay crane, quay protocol, discrete event simulation

1. Introduction

Container traffic is increasing worldwide. Currently over ninety percent of cargo transported worldwide is shipped as containerized cargo. As supply chains become more global and the use of containerized cargo increases, ports throughout the world are improving operations and undergoing major expansions. At the same time the cost of terminal expansion and equipment are significant. For example, a single quay crane cost several million dollars.

A major issue facing container terminals is how to effectively and efficiently operate these expensive resources. This paper addresses the operation of one of these expensive resources, the operation of quay cranes. Two quay operational protocols are evaluated:

1) unload one container, load one container and then repeat the cycle

2) unload all containers and then load all containers.

2. Previous Research

Ballis et.al. [1] have done an extensive survey of numerous models that evaluated the quay to container transfer. In the majority of these models containers are unloaded from ships by quays onto transfer vehicles that move the containers to a container yard where yard cranes unload the transfer vehicles.

Vis and de Koster [2] have conducted an overview of various movements of containers within a container terminal.

Steeken et.al. [3] have reviewed container terminal operations.

Saanen and Valkengoed [4] have compared three different automated container storage concepts in terms of productivity, flexibility and area utilization to determine the best automated high-density concept.

Zhang and Kim [5] have evaluated the dual cycle of a quay crane at container terminals.

Garrido and Allendes [6] have modeled the use of various resources to move containers inside a container terminal.

Kozan and Preston [7] have developed a mathematical model of container movement between ships and various storage locations inside a container terminal.

Kim and Kap [8] have developed an algorithm for routing straddle cranes to move containers in a container terminal.

Harris et.al. [9] have developed a simulation model of a container terminal. Alabama Port officials were very interested in validation of the design capacities of the container terminal. Of special interest were the utilization of the berths, cranes and stackers and the maximum container throughput of the terminal.

Schroer et.al [10] have documented a conceptual framework for rapidly developing simulation models of seaport terminals. One of the first simulation models developed using this framework was the container terminal model by Harris et.al. [9].

3. Container Terminal Operations

Figure 1 gives an overview of the operation of the container terminal. Container ships arrive at the terminal and are unloaded by quay cranes onto chasses. The chasses are then transferred to the container yard where stackers unload the containers. Stackers also load containers onto chasses at the container yard that are then transferred back to the ship. The quay cranes then load the containers onto the ships for export.

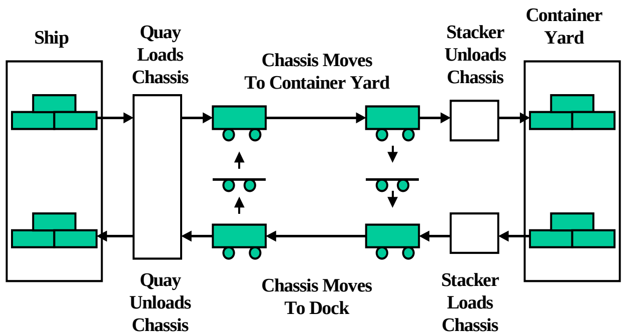

Fig. 1: Container port overview

Figures 2 and 3 are several photos of quay cranes in operation at the newly opened container terminal at the Port of Mobile.

Fig. 2: Quay cranes unloading containers

Fig. 3: Quay crane loading a container onto a chassis

4. Quay Operational Protocols

This paper evaluates the impact of two quay operational protocols on the unloading and loading of containers at a container terminal. The two quay operational protocols are:

1. unload one container and then load one container
2. unload all containers and then load all containers.

More detailed descriptions of the protocols are given in Table 1.

Table 1. Quay operational protocols

Protocol	Description
Protocol1	1.Quay moves into position 2.Quay unloads a container from ship onto a chassis (chassis then goes to container yard) 3.Quay repositions to load container 4.Quay loads a container from chassis onto ship (chassis from container yard) 5.Sequence 2-4 repeated until all containers are unloaded and loaded 6.Quay moves away from ship
Protocol2	1.Quay moves into position 2.Quay unloads a container from ship onto chassis (chassis then goes to container yard) 3.Quay moves back for another container 4.Sequence 2-3 repeated until all containers are unloaded 5.Quay loads a container from chassis onto ship 6.Quay moves back for another container (chassis from container yard) 7.Sequence 5-6 repeated until all containers are loaded onto ship 8.Quay moves away from ship

5. Simulation Model

The two simulation models were written in ProcessModel [11. The models are simplified versions of several container models developed for the container terminal at the Port of Mobile (Harris, et. al. 2007). Since this study only focused on the quay crane protocols, other operations such as the movement of containers via truck and train into and out of the container terminal and container inspection procedures are not included in the ProcessModels. An unlimited number of containers are assumed at the container yard for export on ships, thus replacing the arrivals of containers on trucks and trains in the ProcessModels. Likewise, the containers in the container yard are allowed to continually increase.

Parameters of the two ProcessModels are given in Table 2. The two ProcessModels are basically identical with the exception of the logic for the quay operations.

Table 2. Comparison of the ProcessModels

ProcessModel Parameter	Protocol 1	Protocol 2
Activities	23	26
Entities	6	6
Entity Attributes	5	5
Global Variables	9	9
Output Labels	5	5
Logic Statements	62	65

A description of the input data for the PrecessModels is given in Table 3.

Table 3. ProcessModel input data

Input Data	Protocol1	Protocol2
Containers arriving on ship	T(250,300,350)	T(250,300,350)
Containers departing on ship	T(250,300,350)	T(250,300,350)
Time for tug to position ship	T(15,30,25) min	T(15,20,25) min
Time to position quay crane	T(4,5,6) min	T(4,5,6) min
Time for quay unload container from ship onto chassis	T(0.9,1.0,2.0) min	T(0.9,1.0,2.0) min
Time for chassis moving container to yard	T(3,4,5) min	T(3,4,5) min
Time for quay to move back to ship	-	T(0.9,1.0,2.0) min
Stacker time to unload container from chassis at contain. Yard	T(1,2,3) min	T(1,2,3) min

Stacker time to load container from chassis at container yard	T(1,2,3) min	T(1,2,3) min
Time for chassis moving container from yard to ship	T(3,4,5) min	T(3,4,5) min
Time to position quay to load container	T(0.9.1,0,2.0) min	-
Time for quay to load container from chassis onto ship	T(0.9,1.0,2.0) min	T(0.9,1.0,2.0) min
Time for quay to move back to dock	-	T(0.9,1.0,2.0) min
Time to reposition quay crane before ship leaves	T(4,5,6) min	T(4,5,6) min
Time for tug to move ship into harbor	T(15,20,25) min	T(15,20,25) min
Resources		
Ship berths	2	2
Tugs	2	2
Quays	2	2
Stackers	2	2
Chasses	6 or 12 depending on run	6 or 12 depending on run
Time between arrival of ships	3, 2.25 or 1.5 days depending on run	3, 2.25 or 1.5 days depending on run

If the smallest value, the largest value and the most likely value are known for a process, then the outcome can be approximated by the triangular distribution. Most personnel engaged in a process can readily give estimates for the minimum, maximum and most likely values which correspond to the three parameters of the triangular distribution. The "T" in Table 3 represents the T distribution with parameters T(a,b,c). Parameter a is the smallest value, parameter c is the largest value and parameter b the most likely value.

A simplified and rapid approach to data collection is to ask the appropriate questions through interviews with personnel directly involved with the application. This is not only effective, but also a very time saving approach to obtaining data. In these instances the triangular distribution is often used as a subjective description of a population when there are only limited sample data and especially where actual data are scarce and the cost of collection high.

ProcessModel assumptions are:

- Stacker and chassis resources are considered pooled resources and are available for both unloading or loading containers
- Space for a maximum of three chasses with containers in the unloading dock area
- Space for a maximum of three chasses with containers in the loading dock area
- Unlimited container space for storage of containers at the container yard.
- Unlimited containers in the container yard for loading onto ships (the model was simplified since only ship container unlading and loading was being studied)

6. Experimental Design

The experimental design is given in Table 4.

Table 4. Experimental design

Run	Description
Protocol 1	
Baseline Run1	Ship arrives every 3 days and 6 chasses
Run2	Ship arrives every 2.25 days and 6 chasses
Run3	Ship arrives every 1.5 days and 6 chasses
Run4	Ship arrives every 3 days and 12 chasses
Run5	Ship arrives every 2.25 days and 12 chasses
Run6	Ship arrives every 1.5 days and 12 chasses
Protocol 2	
Run7	Ship arrives every 3 days and 6 chasses
Run8	Ship arrives every 2.25 days and 6 chasses
Run9	Ship arrives every 1.5 days and 6 chasses
Run10	Ship arrives every 3 days and 12 chasses
Run11	Ship arrives every 2.25 days and 12 chasses
Run12	Ship arrives every 1.5 days and 12 chasses

Each ProcessModel was run four hours for warm-up and an additional 320 hours to collect data. The 320 hours equates to forty eight-hour shifts.

7. Model Results with Protocol1

Table 5 gives the ProcessModel results using Protocol1. Ship throughput with six chasses was 13 ships for Run1 with a time between arrivals of 3 days. Ship throughput increased to 17 ships (Run2) with a decrease in the time between arrivals to 2.25 days.

However, ship throughput decreased to 6 ships for Run3 when the time between arrivals decreased to 1.5 days. Also for Run3 the number of containers unloaded and loaded decreased and the ship time in the terminal increased to 1,839 minutes as compared to 1,366 for Run2. Likewise, the time a ship was delayed increased from 21 minutes for Run1 to 155 minutes for Run2 and to 625 minutes for Run3.

Also for Run3 the berth utilization increased to 98% indicating that the terminal cannot process ship arrivals every 1.5 days when there only six chasses available for moving containers between the dock and the container yard.

The number of chasses was increased from six to twelve for Runs4-6. Ship throughput was identical for Runs4-5 as compared to Runs1-2. Also the time a ship had to wait for a container and/or a chassis dropped to zero for Run4 and to 18 minutes for Run5 as compared to 155 minutes for Run2. The system is probably unstable with a time between of ship arrivals of 1.5 days.

For Run6 the ship throughput increased to 26 ships as compared to only 6 for Run3. The time the ship had to wait also decreased to 91 minutes for Run6 as compared to 625 minutes for Run3. Resource utilizations were high for Run6. Ship berth utilization was 86%, quay utilization 86%, chassis utilization 86% and stacker utilization 81%. These high utilizations indicate that with ship arrivals of 1.5 days the system may be reaching instability.

8. Model Results with Protocol2

Table 6 gives the ProcessModel results using Protocol2. Ship throughput was 13 ships for Run7 with a time between arrivals of 3 days. Ship throughput for Run8 increased to 16 ships with a decrease in the time between arrivals of 2.25 days. However, the ProcessModel became unstable for Run9 with a zero ship throughput. For Run8 the ship time in the terminal increased to 2,126 minutes as compared to 1,923 for Run7. Likewise, the time a ship was delayed increased from 325 minutes for Run7 to 553 minutes for Run8. Also for Run8 the berth utilization increased to 91%, chassis utilization to 99% and quay utilization to 91%.

The number of chassis was increased from six to twelve for Runs 10-12. Ship throughput was similar for Runs10-11 as compared to Runs7-8. Also the time a ship had to wait for container and/or a chassis dropped to zero for Run10-11.

For Run12 the ship throughput dropped to only 9 ships as compared to 13 for Run10 and 17 for Run11. The time the ship had to wait increased to 295 minutes for Run12 as compared to zero for Runs10-11. Resource utilizations for Run12 were very high for the ship berths indicating a ship arrival rate of 1.5 days caused the system to approach instability.

Table 5. ProcessModel results using Protocol1

	Run1	Run2	Run3	Run4	Run5	Run6
Input Data						
Ship time between arrivals(days)	3	2.25	1.5	3	2.25	1.5
Chasses	6	6	6	12	12	12
Run time (days)	40	40	40	40	40	40
Model Out						
Ship Throughput	13	17	6	13	17	26
Containers Loaded	4,106	5,322	2,390	4,111	5,429	7,892
Containers Unloaded	4,106	5,322	2,390	4,111	5,429	7,892
Ship Time at Terminal (min)	1,248	1,366	1,839	1,227	1,252	1,298
Ship Value Time at Terminal (min)	1,227	1,211	1,214	1,227	1,234	1,207
Ship Wait Time (min)	21	155	625	0	18	91
Utilizations						
Ship Berths (%) (2)	42	60	98	41	55	86
Tugs (%) (2)	1	1	75	1	1	2
Quay Cranes (%) (2)	42	60	32	41	55	86
Stackers (%) (2)	42	54	24	42	44	81
Chasses (%) (6)	85	92	67	-	-	-
Chasses (%) (12)	-	-	-	84	82	86

9. Comparison of Results between Protocol1 and Protocol2

Figure 4 gives the ship time at the terminal as a function of time between ship arrivals when six chassis resources for both protocols. As anticipated ship times at the terminal were greater for Protocol2 as compared to Protocol1.

Figure 5 gives the ship time at the terminal as a function of time between ship arrivals when twelve chassis resources for both protocols. As anticipated ship times at the terminal were greater for Protocol2 as compared to Protocol1.

Figure 6 gives the ship delays with six chasses for both protocols. Figure 7 gives the ship delays with twelve chasses for both protocols. Ship delays were greater for Protocol2 as compared with Protocol1.

However, when the ship time between arrivals dropped to 1.5 days the ship delays increased significant for both protocols. This indicates that the terminal cannot handle ship arrivals every 1.5 days.

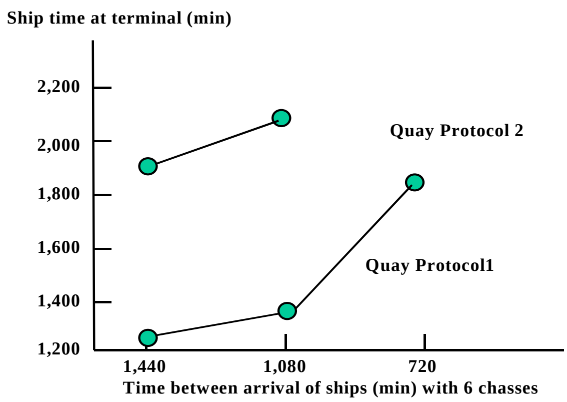

Fig. 4: Ship time at terminal with six chasses

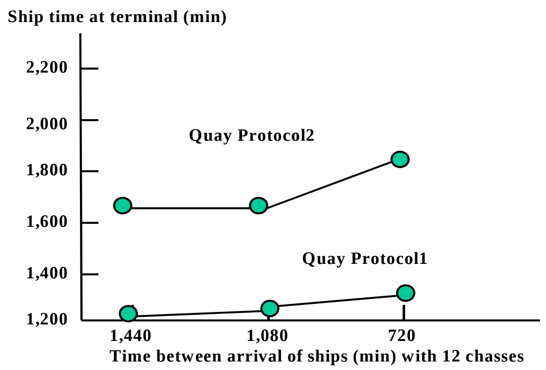

Fig. 5: Ship time at terminal with twelve chasses

Figure 6 gives the ship delays with six chasses for both protocols. Figure 7 gives the ship delays with twelve chasses for both protocols. Ship delays were greater for Protocol2 as compared with Protocol1. However, when the ship time between arrivals dropped to 1.5 days the ship delays increased significant for both protocols. This indicates that the terminal can not handle ship arrivals every 1.5 days.

Table 7 gives a comparison of total ship throughput, ship time at the terminal and corresponding delays for both protocols. Ship throughput was similar for various ship time between arrivals for both protocols. For example, ship throughput was 13 ships for both protocols with a 3 day time between arrivals and six chasses and ship throughput was 13 ships for both protocols with a 3 day time between arrivals with twelve chasses. Also ship throughput was 17 ships for Protocol1 and 16 ships for Protocol2 with a 2.25 day time between arrivals with six chasses and ship throughput was17 ships for both protocols with a 2.25 say time between arrivals with twelve chasses.

However, ship throughput varied considerably when the ship time between arrivals dropped to 1.5 days. With six chasses the ship throughput was only 6 for Run3 Protocol1 and zero for Run9 Protocol2. Likewise, with twelve chasses the ship throughput was 26 for Protocol1 Run6 and only 9 for Protocol2 Run12.

Table 6. ProcessModel results using Protocol2

	Baseline Run7	Run8	Run9	Run10	Run11	Run12
Input Data						
Ship Time Between Arrivals (days)	3	2.25	1.5	3	2.25	1.5
Chasses	6	6	6	12	12	12
Run Time (days)	40	40	40	40	40	40
Model Out						
Ship Throughput	13	16	-	13	17	9
Containers Unloaded	4,060	5,193	-	4,282	5,445	3,222
Containers Loaded	3,871	4,854	-	4,017	5,270	3,222
Ship Time at Terminal (min)	1,923	2,126	-	1,653	1,622	1,833
Ship Value Time at Terminal (min)	1,598	1,573	-	1,653	1,622	1,538
Ship Wait Time (min)	325	553	-	0	0	295
Utilizations						
Ship Berths (%) (2)	65	91	-	55	72	98
Tugs (%) (2)	1	5	-	1	1	67
Quay Cranes (%) (2)	65	91	-	55	72	45
Stackers (%) (2)	40	52	-	42	55	33
Chasses (%) (6)	92	99	-	-	-	-
Chasses (%) (12)	-	-	-	47	51	40

Table 7 also gives a comparison of the ship delays for both protocols. In general, as the time between arrivals of ships decreased the ship delay increased and in most cases significantly when only six chasses were available. For example, with six chasses for Run2 the ship delay was 155 minutes and increased to 553 minutes (+256%) for Run8.

An increase in the number of chasses to twelve greatly reduced the ship delays for both protocols. For example, there were basically no ship delays for Run4 and Run10 with 3 days between arrivals. The ship delay was only 18 minutes for Run5 and zero minutes for Run11 with 2.25 days between arrivals.

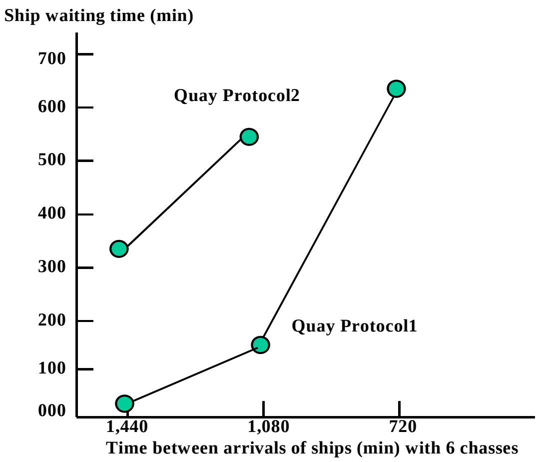

Fig.6: Ship waiting time with six chasses

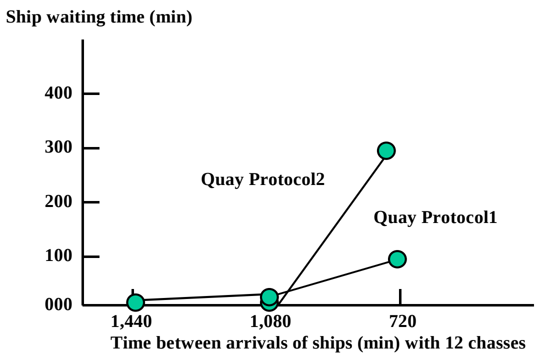

Fig.7: Ship waiting time with twelve chasses

As anticipated with six chasses the time to unload and load a ship was greater for Portocol2 as compared with Protocol1. For example, for Run1 the total ship time was 1,248 minutes as compared to 1,923 minutes (+ 54%) for Run7. Likewise, the total ship time was 1,366 minutes for Run2 as compared to 2,126 minutes (+55%) for Run8.

Even with twelve chasses the time to unload and load a ship was greater for Protocol2 as compared with Protocol1. For example, for Run4 the total ship time was 1,227 minutes as compared to 1,653 minutes (+34%) for Protocol2. Likewise, the total ship time was 1,252 minutes for Run5 as compared to 1,622 minutes (+29%) for Run11.

Table 7. Comparison of ship time at terminal and corresponding delays

	Protocol	Chasses	Ship Time Between Arrivals (days)	Ship Thru put	Ship Time at Terminal (min)	Ship Value Time at Terminal (min)	Ship Wait Time (min)
Run 1	1	6	3	13	1,248	1,227	21
Run 7	2	6	3	13	1,923	1,598	325
Run 2	1	6	2.25	17	1,366	1,211	155
Run 8	2	6	2.25	16	2,126	1,573	553
Run 3	1	6	1.5	6	1,839	1,214	625
Run 9	2	6	1.5	0	-	-	-
Run 4	1	12	3	13	1,227	1,227	0
Run 10	2	12	3	13	1,653	1,653	0
Run 5	1	12	2.25	17	1,252	1,234	18
Run 11	2	12	2.25	17	1,622	1,622	0
Run 6	1	12	1.5	26	1,298	1,207	91
Run 12	2	12	1.5	9	1,833	1,538	295

10. Additional Runs for Protocol1

After analyzing the simulation results it was of interest to determine the arrival rate where ship delays began to occur and to determine the increase in ship delays as the ship time between arrivals decrease. The additional runs are given in Table 8.

Table 8. Additional runs for Protocol1

Run	Description
Run13	Ship arrives every 1.75 days and 12 chasses
Run14	Ship arrives every 2 days and 12 chasses
Run15	Ship arrives every 2.5 days and 12 chasses

The results of these additional runs along with Run4 and Run6 are given in Table 9. Figure 8 gives a plot of the ship delay times for various ship arrival rates. It appears that ship delays begin to occur with a ship time between arrivals of 2.5 days and continues to increase as the time between arrivals decreases.

Interestingly, ship throughput increased even though ship delays increased with a decreased in the ship time between arrivals. Therefore, the ship delays are probably the result of a lack of available resources, especially chasses, or the operational constraint of space for three full chasses on the dock with containers unloaded from a ship.

11. CONCLUSIONS

Protocol1 was the more efficient quay operation. Also twelve chasses are necessary to maximize ship throughput, to minimize any delays in container unloading and loading and to minimize ship time at the terminal. Ship arrivals less than 1.5 days, even with twelve chasses, caused the simulation to become unstable.

In summary the following conclusions are made:

- Ship throughput was similar for various ship time between arrivals of 3.0 and 2.25 days for both protocols. For example, ship throughput was 13 ships for both protocols with a 3 day time between arrivals and six chasses and 13 ships for both protocols with a 3 day time between arrivals with twelve chasses. Also ship throughput was 17 ships for Protocol1 and 16 ships for Protocol2 with a 2.25 day time between arrivals with six chasses and 17 ships for both protocols with a 2.25 day time between arrivals with twelve chasses
- Ship throughput varied considerably when the ship time between arrivals dropped to 1.5 days. With six chasses the ship throughput was only 6 for Protocol1 and zero for Protocol2. Likewise, with twelve chasses the ship throughput was 26 for Protocol1 and only 9 for Protocol2. It appears that the system is unstable with a 1.5 day time between arrivals since resource utilizations were high. These high utilizations indicate that ship arrivals less than 1.5 days would probably result in greater delays and no increase in throughput.
- As the time between arrivals of ships decreased the ship delay increased and in most cases significantly when only six chasses were available. For example, with six chasses for Run2 the ship delay was 155 minutes and increased to 553 minutes (+256%) for Run8.
- An increase in the number of chasses to twelve greatly reduced the ship delays for both protocols. For example, there were no ship delays for Run4 and Run10 with 3 days between arrivals. The ship delay was only 18 minutes for Run5 and zero minutes for Run11 with 2.25 days between arrivals.
- With six chasses the time to unload and load a ship was greater for Portocol2 as compared with Protocol1. For example, for Run1 the total ship time was 1,248 minutes as compared to 1,923 minutes (+ 54%) for Run7. Likewise, the total ship time was 1,366 minutes for Run2 as compared to 2,126 minutes (+55%) for Run8.

Table 9. Results of additional runs

	Run4	Run15	Run5	Run14	Run13	Run6
Input Data						
Ship Time Between Arrivals (days)	3	2.5	2.25	2	1.75	1.5
Chasses	12	12	12	12	12	12
Model Output						
Ship Throughput	13	16	17	19	22	26
Ship Time at Terminal (min)	1,227	1,241	1,252	1,245	1,305	1,298
Ship Value Added Time at terminal (min)	1,227	1,237	1,234	1,208	1,235	1,207
Ship Delay at Terminal (min)	0	4	18	37	70	91
Utilizations						
Ship Berths (2)	41	50	55	61	74	86
Tugs (2)	1	2	1	2	2	2
Quay Cranes (2)	41	50	55	61	74	86
Stackers (2)	42	50	44	61	71	81
Chasses (12)	84	46	82	46	49	86

- With twelve chasses the time to unload and load a ship was greater for Protocol2 as compared with Protocol1. For example, for Run4 the total ship time was 1,227 minutes as compared to 1,653 minutes (+34%) for Protocol2 Run10. Likewise, the total ship time was 1,252 minutes for Run5 as compared to 1,622 minutes (+29%) for Run11.

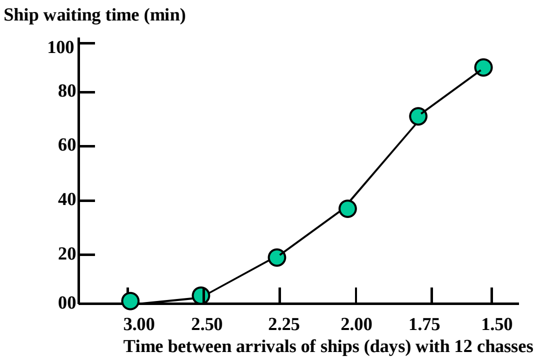

Fig. 8: Ship waiting times using Protocol1

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Authors Bios

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