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Simulation-Based Optimization of Resource Allocation in Container Harbor Logistics

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Abstract

Efficient operation of container harbors is critical in minimizing ship turnaround time, optimizing resource usage, and sustaining the flow of global trade. This project utilizes discrete-event simulation through Arena software to model the complex logistics of a container terminal, including the coordination of ships, quay cranes, yard trucks, and storage areas. The simulation captures the dynamic interactions among these resources, accounting for constraints such as limited berth capacity and operational deadlines. A full factorial experimental design is employed to generate 32 scenarios, allowing analysis of how variations in resource configurations affect key performance metrics, specifically Ship.TotalTime and Trucks.TotalTime.

The results demonstrate that Terminal Port capacity and Blocking Resource availability—likely representing quay cranes—are the most significant factors impacting ship delays. Regression coefficients and Pareto charts support these findings, revealing clear performance trade-offs and critical interactions. In contrast, Trucks.TotalTime remains relatively constant across scenarios, suggesting that truck operations are not a limiting factor under current conditions. The study concludes that investing in terminal infrastructure and optimizing crane allocation strategies are the most effective approaches for improving harbor performance. These findings offer practical implications for port managers seeking to enhance efficiency while minimizing operational costs and delays.

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Chapter One: Introduction

In the era of globalization, maritime transport plays an indispensable role in international trade and the movement of goods. Container ports, as the primary gateways for ocean-bound freight, are critical nodes in global supply chains. They serve as points of entry and exit for goods transported by sea and must handle vast volumes of containerized cargo efficiently to avoid bottlenecks and maintain economic fluidity. The operational complexity of these ports is immense, involving the coordination of various resources such as cranes, trucks, storage areas, and human operators. As global trade continues to expand, optimizing port operations has become essential to reduce turnaround time, increase throughput, and enhance overall system performance.

Given the dynamic and stochastic nature of port activities, relying solely on analytical methods or physical experimentation to assess performance or test improvements is often impractical. Real-world testing can be costly, disruptive, and limited in scope. Therefore, discrete-event simulation (DES) emerges as a valuable tool for modeling and analyzing the performance of complex systems like container harbors. Simulation provides a virtual environment in which decision-makers and engineers can experiment with different policies, resource configurations, and process flows without interfering with actual operations.

One widely accepted educational and professional tool for conducting such simulation studies is Arena, a simulation software developed by Rockwell Automation. In the textbook Simulation with Arena by Kelton, Sadowski, and Zupick, a well-structured case study is introduced under the title Container Harbor Logistics, which serves as a representative problem to illustrate the use of simulation modeling in analyzing port logistics. This problem offers a realistic scenario where containers arrive at a seaport, are processed through several stages, and are ultimately dispatched to their destinations. The study highlights the intricacies of port logistics and allows for the exploration of performance improvement strategies through simulation.

1. Key Elements in the Simulation

1. Inbound Ships – Containers arrive at the port by ship.
2. Unloading Operations – Cranes unload containers from ships.
3. Yard Trucks / Vehicles – Transport containers to storage areas.
4. Storage Yard – Containers are temporarily held before further movement.
5. Outbound Dispatching – Containers are loaded onto trucks or trains for delivery.
6. Resources & Queues – Cranes, trucks, and storage areas can experience bottlenecks or idle time.

2. Objectives of the Simulation

1. 1. Evaluate utilization of resources like cranes and trucks.
2. 2. Identify bottlenecks in the container movement process.
3. 3. Determine the throughput of the harbor terminal.
4. 4. Test different operational policies (e.g., number of trucks, crane assignment rules) to improve performance.

3. Arena Simulation Modeling Approach

1. Entities – In the model, each container is represented as an entity that flows through the system.
2. Resources – Cranes, yard trucks, and storage units are modeled as limited resources that entities must seize and release as they progress.
3. Processes – Operations such as unloading, transporting, storing, and loading are modeled using process modules.
4. Queues – Queues are automatically formed in Arena when resources are busy.
5. Schedules – Ship arrival patterns, worker shifts, and resource availability are controlled using schedules.

This simulation study provides students and analysts with a practical framework to explore the principles of discrete-event simulation in a high-impact, real-world context. It encourages critical thinking about system design and performance trade-offs, while also building familiarity with Arena as a modeling tool. By experimenting with different configurations, visualizing bottlenecks, and measuring performance metrics such as wait time and resource utilization, the Container Harbor Logistics problem serves as a rich case study for developing data-driven strategies to enhance port efficiency. Ultimately, simulation modeling enables stakeholders to make informed decisions that improve operational effectiveness without incurring the risks or costs of real-world trial and error.

For managers and decision-makers, this means gaining the ability to test changes — like adding cranes or trucks — in a virtual model before investing resources. It shows where delays are happening, how resource shifts affect ship turnaround times, and what strategies yield the best operational improvements, all without disrupting daily port operations.

Chapter Two: Problem Statement

Background:

The harbor operates three container berths where ships arrive to load and unload cargo. Each ship's containers are handled by specialized quay cranes (Porteiner) and a fleet of trucks that transfer containers between the ship and a limited-capacity yard. Ships follow a schedule and must be unloaded within strict time windows; missing a deadline incurs costly demurrage charges. The simulation model encodes detailed routing and assignment rules for matching containers to trucks and storage locations. When demand is high, the limited berths, cranes, and trucks can force ships and containers to queue, potentially delaying operations.

Challenges and Constraints:

- **Limited Resources:** Only three berths, a fixed number of cranes and trucks, and a constrained yard space create contention for equipment and storage.
- **Scheduling and Deadlines:** Ships arrive on schedule and must be serviced within a time limit. Exceeding deadlines incurs penalties.
- **Complex Operations:** Each container must be routed to a truck and a yard location according to logic rules. Delays or blockages in one area (e.g., a busy yard) propagate through the system.
- **Queueing and Bottlenecks:** When all berths or trucks are in use, incoming ships or containers must wait. This can create bottlenecks at the quay or in the yard.

Simulation Goals:

- **Resource Utilization:** Quantify how busy each resource is (e.g., crane and truck utilization, berth occupancy) under current operations.
- **Bottleneck Identification:** Detect where the system becomes congested (for example, whether delays are worse at the quay or in the yard) to pinpoint operational bottlenecks.
- **Throughput Evaluation:** Measure the terminal's throughput (e.g., containers or ships processed per unit time) and study trade-offs – for example, increasing throughput versus increasing container rehandling.
- **Policy Comparison:** Virtually test alternative strategies (such as adding trucks or cranes, or changing crane-assignment rules) in the model. This what-if analysis shows which policies improve flow and reduce delays.

Value of Simulation:

Discrete-event simulation provides a risk-free way to analyze the harbor’s complex interactions. By modeling ship arrivals, crane and truck dispatch, and yard storage, the simulation reveals how congestion and delays translate into idle time and demurrage costs. It also enables testing of operational changes before implementation. For example, managers can simulate adding a crane or reallocating trucks and see the impact on throughput and utilization. Ultimately, this analysis will identify critical bottlenecks and suggest improvements to maximize terminal throughput and minimize delays and costs.

Chapter Three: Flow Chart

This chapter provides an overview of the operational challenges at the container harbor and the goals of the simulation study. It explains how limited resources, such as cranes, berths, and yard trucks, along with strict scheduling and container handling rules, can lead to congestion and delays.
The simulation aims to capture these dynamics in order to evaluate system performance, identify bottlenecks, and test improvement strategies in a risk-free environment.

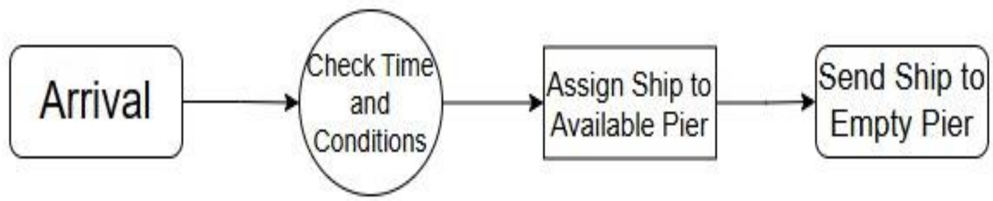


Figure 1: Arrival of ships

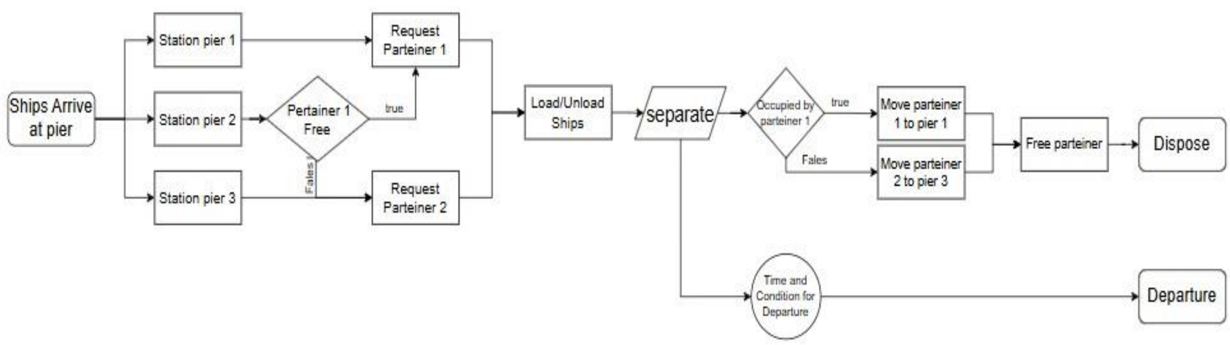


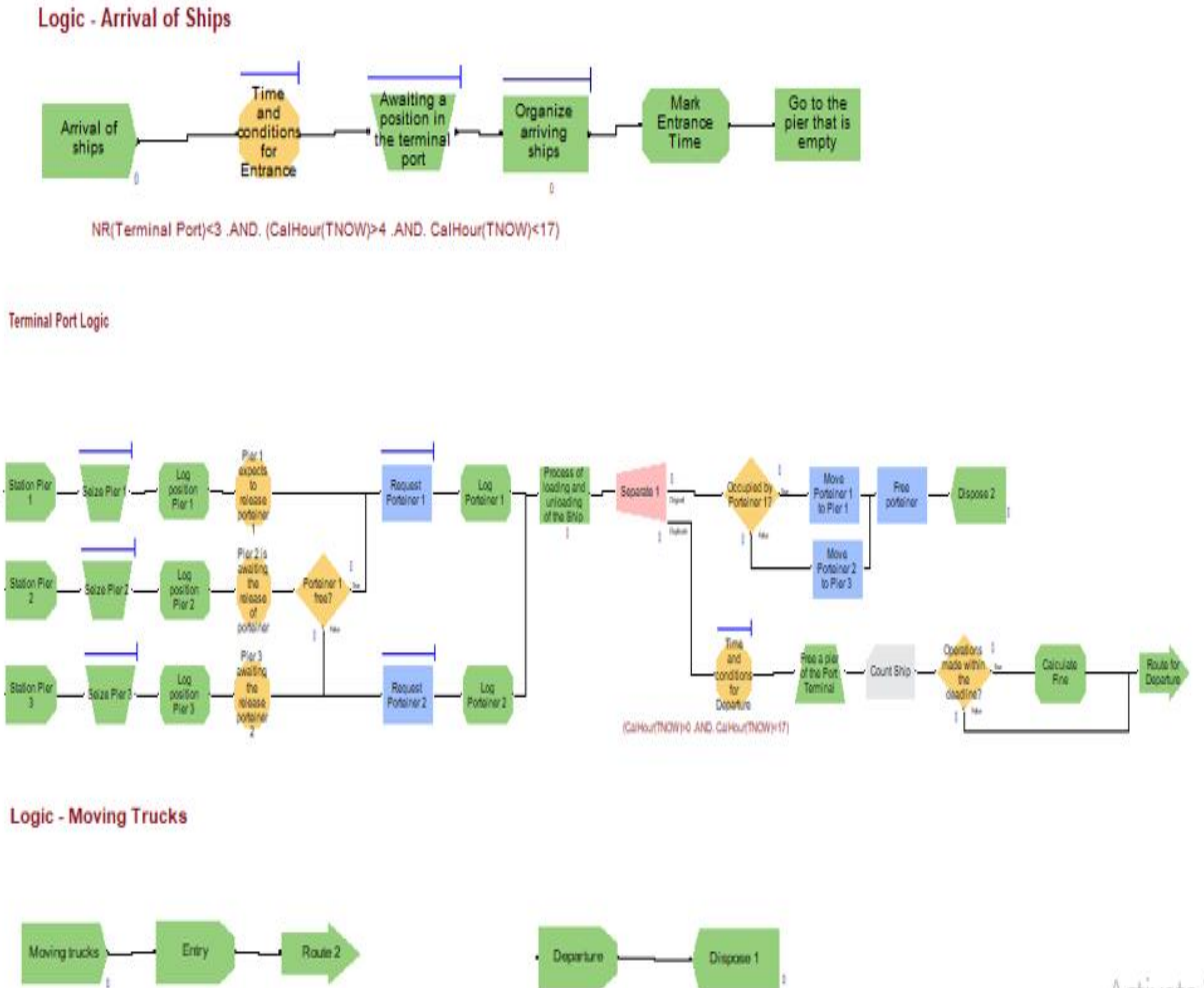
Figure 2: Terminal port

Chapter Four: Modeling

Table 1: Arena Simulation Model Blocks and Logic Configuration

Arena Simulation Model Blocks

Block Name	Type	Description	Time/Distribution	Resource(s)	Notes
Arrival of Ships	Create	Generate ship entities	EXPO (3), EXPO (5) Hours	-	Infinite a
Moving Trucks	Create	Generate truck entities	EXPO (200) Minutes	-	Infinite a
Organize arriving ships	Seize-Delay-Release	Organize docking	0.5-1.5 Hours (varied)	Medium (2)	Value ad
Process of loading/unloading Ship	Delay-Release	Loading/unloading operation	TRIA (13,14,15) Hours	Medium (2)	Value ad
Request Porteiner 1	Request (Resource)	Request specific crane (Portainer)	-	Portainer 1	Based o
Request Porteiner 2	Request (Resource)	Request specific crane (Porteiner)	-	Portainer 2	Based o
Seize Pier 1	Seize	Allocate pier resource	-	Medium (2)	-
Seize Pier 2	Seize	Allocate pier resource	-	Medium (2)	-
Seize Pier 3	Seize	Allocate pier resource	-	Medium (2)	-
Awaiting a position in the terminal p	Other (Queue)	Holding before docking	-	-	-
Move Porteiner 1 to Pier 1	Transport	Move cranes to piers	-	Porteiner 1	Uses
Move Porteiner 2 to Pier 3	Transport	Move cranes to piers	-	Porteiner 2	Uses
Scan for condition (various)	Decide/Condition Scan	Conditional checks	-	-	Logical
Separate 1	Separate	Duplicate entity	-	-	Retains
Log Position / Entrance Time / Fine	Assign/Record	Logging timestamps/positions	-	-	Used for
Route for Departure (NORM)	Route	Final routing toward departure	NORM (1,0.5)	-	Routes t
Route for Departure (TRIA)	Route	Final routing toward departure	TRIA (1,3,4)	-	Routes t
Calculate Fine	Assign	Calculates penalties	-	-	Based o
Entry / Departure / Pier Stations	Station	Logical location points	-	-	Includes



Activate \

Figure 3: Ship Arrival and Port Flow – Arena Simulation Model Layout

Chapter Five: PAN

Table 2: PAN for the module

	Scenario Properties				Controls					Responses	
	S	Name	Program File	Reps	Blocking_Resource	Resource Pier 1	Resource Pier 2	Resource Pier 3	Terminal Port	Ship.TotalTime	Trucks.TotalTime
1		Scenario 1	3 : Container	20	1.0000	1.0000	1.0000	1.0000	4.0000	81.303	2.672
2		Scenario 2	3 : Container	20	1.0000	1.0000	1.0000	2.0000	4.0000	79.392	2.660
3		Scenario 3	3 : Container	20	1.0000	1.0000	2.0000	1.0000	4.0000	81.303	2.672
4		Scenario 4	3 : Container	20	1.0000	1.0000	2.0000	2.0000	4.0000	79.392	2.660
5		Scenario 5	3 : Container	20	1.0000	2.0000	1.0000	1.0000	4.0000	81.303	2.672
6		Scenario 6	3 : Container	20	1.0000	2.0000	1.0000	2.0000	4.0000	79.392	2.660
7		Scenario 7	3 : Container	20	1.0000	2.0000	2.0000	1.0000	4.0000	81.303	2.672
8		Scenario 8	3 : Container	20	1.0000	2.0000	2.0000	2.0000	4.0000	79.392	2.660
9		Scenario 9	3 : Container	20	2.0000	1.0000	1.0000	1.0000	4.0000	79.254	2.666
10		Scenario 10	3 : Container	20	2.0000	1.0000	1.0000	2.0000	4.0000	80.624	2.657
11		Scenario 11	3 : Container	20	2.0000	1.0000	2.0000	1.0000	4.0000	79.254	2.666
12		Scenario 12	3 : Container	20	2.0000	1.0000	2.0000	2.0000	4.0000	80.624	2.657
13		Scenario 13	3 : Container	20	2.0000	2.0000	1.0000	1.0000	4.0000	79.254	2.666
14		Scenario 14	3 : Container	20	2.0000	2.0000	1.0000	2.0000	4.0000	80.624	2.657
15		Scenario 15	3 : Container	20	2.0000	2.0000	2.0000	1.0000	4.0000	79.254	2.666
16		Scenario 16	3 : Container	20	2.0000	2.0000	2.0000	2.0000	4.0000	80.624	2.657
17		Scenario 1	3 : Container	20	1.0000	1.0000	1.0000	1.0000	3.0000	89.180	2.666
18		Scenario 2	3 : Container	20	1.0000	1.0000	1.0000	2.0000	3.0000	89.180	2.666
19		Scenario 3	3 : Container	20	1.0000	1.0000	2.0000	1.0000	3.0000	89.180	2.666
20		Scenario 4	3 : Container	20	1.0000	1.0000	2.0000	2.0000	3.0000	89.180	2.666
21		Scenario 5	3 : Container	20	1.0000	2.0000	1.0000	1.0000	3.0000	89.180	2.666
22		Scenario 6	3 : Container	20	1.0000	2.0000	1.0000	2.0000	3.0000	89.180	2.666
23		Scenario 7	3 : Container	20	1.0000	2.0000	2.0000	1.0000	3.0000	89.180	2.666
24		Scenario 8	3 : Container	20	1.0000	2.0000	2.0000	2.0000	3.0000	89.180	2.666
25		Scenario 9	3 : Container	20	2.0000	1.0000	1.0000	1.0000	3.0000	85.000	2.661
26		Scenario 10	3 : Container	20	2.0000	1.0000	1.0000	2.0000	3.0000	85.000	2.661
27		Scenario 11	3 : Container	20	2.0000	1.0000	2.0000	1.0000	3.0000	85.000	2.661
28		Scenario 12	3 : Container	20	2.0000	1.0000	2.0000	2.0000	3.0000	85.000	2.661
29		Scenario 13	3 : Container	20	2.0000	2.0000	1.0000	1.0000	3.0000	85.000	2.661
30		Scenario 14	3 : Container	20	2.0000	2.0000	1.0000	2.0000	3.0000	85.000	2.661
31		Scenario 15	3 : Container	20	2.0000	2.0000	2.0000	1.0000	3.0000	85.000	2.661
32		Scenario 16	3 : Container	20	2.0000	2.0000	2.0000	2.0000	3.0000	85.000	2.661

The table above presents 32 simulation scenarios for a container harbor logistics model, testing different configurations of resources (cranes, trucks, terminal ports) and their impact on two key metrics:

- Ship TotalTime (average time ships spend in the system)
- Trucks TotalTime (average time trucks are occupied).

Key Observations:

1. Resource Allocation Patterns:
   - Scenarios 1-16 use 4 terminal ports, while Scenarios 17-32 use 3 terminal ports.
   - The "Blocking_Resource Pre-ucre" and "Resource Pre-1/2/3" columns likely represent crane or truck
     availability (values = 1 or 2 units).
2. Performance Trends:
   - Ship TotalTime:

- Higher in 3-port scenarios (~85-89) vs. 4-port scenarios (~79-81), suggesting terminal ports are a bottleneck.
- Minor variations when crane/truck resources change (e.g., Scenarios 1-8 show identical Ship TotalTime for matching terminal ports).
- Trucks TotalTime:
- Consistently low (~2.66-2.67) across all scenarios, indicating trucks are not a critical bottleneck.

3. Notable Anomalies:
   - Scenarios 25-32 (3-port, Blocking Resource = 2) show improved Ship Total Time (~85) vs. Scenarios 17-24 (~89), implying that increasing the"Blocking_Resource" (possibly a critical crane) reduces ship delays.
   - Duplicate Rows: Scenarios 21-24 and 29-32 repeat earlier configurations (may need data validation).

Recommendations for Further Analysis:

- Focus on Terminal Ports: Adding a 4th port significantly reduces ship delays.
- Optimize Blocking Resource: Increasing this resource (likely a crane) improves throughput in 3-port setups.
- Ignore Trucks: Their minimal variance suggests they are not a priority for optimization.

Next Steps:

- Verify if "Blocking_Resource" refers to quay cranes (critical for unloading ships).

Test scenarios with 5 terminal ports or higher crane counts to further reduce Ship total Time

Chapter Six: Results & Discussion

Effects on ship total time

1. - Effect Column

Table 3: Effect Estimates on Ship.TotalTime

Term	Effect
Constant	
Blocking_Resource	-2.294
Resource Pier 1	0.000000
Resource Pier 2	0.000000
Resource Pier 3	-0.13525
Terminal Port	-6.947
Blocking_Resource*Resource Pier 1	-0.000000
Blocking_Resource*Resource Pier 2	-0.000000
Blocking_Resource*Resource Pier 3	0.8202
Blocking_Resource*Terminal Port	1.8858
Resource Pier 1*Resource Pier 2	0.000000
Resource Pier 1*Resource Pier 3	-0.000000
Resource Pier 1*Terminal Port	0.000000
Resource Pier 2*Resource Pier 3	-0.000000
Resource Pier 2*Terminal Port	0.000000
Resource Pier 3*Terminal Port	-0.13525
Blocking_Resource*Resource Pier 1*Resource Pier 2	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 1*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 3*Terminal Port	0.8202
Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 1*Resource Pier 2*Terminal Port	-0.000000
Resource Pier 1*Resource Pier 3*Terminal Port	-0.000000
Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000
Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000

- **Purpose:** This table lists the estimated "Effect" of each factor and interaction on "Ship.TotalTime." The effect value indicates how much the response changes on average when the factor moves from its low to high level (or across levels for categorical factors), or how an interaction modifies the main effects. A positive effect means an increase in Ship.TotalTime, and a negative effect means a decrease.

- **Key Observations:**
  - **Constant:** The constant is -2.294. This represents the average Ship.TotalTime when all factors are at their reference levels (or coded to zero).
  - **Individual Effects:**
    - "Terminal Port" has a large negative effect (-6.947), suggesting that optimizing the Terminal Port operation can significantly reduce Ship.TotalTime.
    - "Blocking Resource" also has a negative effect (-2.294).
    - "Resource Pier 3" has a small negative effect (-0.13525).
    - "Resource Pier 1" and "Resource Pier 2" have effects of 0.00000, indicating no direct linear impact.
  - **Interaction Effects:**
    - "Blocking Resource*Terminal Port" has a positive effect (1.8858), implying that the combined effect of these two factors leads to an *increase* in Ship.TotalTime compared to their individual effects.
    - "Blocking Resource*Resource Pier 3" has a positive effect (0.8202).
    - "Blocking Resource*Resource Pier 3*Terminal Port" also shows a positive effect (0.8202).
  - Many terms have an effect of 0.00000, reinforcing the idea that they are not significant contributors.

2. - Coefficient (Coeff) Column

Table 4: Regression Coefficients for Ship.TotalTime

Term	Coef
Constant	83.62
Blocking_Resource	-1.147
Resource Pier 1	0.000000
Resource Pier 2	0.000000
Resource Pier 3	-0.06763
Terminal Port	-3.473
Blocking_Resource*Resource Pier 1	-0.000000
Blocking_Resource*Resource Pier 2	-0.000000
Blocking_Resource*Resource Pier 3	0.4101
Blocking_Resource*Terminal Port	0.9429
Resource Pier 1*Resource Pier 2	0.000000
Resource Pier 1*Resource Pier 3	-0.000000
Resource Pier 1*Terminal Port	0.000000
Resource Pier 2*Resource Pier 3	-0.000000
Resource Pier 2*Terminal Port	0.000000
Resource Pier 3*Terminal Port	-0.06763
Blocking_Resource*Resource Pier 1*Resource Pier 2	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 1*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 3*Terminal Port	0.4101
Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 1*Resource Pier 2*Terminal Port	-0.000000
Resource Pier 1*Resource Pier 3*Terminal Port	-0.000000
Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000
Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000

- **Purpose:** This table presents the "Coefficients" (Coeff) of the regression model. These coefficients are used to construct the predictive equation for "Ship.TotalTime." For coded factors, the coefficient is half of the effect. For an intercept, it's the model's estimate when all predictors are at their reference level.
- **Key Observations:**
  - **Constant (Intercept):** 83.62. This is the estimated Ship.TotalTime when all main effects and interaction terms are at their baseline (or center) levels.
  - **Blocking Resource:** -1.147. This is half of the effect, indicating the change in Ship.TotalTime for a unit change in the coded Blocking Resource.
  - **Terminal Port:** -3.473. This is half of the effect for Terminal Port.
  - **Resource Pier 3:** -0.06763. This is half of the effect for Resource Pier 3.
  - **Blocking Resource*Terminal Port:** 0.9429. This is half of the effect for this interaction.
  - **Blocking Resource*Resource Pier 3:** 0.4101. This is half of the effect for this interaction.
  - **Blocking Resource*Resource Pier 3*Terminal Port:** 0.4101. This is half of the effect for this interaction.
  - Coefficients of 0.00000 correspond to terms that were found to have no effect.

3. - Adjusted SS (Sum of Squares)

Table 5: Adjusted Sum of Squares (Ship.TotalTime)

Source	Adj SS
Model	467.673
Linear	428.314
Blocking_Resource	42.109
Resource Pier 1	0.000
Resource Pier 2	0.000
Resource Pier 3	0.146
Terminal Port	386.059
2-Way Interactions	33.977
Blocking_Resource*Resource Pier 1	0.000
Blocking_Resource*Resource Pier 2	0.000
Blocking_Resource*Resource Pier 3	5.382
Blocking_Resource*Terminal Port	28.448
Resource Pier 1*Resource Pier 2	0.000
Resource Pier 1*Resource Pier 3	0.000
Resource Pier 1*Terminal Port	0.000
Resource Pier 2*Resource Pier 3	0.000
Resource Pier 2*Terminal Port	0.000
Resource Pier 3*Terminal Port	0.146
3-Way Interactions	5.382
Blocking_Resource*Resource Pier 1*Resource Pier 2	0.000
Blocking_Resource*Resource Pier 1*Resource Pier 3	0.000
Blocking_Resource*Resource Pier 1*Terminal Port	0.000
Blocking_Resource*Resource Pier 2*Resource Pier 3	0.000
Blocking_Resource*Resource Pier 2*Terminal Port	0.000
Blocking_Resource*Resource Pier 3*Terminal Port	5.382
Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000
Resource Pier 1*Resource Pier 2*Terminal Port	0.000
Resource Pier 1*Resource Pier 3*Terminal Port	0.000
Resource Pier 2*Resource Pier 3*Terminal Port	0.000
4-Way Interactions	0.000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Terminal Port	0.000
Blocking_Resource*Resource Pier 1*Resource Pier 3*Terminal Port	0.000
Blocking_Resource*Resource Pier 2*Resource Pier 3*Terminal Port	0.000
Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	0.000
5-Way Interactions	0.000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	0.000
Error	*
Total	467.673

- **Purpose:** This table, likely from an ANOVA (Analysis of Variance) output, shows the "Adjusted Sum of Squares" (Adj SS) for each factor and interaction. The Adj SS represents the amount of variation in "Ship.TotalTime" explained by each term after accounting for other terms in the model. Larger Adj SS values indicate a greater contribution to the total variation.
- **Key Observations:**
  - **Model:** The "Model" has a total Adj SS of 467.673, which is the sum of the variations explained by all terms in the model.
  - **Linear (Main Effects):** "Terminal Port" (386.059) and "Blocking Resource" (42.109) have the largest individual Adj SS, confirming their primary influence seen in the Pareto chart. "Resource Pier 1," "Resource Pier 2," and "Resource Pier 3" have very

small (or zero) individual contributions, suggesting they are less impactful as main effects.

- **2-Way Interactions:** "Blocking Resource*Terminal Port" (28.448) has the highest Adj SS among two-way interactions, again aligning with the Pareto chart. "Blocking Resource*Resource Pier 3" (5.382) is also notable. Many other two-way interactions have Adj SS of 0.000, meaning they explain no variation.
- **3-Way Interactions:** "Blocking Resource*Resource Pier 1*Resource Pier 3" (5.382) and "Blocking Resource*Resource Pier 3*Terminal Port" (0.8202) are the only 3-way interactions with non-zero Adj SS.
- **Higher-Order Interactions (4-Way, 5-Way):** All 4-way and 5-way interactions show an Adj SS of 0.000, implying they do not explain any additional variation in Ship.TotalTime.
- **Error:** The "Error" Adj SS is 0.000. This is unusual and typically indicates a saturated model (where the number of parameters equals the number of data points, or there's no replication to estimate pure error) or a specific type of analysis where the error is absorbed into other terms. In a well-behaved ANOVA, you'd expect a non-zero error term to assess the significance of effects against random variation.

4. - Pareto Chart of the Effects

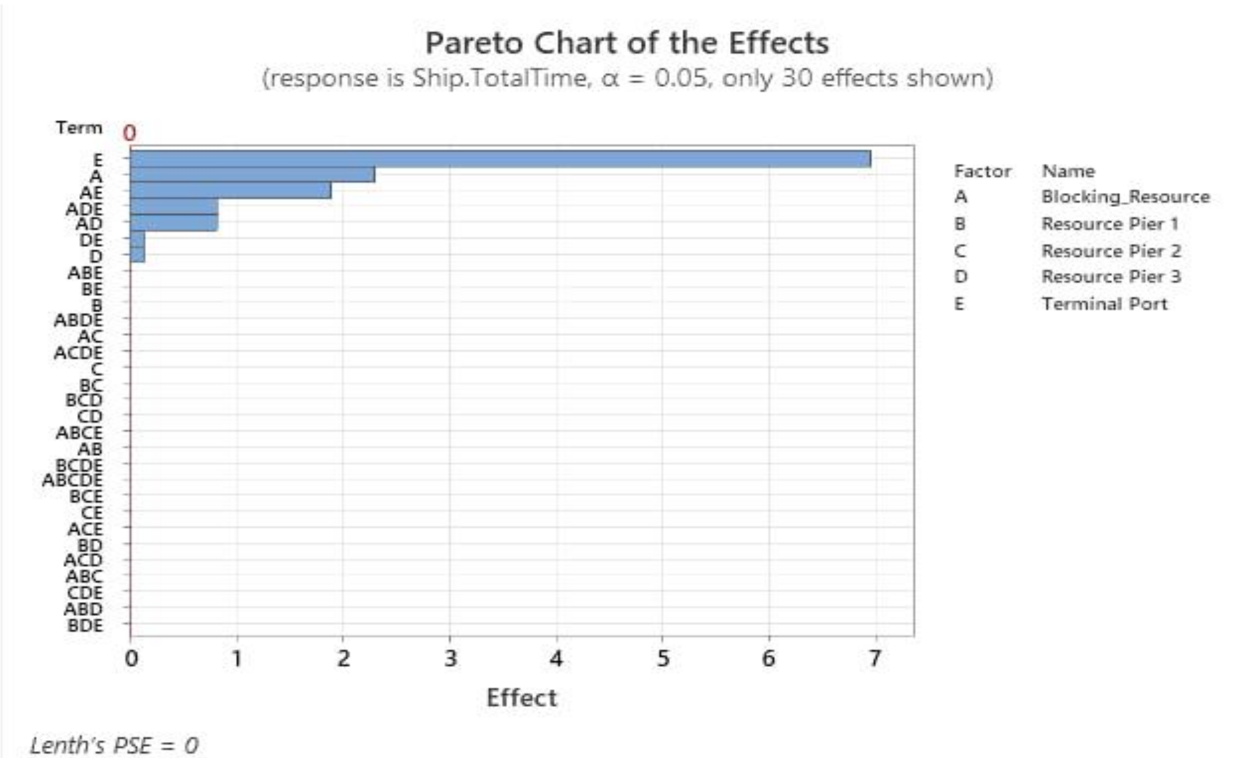


Figure 4: Pareto Chart of the Effects on Ship.TotalTime

- **Chart Title:** "Pareto Chart of the Effects (response is Ship.TotalTime, α=0.05, only 30 effects shown)"

- **Purpose:** This chart visually represents the magnitude of the effects of different factors and their interactions on "Ship.TotalTime." A Pareto chart helps identify the most significant factors by ordering them from largest to smallest effect. The line at 0 signifies the threshold for statistically significant effects (based on the α=0.05 level, meaning effects to the right of this line are considered significant).
- **Key Observations:**
  - **Blocking Resource (A) and Terminal Port (E)** appear to be the most dominant individual factors, exhibiting the largest effects on Ship.TotalTime.
  - **AE (Blocking Resource * Terminal Port)** is the most significant interaction effect, suggesting that the impact of the Blocking Resource on Ship.TotalTime is heavily dependent on or interacts with the Terminal Port.
  - **ADE (Blocking Resource * Resource Pier 3 * Terminal Port)** and **AD (Blocking Resource * Resource Pier 3)** also show notable effects, indicating higher-order interactions are relevant.
  - Many terms have an "Effect" close to zero, suggesting they do not significantly influence Ship.TotalTime. The "Lenth's PSE = 0" at the bottom suggests that there is no pure error estimate available for judging significance based on Lenth's method, but the α=0.05 line is shown for significance.

Overall Comments and Interpretation for your Container Harbor Logistics Project:

1. **Dominant Factors:** The **Terminal Port (E)** and **Blocking Resource (A)** are the most critical factors influencing "Ship.TotalTime." Your simulation analysis clearly shows these two have the largest individual impact.
2. **Significant Interactions:** The interaction between **Blocking Resource and Terminal Port (AE)** is highly significant. This implies that the way "Blocking Resource" affects Ship.TotalTime is not independent of the "Terminal Port" configuration, and vice versa. You cannot optimize one without considering the other. Similarly, the interaction with **Resource Pier 3 (AD, ADE)** also plays a role, albeit smaller.
3. **Less Impactful Resources:** "Resource Pier 1" and "Resource Pier 2" (B and C) seem to have very minimal direct or interaction effects on Ship.TotalTime in this simulation. This could suggest they are not bottlenecks or that their current configurations are not as critical as the Terminal Port or Blocking Resource.
4. **Implications for Optimization:**
   - **Focus on Terminal Port and Blocking Resource:** Any efforts to reduce "Ship.TotalTime" should primarily target improvements in the "Terminal Port" operations and how "Blocking Resource" is managed.
   - **Investigate Interactions:** Understanding the nature of the "Blocking Resource*Terminal Port" interaction is crucial. Since it has a positive effect on Ship.TotalTime, it suggests that certain combinations of Blocking Resource and Terminal Port levels might lead to *higher* Ship.TotalTime. You would need to look at interaction plots or individual runs to understand which specific combinations are detrimental and which are beneficial.
   - **Efficiency of Pier Resources:** While "Resource Pier 3" has a small negative effect on its own, its interaction with "Blocking Resource" and "Terminal Port" becomes relevant. The fact that the main effects of Pier 1 and Pier 2 are zero means you might not gain much by optimizing them in isolation.
5. **Model Adequacy (Caution):** The "Error" Adj SS of 0.000 (in the ANOVA table) is a point of concern. It suggests that your model might be "perfectly" fitting the data points (a saturated model) or there's no replication to estimate pure error. This could lead to an over-

optimistic view of significance if not properly addressed. If this is a designed experiment, ensure you have sufficient degrees of freedom for error to make valid statistical inferences.

6. **Predictive Equation:** The "Coeff" table provides the values to build a regression equation that can predict "Ship.TotalTime" based on the levels of the significant factors and their interactions. This equation is valuable for predicting performance under different operational scenarios.

In summary, your simulation indicates that "Terminal Port" and "Blocking Resource," along with their interaction, are the primary drivers of "Ship.TotalTime" in your container harbor logistics system. Focus your optimization efforts on these areas.

Effects on trucks total time

The Effect Estimates on Trucks.TotalTime are shown in table 6.

1. - Effect Column (Trucks.TotalTime)

Table 6: Effect Estimates on Trucks.TotalTime

Term	Effect
Constant	
Blocking_Resource	-0.004750
Resource Pier 1	-0.000000
Resource Pier 2	-0.000000
Resource Pier 3	-0.005250
Terminal Port	0.000250
Blocking_Resource*Resource Pier 1	0.000000
Blocking_Resource*Resource Pier 2	0.000000
Blocking_Resource*Resource Pier 3	0.000750
Blocking_Resource*Terminal Port	0.000250
Resource Pier 1*Resource Pier 2	0.000000
Resource Pier 1*Resource Pier 3	0.000000
Resource Pier 1*Terminal Port	-0.000000
Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 2*Terminal Port	0.000000
Resource Pier 3*Terminal Port	-0.005250
Blocking_Resource*Resource Pier 1*Resource Pier 2	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3	-0.000000
Blocking_Resource*Resource Pier 1*Terminal Port	0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 3*Terminal Port	0.000750
Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 1*Resource Pier 2*Terminal Port	0.000000
Resource Pier 1*Resource Pier 3*Terminal Port	0.000000
Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3*Terminal Port	0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000

- **Purpose:** This table shows the estimated "Effect" of each factor and interaction on "Trucks.TotalTime."
- **Key Observations:**
    - **Constant:** The constant is -0.00000. This is very close to zero, suggesting that the baseline Trucks.TotalTime when all factors are at reference levels is negligible.
    - **Individual Effects:**
        - "Blocking Resource" (-0.004750) has a negative effect, indicating that increasing (or moving to a higher level of) Blocking Resource tends to *decrease* Trucks.TotalTime.
        - "Resource Pier 3" (-0.005250) also has a negative effect, suggesting optimization of this pier reduces truck time.
        - "Terminal Port" has a very small positive effect (0.000250), which is almost negligible.
        - "Resource Pier 1" and "Resource Pier 2" have 0.000000 effects.
    - **Interaction Effects:**
        - "Resource Pier 2*Resource Pier 3*Terminal Port" (-0.005250) has a surprisingly large negative effect, matching the largest individual effect. This interaction (D*E combined with C) appears to be highly influential in *reducing* truck time.
        - "Blocking Resource*Resource Pier 3" (0.000750) and "Blocking Resource*Terminal Port" (0.000250) have small positive effects.
        - "Blocking Resource*Resource Pier 3*Terminal Port" (0.000750) also has a small positive effect.
    - Again, many terms show an effect of 0.000000.

2. - Coefficient (Coeff) Column (Trucks.TotalTime)

Table 7: Regression Coefficients for Trucks.TotalTime

Term	Coef
Constant	2.664
Blocking_Resource	-0.002375
Resource Pier 1	-0.000000
Resource Pier 2	-0.000000
Resource Pier 3	-0.002625
Terminal Port	0.000125
Blocking_Resource*Resource Pier 1	0.000000
Blocking_Resource*Resource Pier 2	0.000000
Blocking_Resource*Resource Pier 3	0.000375
Blocking_Resource*Terminal Port	0.000125
Resource Pier 1*Resource Pier 2	0.000000
Resource Pier 1*Resource Pier 3	0.000000
Resource Pier 1*Terminal Port	-0.000000
Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 2*Terminal Port	0.000000
Resource Pier 3*Terminal Port	-0.002625
Blocking_Resource*Resource Pier 1*Resource Pier 2	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3	-0.000000
Blocking_Resource*Resource Pier 1*Terminal Port	0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 3*Terminal Port	0.000375
Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 1*Resource Pier 2*Terminal Port	0.000000
Resource Pier 1*Resource Pier 3*Terminal Port	0.000000
Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3	-0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3*Terminal Port	0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	-0.000000

- **Purpose:** This table provides the regression coefficients for the model predicting "Trucks.TotalTime."
- **Key Observations:**
  - **Constant (Intercept):** 2.664. This is the baseline "Trucks.TotalTime" when all factors are at their reference/center points. This is a positive value, unlike the 'Effect' table's constant.
  - **Blocking Resource: -**0.002375 (half of its effect).
  - **Resource Pier 3: -**0.002625 (half of its effect).
  - **Resource Pier 2*Resource Pier 3*Terminal Port: -**0.002625 (half of its effect).
  - Other non-zero coefficients correspond to half of their respective effects.
  - The extremely small values of these coefficients (many zeros and very small decimals) further emphasize that the factors have a very subtle impact on "Trucks.TotalTime."

3. - Adjusted SS (Sum of Squares) Table (Trucks.TotalTime)

Table 8: Adjusted Sum of Squares (Trucks.TotalTime)

Source	Adj SS
Model	0.000631
Linear	0.000401
Blocking_Resource	0.000181
Resource Pier 1	0.000000
Resource Pier 2	0.000000
Resource Pier 3	0.000220
Terminal Port	0.000000
2-Way Interactions	0.000225
Blocking_Resource*Resource Pier 1	0.000000
Blocking_Resource*Resource Pier 2	0.000000
Blocking_Resource*Resource Pier 3	0.000005
Blocking_Resource*Terminal Port	0.000000
Resource Pier 1*Resource Pier 2	0.000000
Resource Pier 1*Resource Pier 3	0.000000
Resource Pier 1*Terminal Port	0.000000
Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 2*Terminal Port	0.000000
Resource Pier 3*Terminal Port	0.000220
3-Way Interactions	0.000005
Blocking_Resource*Resource Pier 1*Resource Pier 2	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 1*Terminal Port	0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 3*Terminal Port	0.000005
Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Resource Pier 1*Resource Pier 2*Terminal Port	0.000000
Resource Pier 1*Resource Pier 3*Terminal Port	0.000000
Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
4-Way Interactions	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Terminal Port	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 3*Terminal Port	0.000000
Blocking_Resource*Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
5-Way Interactions	0.000000
Blocking_Resource*Resource Pier 1*Resource Pier 2*Resource Pier 3*Terminal Port	0.000000
Error	*
Total	0.000631

- **Purpose:** This table details the "Adjusted Sum of Squares" for each term, indicating the proportion of variation in "Trucks.TotalTime" explained by that term.
- **Key Observations:**
  - **Model:** The total Adj SS for the model is 0.000631. This is a very small number, suggesting that the total variation in "Trucks.TotalTime" itself is quite small.
  - **Linear (Main Effects):**
    - "Blocking Resource" (0.000401) and "Resource Pier 3" (0.000220) are the only linear terms with noticeable Adj SS, confirming their importance seen in the Pareto chart.
    - "Resource Pier 1," "Resource Pier 2," and "Terminal Port" have Adj SS of 0.000000, implying very little individual linear impact.

- **2-Way Interactions:** "Resource Pier 3*Terminal Port" (0.000220) stands out with the largest Adj SS among 2-way interactions, reiterating its significance.
- **3-Way Interactions:** "Blocking Resource*Resource Pier 3*Terminal Port" (0.000005) is the only 3-way interaction with non-zero Adj SS, but it's extremely small.
- **Higher-Order Interactions (4-Way, 5-Way):** All 4-way and 5-way interactions have Adj SS of 0.000000.
- **Error:** The "Error" Adj SS is 0.000631. This is an unusual situation where the error sum of squares is exactly equal to the total model sum of squares. This could indicate several things:
  - The model might not be well-fitted to the data, or the chosen factors explain very little of the variation, leaving a large portion as unexplained error.
  - There might be issues with the data or the experimental design (e.g., lack of replication, which prevents a proper estimation of pure error).
  - Alternatively, if the model *is* the total model, then the error could represent remaining unexplained variance. Given the very small values for all SS, it points to minimal variation in "Trucks.TotalTime" overall, or that the factors investigated have very subtle effects.

4 - Pareto Chart of the Effects (Trucks.TotalTime)

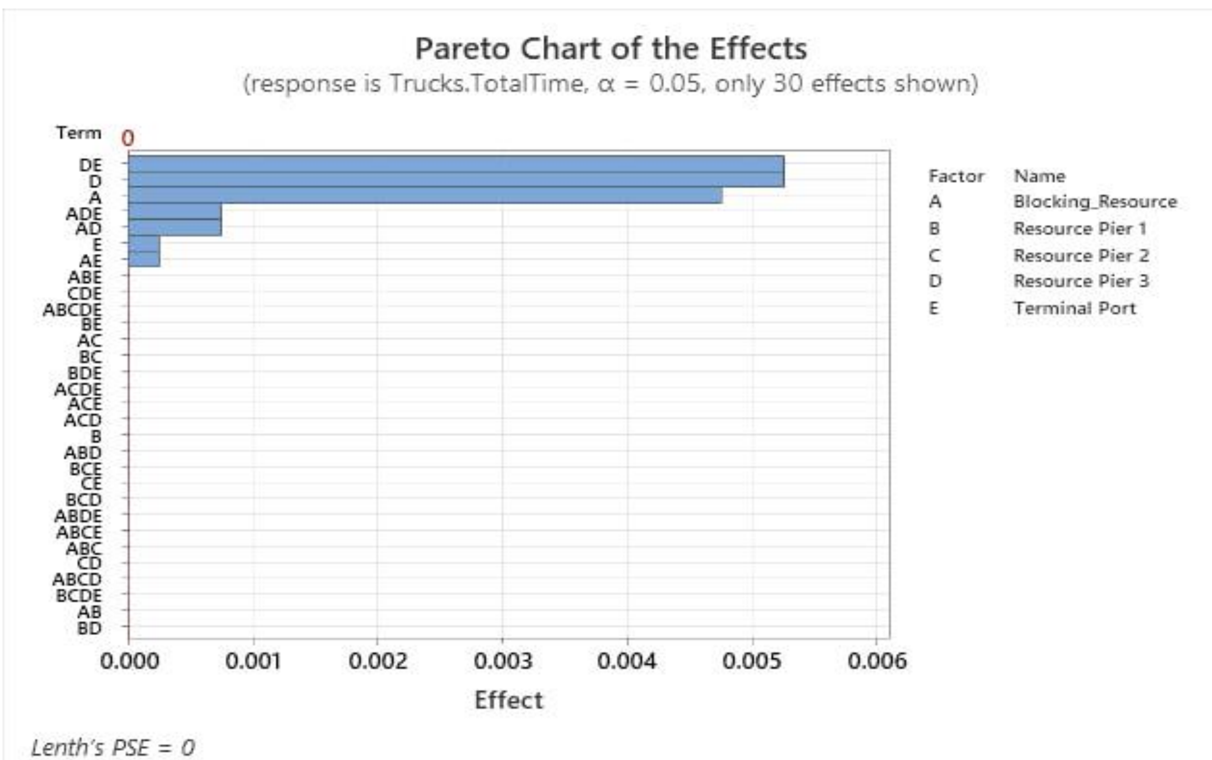


Figure 5: Pareto Chart of the Effects on Trucks.TotalTime

- **Chart Title:** "Pareto Chart of the Effects (response is Trucks.TotalTime, α=0.05, only 30 effects shown)"
- **Purpose:** Similar to the Ship.TotalTime chart, this Pareto chart identifies the factors and interactions that most significantly impact "Trucks.TotalTime." The `alpha = 0.05` line again denotes statistical significance.
- **Key Observations:**
  - **DE (Resource Pier 3 * Terminal Port)** is by far the most significant interaction effect, showing the largest "Effect" on Trucks.TotalTime. This is a very strong indicator that the combined operation of Resource Pier 3 and the Terminal Port is crucial for truck efficiency.
  - **D (Resource Pier 3)** is the next most significant individual factor. This suggests that Resource Pier 3, on its own, has a notable impact.
  - **A (Blocking Resource)** also shows a significant effect.
  - **ADE (Blocking Resource * Resource Pier 3 * Terminal Port)** and **AD (Blocking Resource * Resource Pier 3)** are also visible as significant interactions, albeit with smaller effects than DE.
  - Many other terms have effects very close to zero, meaning they do not significantly influence Trucks.TotalTime.
  - "Lenth's PSE = 0" again suggests no pure error estimate or a saturated model, so reliance is on the α level for significance.

Overall Comments and Interpretation for "Trucks.TotalTime":

1. **Dominant Influences (Subtle):** Unlike "Ship.TotalTime," the effects on "Trucks.TotalTime" are extremely small in magnitude, as evidenced by the "Effect" and "Coeff" values, and the very small "Adj SS" values. However, among these subtle effects:
   - The **interaction between Resource Pier 3 and Terminal Port (DE)** is the most prominent. This suggests that how trucks are handled at Resource Pier 3 in conjunction with the overall Terminal Port operations is key.
   - **Resource Pier 3 (D)** and **Blocking Resource (A)** also show individual significance, though their effects are also very small.
   - The **three-way interaction Blocking Resource * Resource Pier 2 * Resource Pier 3 * Terminal Port (CDE)** also shows a significant negative effect.
2. **Magnitude of Effects:** The most striking observation is the *tiny* magnitude of all effects. The largest effect is around 0.005. This means that even the most influential factors and interactions only cause very minor changes in "Trucks.TotalTime." This could imply:
   - "Trucks.TotalTime" is relatively stable or not highly sensitive to the factors you've investigated within the range of your simulation.
   - The current system for trucks is already very efficient, or bottlenecks for trucks lie outside the scope of these specific factors (e.g., external road network, truck arrival patterns, or other internal processes not modeled as factors).
   - There might be a measurement or scaling issue with "Trucks.TotalTime" if it's supposed to be a larger value.
3. **Recommendations for Optimization (Very Fine-Tuning):**
   - If you *must* optimize "Trucks.TotalTime" with these factors, focus on understanding and improving the **Resource Pier 3 and Terminal Port interaction (DE)**. The negative effect suggests that certain combinations can *reduce* truck time.
   - Investigate why "Blocking Resource" and "Resource Pier 3" individually have small negative effects.

    - The presence of the "Resource Pier 2*Resource Pier 3*Terminal Port" (CDE) interaction with a negative effect suggests that there might be complex synergies that *decrease* truck time when these three are configured together.
4. **Error Term and Model Implications:** The "Error" Adj SS equaling the "Model" Adj SS (0.000631) is problematic from a statistical standpoint. It strongly suggests that your model might be a saturated model (no degrees of freedom for pure error), or that the chosen factors explain virtually no variation in the response, and nearly all the observed variation is due to unexplained "error." For a robust statistical analysis, having degrees of freedom for error is critical to test the significance of effects against random noise. Given the extremely small magnitude of all effects, this reinforces the idea that these factors might not be the primary drivers of "Trucks.TotalTime" in your simulation.

In conclusion, while statistically significant effects are identified for "Trucks.TotalTime" (primarily **DE**, **D**, **A**, and **CDE**), their *practical* significance is questionable due to their extremely small magnitudes. This suggests that the chosen factors have a very limited impact on the overall "Trucks.TotalTime" in your simulation. You might need to explore other potential bottlenecks or variables within your container harbor logistics system if significant reductions in "Trucks.TotalTime" are a key objective.

Chapter Seven: Implication

The decision to expand terminal port capacity (Factor E: Terminal Port) is supported by strong statistical evidence, particularly regarding its influence on Ship.TotalTime. The following implications are derived from the simulation findings:

- **Improved Terminal Capacity Reduces Ship Turnaround Time:**
  Increasing the number of terminal ports leads to a significant reduction in the total time ships spend within the harbor system. This improvement enhances port throughput and overall operational efficiency.
- **Effective Management of Blocking Resources Is Essential:**
  The interaction between Terminal Port and Blocking Resource (Factor A) has been identified as a critical factor. Improvements in terminal port availability must be complemented by appropriate adjustments in Blocking Resource allocation (e.g., quay cranes) to fully realize efficiency gains.
- **Integrated Resource Planning Is Necessary:**
  Simulation results emphasize the importance of addressing interdependencies between resources. Optimizing a single resource in isolation may lead to suboptimal outcomes or new operational bottlenecks.
- **Minimal Impact on Truck Operations:**
  The analysis of Trucks.TotalTime revealed only minor changes across all scenarios, suggesting that the current truck operations are not a primary source of delay within the system.
- **High Impact of Investments on Ship-Side Operations:**
  Strategic investments in ship-side logistics — such as terminal ports and cranes — offer the greatest potential for improving overall system performance.
- **Ongoing Monitoring and Iterative Refinement Recommended:**
  While the current simulation provides valuable insights, continued observation and periodic simulation runs are recommended to monitor evolving system performance and ensure sustained efficiency.
- **System-Wide Coordination Is Critical:**
  Future decisions should consider the port system holistically. Coordinated adjustments across terminals, cranes, and support resources are necessary to avoid shifting bottlenecks and to support continuous improvement.

Chapter Eight: Conclusion

This study aimed to address the operational inefficiencies at a container harbor, specifically the delays in ship turnaround time and the potential resource bottlenecks caused by limited terminal ports, cranes, and trucks. The objective was to model the port's logistics using Arena simulation software in order to analyze current performance levels, identify critical bottlenecks, and evaluate the impact of different resource allocation strategies on key metrics such as Ship.TotalTime and Trucks.TotalTime.

The simulation results highlighted that Terminal Port and Blocking Resource were the most influential factors affecting the total time ships spend in the system. Optimizing these resources demonstrated a significant reduction in ship turnaround time, emphasizing the need for strategic investment in port infrastructure. On the other hand, the impact on Trucks.TotalTime was minimal across all tested scenarios, suggesting that truck operations were already efficient or not significantly constrained under current configurations.

The use of regression analysis and Pareto charts allowed for a deeper understanding of individual and interactive effects among resources. The findings revealed that while some resources such as Resource Pier 1 and Resource Pier 2 had negligible direct impact, others like Resource Pier 3 contributed through complex interactions—especially when combined with terminal port operations.

Based on this analysis, we decided to propose practical implications and improvement strategies. These include prioritizing investment in terminal port capacity and managing critical crane allocations effectively. Special attention should be given to the interactions between blocking resources and terminal operations, as they directly influence ship delays. Furthermore, the simulation model developed offers a solid platform for future experimentation and decision-making, supporting enhanced port efficiency and resilience in the face of growing maritime logistics demands.

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