Optimizing Truck Flow in Ship Unloading: A Real-Time Simulation Approach for the Port of Itaqui

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Abstract: Truck congestion in port yards is a significant issue that impacts the operational efficiency and competitiveness of port terminals. This study examines the logistics flow dynamics in the ship unloading area of the Port of Itaqui. Through modeling and simulation methodologies, it aims to identify bottlenecks and optimize operations. We collected and analyzed port data to establish simulation parameters, which were categorized into various groups, including system administration, truck flows, and required resources. Based on the conceptual modeling of truck and ship movements, we developed a simulation system that visualizes the effects of different operational decisions. The results of the simulation are crucial for identifying critical points and formulating strategies to reduce congestion.

1 INTRODUCTION

The unloading operations of bulk products in ports represent a fundamental step in the global logistics and distribution of goods. These products, including grains, minerals, coal, and liquids, are transported in large quantities and require specialized infrastructure and procedures to be unloaded efficiently and safely. The efficiency of these operations is crucial, as delays can result in increased costs, congestion, and a negative impact on the supply chain (Du et al., 2023).

One of the main challenges in these operations is balancing unloading speed with operational safety. Due to the large volume of material to be handled, the risk of accidents and environmental damage is significant. Moreover, the variability in the characteristics of bulk products, such as density and particle size, can directly impact the efficiency of unloading equipment and the stability of port structures (de León et al., 2021).

Another critical aspect is the optimization of operational costs. The maintenance of equipment, workforce training, and management of operation times directly influence the total costs of port operations. Therefore, finding the ideal balance between efficiency, safety, and cost is a constant challenge for port operators.

The Port of Itaqui, in the state of Maranhão (see 1), known for handling solid and liquid bulk, stands out for its deep waters, rail connections, and structured terminals, providing competitive logistics for its clients. Historically, the port has focused on grain exports, especially soybeans and corn, and receiving petroleum products such as diesel, gasoline, and fertilizers. In 2022, Itaqui reached its highest cargo volume in history, handling 33.61 million tons, with solid bulk accounting for 23 million tons, a 19% increase over the previous year. In 2023, for the first time, the port registered the handling of 2 million tons of soybeans in a single month, consolidating its position as the 4th largest public port in Brazil, according to the 2023 Aquatic Performance Report released by ANTAQ (National Agency for Waterway Transportation (ANTAQ), 2024).

This study aims to address key operational challenges at the Port of Itaqui by identifying bottlenecks

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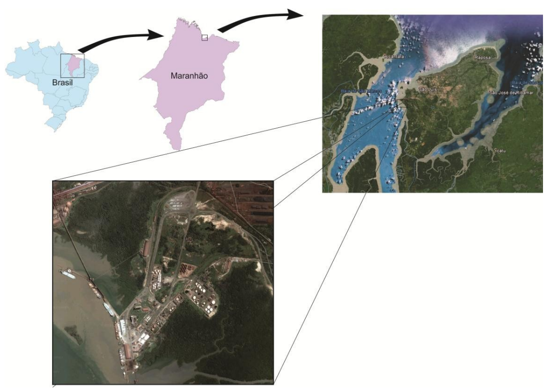

Figure 1: Port of Itaqui, on the west coast of the island (São Marcos Bay), 11 km from São Luís (EMAP - Empresa Maranhense de Administração Portuária, 2024).

in truck flow, both within the port's infrastructure and at external logistical support points. It also seeks to clarify the relationship between truck volume in the primary operational area and the ship discharge rate, offering a detailed understanding of how many trucks are needed to efficiently meet active contracts. These insights are crucial for optimizing resource allocation and streamlining port operations.

Directly observing dynamics in the physical port environment poses significant challenges due to spatial and logistical constraints. To overcome these limitations and gain a comprehensive understanding of how each component affects port operations, this study has developed an innovative real-time simulation system. The main contribution of this simulator is allows for a detailed examination of the current port conditions and serves as a dynamic platform to test the effects of variable adjustments on truck flow, ship discharge efficiency, and overall port activity. Moreover, with this system, it becomes possible to create data-driven strategies that address operational inefficiencies, thereby enhancing both the throughput and resilience of the Port of Itaqui's logistics framework.

The rest of the article is structured as follows: Section 2 presents the theoretical framework necessary for understanding the work developed; Section 3 details the methodological procedures used for the development of the simulator; Section 4 provides the description of the simulated scenarios and the analysis of the results obtained; and finally, Section 5 presents the conclusions and possibilities for future work.

2 RELATED WORK

There are several causes for truck congestion in ports. Many ports face space constraints, limiting their ability to efficiently handle large volumes of trucks. This problem is exacerbated by the growth of the international market, which increases the demand for port services beyond the available capacity (Napitupulu et al., 2022).

Bulk cargo unloading operations at ports are essential components of the supply chain, directly affecting the efficiency and effectiveness of logistics operations. These activities involve complex interactions between various elements, such as scheduling, coordination, and cargo handling. To understand the main concepts involved and their impact on supply chain efficiency, we can analyze the following aspects:

Truck Appointment Systems (TAS): Implementing TAS in port terminals can significantly increase yard efficiency, reduce congestion, and balance demand with available capacity. This system helps minimize truck wait times and container handling, essential factors for maintaining smooth operations at the port's land interface (Wang et al., 2023). TAS allows for better distribution of trucks throughout the day, optimizing infrastructure use and reducing unnecessary queues, resulting in more efficient operations.

Train Scheduling: In ports specializing in bulk cargo, train scheduling for unloading is a complex task due to uncertainties in processing times. Effective scheduling, whether deterministic or stochastic, is essential to ensure deadlines are met, and cargo transfer to warehouses occurs in a timely manner. Techniques such as mixed integer programming, constraint programming, and greedy randomized algorithms are commonly used to optimize these operations (Menezes et al., 2016).

Disruption Management: Bulk cargo operations often face disruptions, making effective uncertainty management essential. Frequent rescheduling and enhanced dispatching rules can mitigate the deterioration of operational performance, ensuring adherence to schedules and consequently increasing overall efficiency (Menezes et al., 2016). The ability to quickly adjust the schedule in the face of unexpected events is a determining factor in avoiding delays and minimizing operational impacts.

Port operations, especially those related to the unloading of bulk products, face significant challenges due to truck congestion. To analyze and mitigate this problem, many authors explore modeling and simulation approaches widely used to optimize truck flow and minimize delays. Among the most common approaches are discrete event simulation models, which allow the replication of port operations in virtual scenarios, simulating the impact of different operational variables, such as truck flow, unloading times, and infrastructure bottlenecks (Iannone et al., 2016). Additionally, agent-based modeling (ABM) techniques have been used to model the interactions between trucks, port operators, and available resources, considering behavioral variability and uncertainties in operations (Uthpala et al., 2023). Stochastic optimization models and linear programming also appear in the literature to solve allocation and scheduling problems, aiming to minimize waiting times and congestion.

The Port of Los Angeles successfully implemented PierPass, a program that shifts part of port operations to off-peak hours, significantly reducing daytime congestion. Another successful case was the use of Truck Appointment Systems (TAS) at the Port of Hamburg, Germany, where optimized truck arrival coordination managed to balance port capacity with demand, improving efficiency and truck flow (Notteboom et al., 2022). However, there are also failures in congestion management. At the Port of Santos, Brazil, the implementation of flow control technologies was insufficient due to the lack of proper integration with operations outside the port, resulting in long truck queues and delays, demonstrating that the effectiveness of solutions like TAS depends on expanded infrastructure and coordination policies (Hilsdorf and Nogueira Neto, 2015).

Although modeling and simulation have provided advances in understanding truck flow, there are still opportunities to better explore integrating intelligent logistics systems, such as new approaches and strategies to more proactively predict and mitigate congestion. Moreover, most studies focus on large-scale ports, leaving a gap concerning the application of these solutions in medium and small ports, which often do not have the same technological resources or financial capacity to implement advanced management solutions.

3 METHODOLOGY

The methodology applied in this work consists of multiple steps, including the definition of the object studied and its problems, the analysis of port data, and the development of a simulation system (see Figure 2). The system covers not only the conceptual models but also its computational applications. Each step is detailed in the following sections.

3.1 Object of Study and Its Problems

Meetings were held with managers and operators, and technical on-site visits were to understand the different scenarios characterizing the logistical and opera-

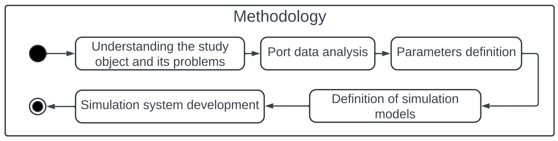

Figure 2: Methodology diagram.

tional flow in the ship unloading area at the Port of Itaqui. These interactions provided a deeper insight into the cyclical activities of the trucks, the stages of the port flow, the role of operators in the port's primary area, and the importance of equipment such as scales and scanners to maintain the efficient flow of trucks.

Based on these observations, the following key concepts are defined for the operability of port activities:

- **Truck Flow (carousel).** Refers to the cyclical movement of trucks between the different phases of unloading products from ships and subsequently delivering them to customers. This flow is essential to maintain the pace of port operations and prevent bottlenecks.
- **Window.** This refers to a registry system at the Port associated with a contract. Each window is linked to a specific ship, a product type, a client, and the number of trucks involved in transportation.
- **Pull.** This is the authorization granted to a truck to leave the "logistical support area" and proceed to the remaining stages of the flow process within the port.

Based on these concepts, it can be said that controlling the truck flow at the port is essentially controlling the flow of trucks for each window in operation. This control is carried out by port operators, who use two key parameters to manage the pull:

- **Initial Pull.** A manually defined parameter specifying the number of trucks that should be between the stages of "Access Gate Entry" and the "Collection Point" (quay area) for each window
- **Blocking Pull.** Also manually defined, this parameter sets the maximum limit of trucks between the stages of "Access Gate Entry" and "Access Gate Exit" for each window.

To identify the influences of controlling the flows of each window and the various impacts that pull parameters have across the Port, data analysis has begun.

3.2 Analysis of Port Data

Data collection and analysis of the operational processes at the Port of Itaqui were performed to conduct an accurate simulation. These analyses included the following aspects:

- **Average Time of Truck Stages in the Flow.** Analysis of the average times trucks spend in each process phase, from entry to exit, including unloading time and internal movements.
- **Number of Trucks at each Stage of the Flow.** Evaluation of the number of trucks moving between the different stages of the port process, aiming to understand how truck density affects operational performance.
- **Analysis of the Pulls Performed by Operators.** Study of operator behavior regarding pull control, identifying patterns and impacts on the smoothness of truck flow.

Based on these analyses, simulation control parameters were defined to manage the behavioral and technical aspects of the simulated scenarios. These parameters were organized into ten groups: configuration, existence, truck flows, timing, delays, load, resources, pull, and context. Each group encompasses specific elements that reflect real-world operational conditions in the port sector, including the movement and handling of trucks, allocation of critical resources, and management of delays and load weights. After defining the simulator input parameters and identifying the aspects to be implemented and observed, conceptual models were developed to represent the operations of these components.

3.3 Simulation Models

The simulation model was structured in four great flows: trucks' flow, ships' flow, pulls, and simulation, besides auxiliary managers of resources, windows, and operators.

3.3.1 Trucks' Flow Model

The model shown in Figure 3 is the primary reference for understanding the simulator's behavior. It helps identify potential bottlenecks at each ship's unloading process stage. The key steps in this flow are:

- **External Yard.** This is where trucks wait to be pulled to begin their activities. It is also the place where trucks return to start a new cycle after delivering products to the client;
- **Truck Retention Yard (TRY).** After being pulled, this is where trucks go to be weighed on the TRY scale. This stage is important for the subsequent weighing of the trucks loaded with the products from the ships;

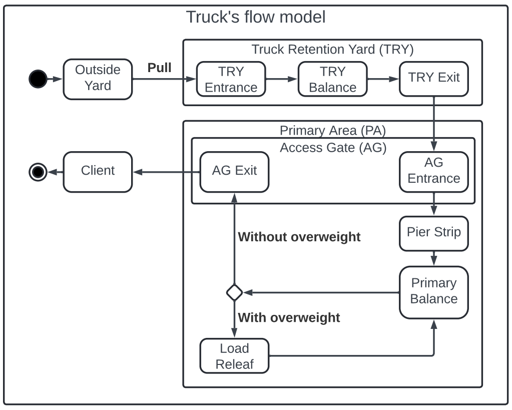

Figure 3: Trucks' flow model.

- **Primary Area:**
  - **Access Gate (GA).** A checkpoint responsible for identifying trucks entering and exiting the primary area;
  - **Quay Strip.** The location where the grabbing cranes are situated, where the trucks are loaded with products from the ships;
  - **Primary Scale.** Weighing of the truck to identify overweight loads;
  - **Load Relief.** The location where trucks offload excess weight that exceeds the truck's capacity;
- **Client.** This is the stage where the products collected from the port trucks are delivered to the contracting clients.

3.3.2 Ships' Flow Model

Next, the ship flow model was developed, as shown in figure 4. This model is essential for simulating sufficiently long periods, allowing the arrival and departure of ships from the port docks. The interaction between the ship and truck flows is crucial, as it directly influences the port's capacity to handle large cargo volumes efficiently. The main stages of the ship activity cycle are presented in this model:

- **Docking and Undocking.** When the ship arrives and departs from the port. It is important to introduce new products into the simulation so that operations do not cease;
- **Window Registration.** This involves registering contracts for each product, ship, and customer in the simulation. This step is essential to define new windows and allow new operations within the port;

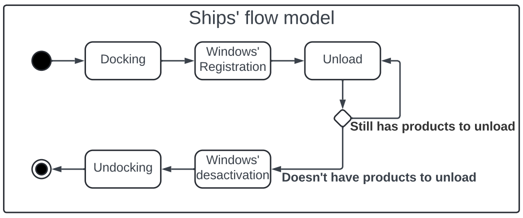

Figure 4: Ships' flow model.

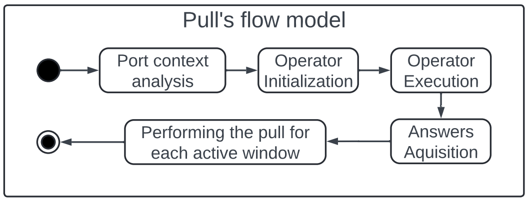

Figure 5: Pull's flow model.

- **Unloading.** The stage where trucks unload products from the ships while they are docked;
- **Window Deactivation.** After all the products from the ship are unloaded, all its windows are deactivated, and the undocking process begins.

3.3.3 Pulls' Flow Model and Operators Manager

To properly define and execute port activities through pull control, a model reflecting the pull execution flow was developed, as shown in figure 5. This model is essential as it outlines the steps in activating the port's operations. By using this model, it becomes easier to define the methodology for setting parameters, such as the initial pull and block pull, which are determined by the operator. Below are the main stages of the pull activity flow:

- **Port Context Analysis.** At this stage, the simulator compiles data related to the presence of trucks in the primary area and delivers it to the operator;
- **Operator Initialization.** The stage where the method to be used for executing the pull is defined;
- **Operator Execution.** The operator performs calculations based on the current port context to determine the pull values;
- **Response Acquisition.** At this stage, the simulator converts the values defined by the operator into the parameters "initial pull" and "block pull";
- **Pull Execution for Each Active Window.** The pull is then properly executed, pulling the trucks for each active window at that moment.

Two operation models were also developed to define the pull methodology. The first model, titled "guided pull," presented in Table 1, defines a guide for the initial pull and block pull parameters based on analyzing actual pull data performed at the port. This model determines predefined values for the parameters "initial pull" and "block pull" according to the number of docked ships in operation and the number of windows open simultaneously per ship. These values were empirically defined by professionals working at the Itaqui port.

Table 1: Operation model for a port-driven pull system.

Ships	Open windows	Initial pull	Blocking pull
1	1	15	60
	2	9	30
	3	6	20
	4	5	15
	5	5	12
2	1	15	30
	2	6	15
	3	5	10
	4	5	8
	5	3	6
3	1	8	20
	2	6	10
	3	5	7
	4	5	5
	5	3	4

The second model, titled "minimum pull," always performs the smallest possible pull that guarantees the correct execution of port operations. This model relies on two input parameters: "minimum queue size at the dockside" and "maximum queue size at the dockside." The queue at the dockside defines the number of trucks that are either using a collector, waiting for one, or moving towards one. Thus, the model always tries to pull the smallest possible value within the range defined by these parameters.

3.3.4 Simulation's Flow Model

The simulation flow, presented in Figure 6, was created from the truck and ship flow models and the resource and window managers. This flow integrates all the system's elements, allowing for a holistic analysis of port operations. It enables the simulation of various scenarios, including changes in the number of ships, types of cargo, truck availability, and operational conditions. The simulation model encompasses six main managers:

- **Service Manager.** Controls all services and other managers. In addition to initializing each manager's operation, it manages the creation of clients for the simulation, updates the simulation parameters throughout its execution, controls the

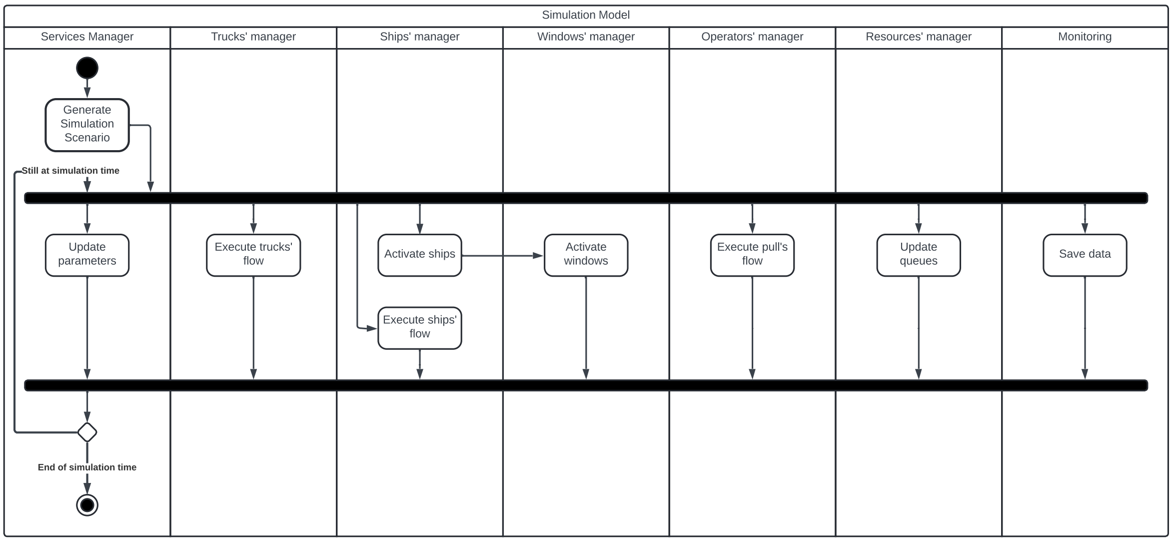

Figure 6: Simulation model.

simulation time, and ensures the program concludes once the maximum duration of operations is reached.

- **Truck Manager.** Responsible for ensuring that each truck follows the flow presented in figure 3 correctly, as well as generating and activating new trucks when necessary.
- **Ship Manager.** Responsible for executing the flow of each ship throughout the simulation and managing its products.
- **Window Manager.** Controls and defines which windows enter and exit activity.
- **Operator Manager.** Responsible for executing the pulls throughout the simulation based on the operator modeling described in Section 3.3.
- **Resource Manager.** Controls the use of scales, gates, and collectors throughout the operation and is crucial for sending messages for their monitoring.

Monitoring. Responsible for observing the simulation and storing the state of each truck, ship, resource, and port region. It is essential to save the simulation results, provide important data to all other managers, and ensure smooth operations.

The simulation model comprises two main activity groups: the first is the initialization of the simulation context, in which all managers start their processes, and the second is the simulation execution, where all managers perform their activities in parallel within a loop as long as the simulation time has not finished.

3.4 Simulation System Development

The simulation models for the Port of Itaqui were implemented using SimPy (Simpy, 2024), a Python library designed for discrete-event simulation. Each main model—truck flow, ship flow, and resource management—was structured as a separate process within SimPy. The truck flow model simulates the movement of trucks through various stages, such as waiting in the external yard, weighing, and cargo collection at the dock. Resources like scales and collection points were modeled using SimPy's Resource class, ensuring that multiple trucks or ships can interact with these limited resources realistically. The simulation uses Python generator functions to manage parallel activities, allowing trucks, ships, and other entities to progress simultaneously through their respective stages. SimPy's real-time event scheduling enables precise control over these operations, adhering to constraints like waiting times and resource availability.

Additionally, verification and validation routines were implemented to ensure model accuracy. This included comparing the simulation results with historical data from the Port of Itaqui and conducting sensitivity tests to understand how changes in key parameters impact system performance.

The resulting simulation system allows for the analysis of port operation flows and provides a platform to test interventions that can improve efficiency, reduce congestion, and optimize resource management at the port.

4 RESULTS AND DISCUSSION

In this section, the results obtained from the simulation of the pre-determined scenarios will be presented and discussed. The main objective is to evaluate the impact of the controlled variables on truck flow and identify potential bottlenecks in port operations. The simulation was structured to test various parameters, such as event timing, pull control, and resource capacity, considering different operational conditions.

Each simulation generates, as its final result, a multi-page spreadsheet that covers various aspects of port logistics. The spreadsheet was built based on the simulation models and presents the following information:

- **Truck Flows.** Contains the complete history of truck flows within the port, covering each step taken by each truck. It also tracks all stages of the logistical process, including weightings, entries, and exits from specific port areas;
- **Pulls.** Lists the number of trucks pulled within time windows, relating them to the ship, client, and product. It also provides information on the "initial pull" and "blocking pull" parameters applied by the operator, as well as the status of trucks in the unloading areas;
- **Delays.** Records truck delays at different stages of the carousel;
- **Trucks per Area.** Monitors the number of trucks in each area throughout the truck flow;
- **Trucks per Ship.** Displays the distribution of trucks by ship in the primary area and overall port flow;
- **Scales, Access Gates, and Scanners.** Details the queue waiting time and processing time in the main operational areas of the port.

The simulator has important base configurations that are valid for executing all simulation scenarios presented in section 4.1. These include the total simulation duration—configured for 48 hours, the base time unit, i.e., the discrete-time interval advanced at each step of the simulator—set to 1 minute, the number of clients and trucks per client—configured to 4 and 30, respectively, the number of ships docked at the same time, the number of products loaded by each ship, and the number of active windows per docked ship—configured to 1, 2, and 5, respectively. Finally, the base configuration for port resources includes determining the number of scales in the Truck Retention Yard (TRY) and the Primary Area (AP), both of which are set to 2. Additionally, the number of grab cranes per ship is set to 1. This configuration is parameterized and serves as a common context for various simulation scenarios.

4.1 Discussion Analysis of Simulation Scenarios

To analyze the behavior of truck flow in the port area, a systematic variation of 8 parameters was proposed:

- Availability of trucks to be pulled;
- Number of docked ships;
- Number of active windows per docked ship;
- Availability of scales along the port flow;
- Availability of grab cranes;
- Minimum percentage of truck overload;
- Minimum percentage of truck delays for each stage of the flow;
- Minimum and maximum limits for pulls in the minimum pull model.

The following results are from different simulation scenarios executed on an Intel® Core™ i7-12700F computer with 32 GiB of RAM. For each variation, it is important to observe and understand how each one affects the duration of truck flows, the unloading rate of products from each ship, and the presence of bottlenecks throughout the carousel.

4.1.1 Number of Ships Docked and Active Windows per Ship

As presented in the conceptual model, the guided pull model depends on the number of ships docked and active windows per ship. Thus, to validate the influence of this model, the parameters for the number of ships docked in the port and the number of open windows simultaneously per ship vary from 1 to 3 and from 1 to 5, respectively. The simulations produced the results presented in this section from the variation of these parameters.

Figures 7, 8, and 9 display the average number of trucks in the primary area and its respective subregions over the entire simulation period, which was divided into 10-minute intervals. This data corresponds to scenarios with one, two, and three ships docked at the port. This allows for a clear observation of how guided pull affects port activities.

In all three figures, seasonality is evident, characterized by smaller peaks and valleys throughout the operations. This pattern arises from the cyclical nature of truck and ship movements, which occur periodically. The primary factor contributing to this periodicity is the pull operation, which activates groups of

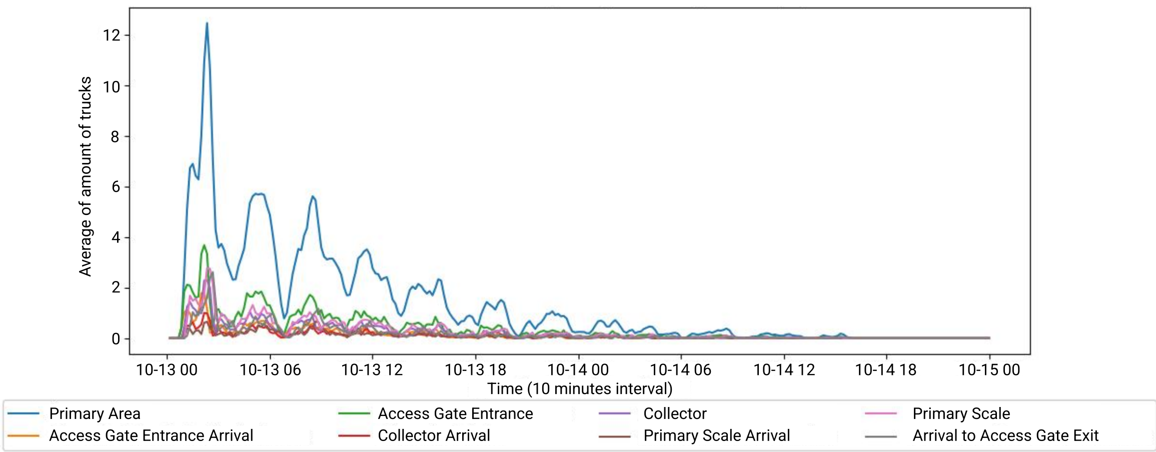

Figure 7: Average of the amount of trucks per region through time for 1 ship.

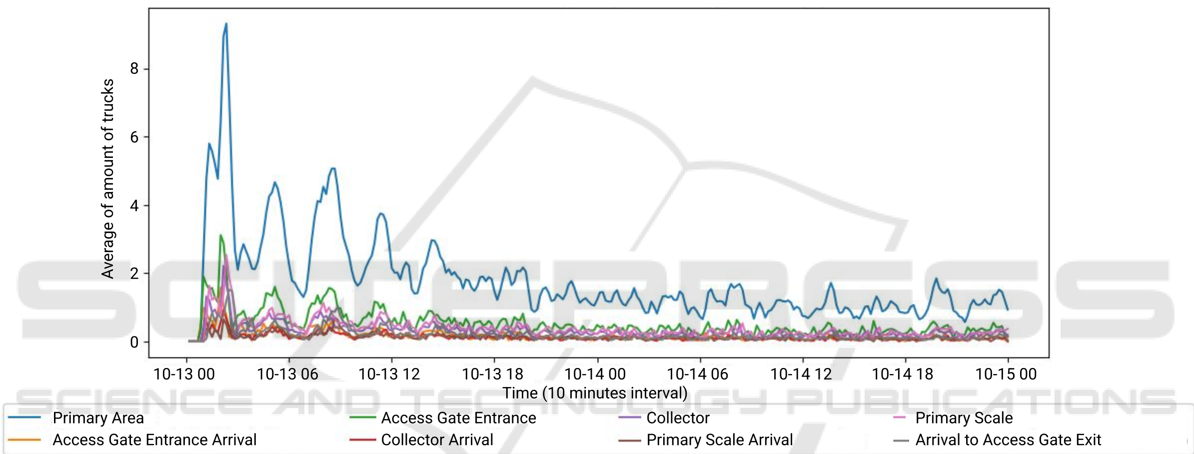

Figure 8: Average of the amount of trucks per region through time for 2 ships.

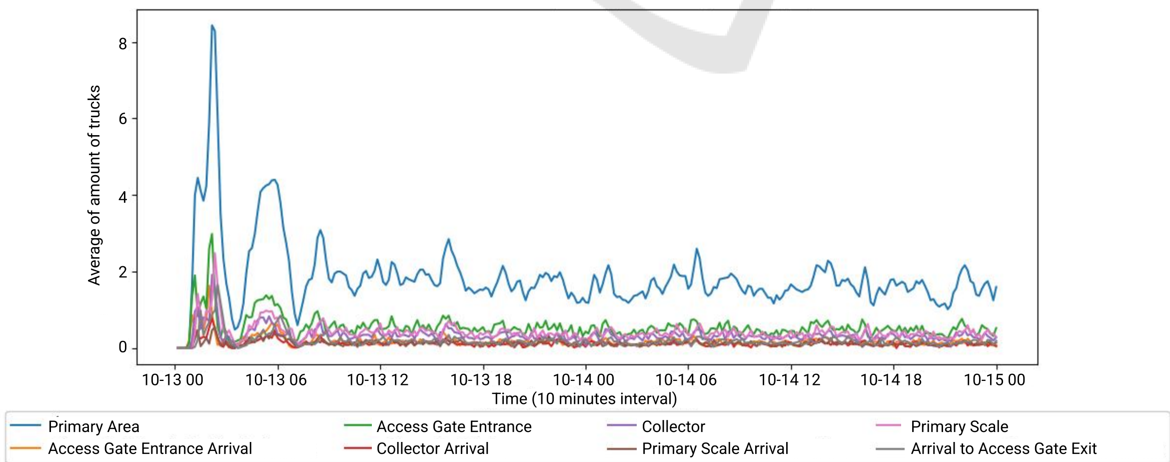

Figure 9: Average of the amount of trucks per region through time for 3 ships.

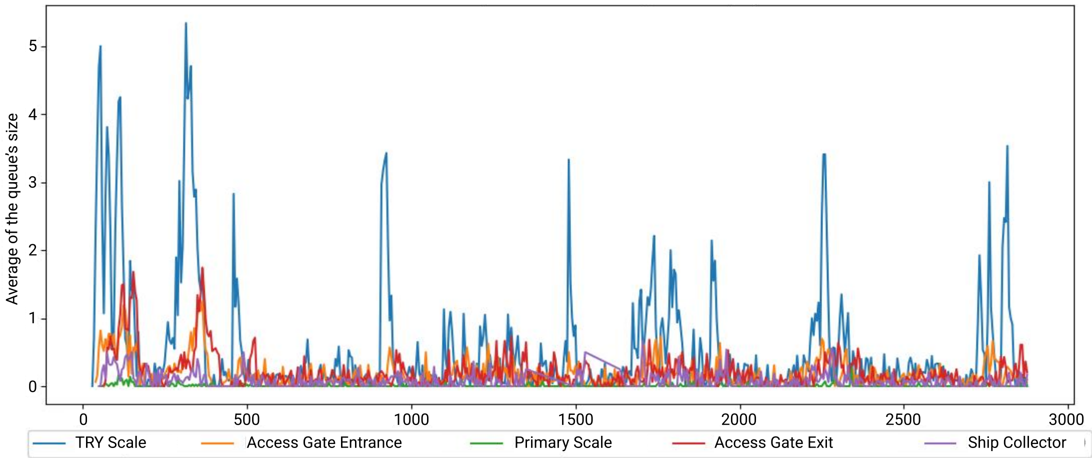

Figure 10: Average of the queues' size per resource through time for 3 ships.

trucks. These trucks move together in a coordinated manner through the carousel, creating a "burst" effect in their movement.

At the beginning of operations, many trucks are concentrated in the primary area. However, by the end of the process, there are few or no trucks remaining. This change occurs due to the flow of ships; once they deliver their cargo, they depart the port to make space for incoming ships. As a result, there is a temporary decrease in port activities.

In Figure 7, we observe the behavior of port operations when only one ship can dock at a time, highlighting the variation in the number of active windows available simultaneously. Towards the end of the graph, it becomes evident that no more trucks are in the primary area, as all windows have been filled. This indicates that no additional products will be delivered, leading the ship to leave the port and resulting in a prolonged period of idleness. This situation is undesirable because it not only limits service to a few ships at a time but also extends the waiting period for the arrival of new ships. Consequently, this increases overall operational costs by delaying service to vessels and the delivery of products to customers.

Figures 8 and 9 illustrate the port regions when two and three ships are docked, respectively. In both scenarios, the operations remain active throughout the simulation period. This suggests that even when all tasks for a ship are completed, there is only a temporary reduction in activities, which is clearly evident in Figure 8 and more subtly in Figure 9. The key takeaway is that the port is better equipped to meet customer demands and maintain continuous operations when multiple ships are docked simultaneously.

In all the scenarios presented, it is evident that no sub-region within the primary area reaches four trucks. This suggests no significant bottlenecks in these port areas for the scenarios examined. The queues' sizes for each port resource were analyzed to assess potential congestion in the port regions. Figure 10 illustrates the average queue size over the simulation period, recorded every minute, for each scale, gate, and collector present in the port during the scenario with three ships docked.

Among the presented resources, the scales in the truck retention yard are the only ones that show a larger queue size, indicating a bottleneck point that can be observed. The other resources present in the primary area align with the behavior presented in Figures 7, 8, and 9, as they do not show considerable queues. Thus, it becomes evident to identify idleness and congestion in port activities through the simulation and variation of the number of docked ships and active windows.

4.1.2 Variation of Input Values for the Minimum Pull Model

As presented in the conceptual modeling, the minimum pull model depends on the variation of parameters, such as the minimum and maximum queue sizes in the quay area (collection region). Thus, to validate the influence of these aspects, these parameters were varied in intervals of 1 to 10 and 10 to 20, respectively. Through these configurations, the simulations produced the results presented in this section.

Figures 11, 12, 13, and 14 illustrate the average number of trucks in the primary area and surrounding regions throughout the entire simulation, which was divided into 10-minute intervals. This analysis pertains to a ship docked at the port with five active windows. Figures 11 and 13 showcase the port's behavior according to the minimum pull method. In contrast, Figures 12 and 14 highlight the effects of the guided pull method. This allows for comparing the two pull methods, outlining their advantages and disadvantages for the port.

In Figures 11 and 12, the standard seasonality present at the port remains evident. However, larger variations between peaks and valleys are observed in the first figure compared to the second. This occurs because in the second figure — where the guided pull model carries out the pulls — the trucks enter operation more uniformly due to the consistency of the pull method. Another important factor is the difference in the number of trucks in the “Exit Access Gate (Client)” area, representing the number of trucks delivering products unloaded from the ships. This difference arises again due to the difference in pull patterns. In Figure 11, where the pulls are performed by the minimum pull model, the model determines that the minimum required value of the “initial pull” parameter for port operations to be correctly executed must be higher at the beginning of operations. On the other hand, since the model considers the current state of the port in the primary area, there is more significant fluctuation in the values of the pull parameters, which is why there are moments with few or no trucks in operation.

Based on the behaviors shown in both graphs, it can be concluded that the minimum pull model serves windows more efficiently. In Figure 11, port activities are completed, while in Figure 12, they are still ongoing. Additionally, the significant difference in the number of trucks delivering products to customers between the two graphs further supports this conclusion. Figure 11 shows a considerably larger number of deliveries occurring in a short period. Therefore, the minimum pull model proves to be an effective strategy for managing port operations.

As the minimum queue size at the quay increases, certain behaviors persist, as shown in Figure 13. This figure is characterized by the minimum pull model, while Figure 13 is characterized by the guided pull model. There are two subtle differences between the graphs in Figures 11 and 12 that are important to highlight for the minimum pull model: first, in Figure 13, the number of trucks accumulating in the area approaching the truck retention yard (TRY) is lower; second, the time required to complete the active windows is slightly shorter. These two factors suggest that fewer trucks remain in the truck retention yard despite minor fluctuations in the number of trucks in the primary area and deliveries to customers. This allows for greater continuity in the operational flow. However, it is crucial also to analyze other factors, such as idleness and the service distribution for active windows.

The differences in fluctuations between the two curves are significant, as shown in Figures 13 and 14. The first graph shows noticeable instances where no trucks are in the primary area. This suggests that the pull methodology used experiences various periods of idleness, indicating frequent drops in delivery volume. In contrast, the second graph displays more periodic and predictable behavior. It is more uniform and shows a higher level of continuity in port activities. Therefore, although deliveries may be completed later, the guided pull model ensures that the port remains consistently active.

A significant difference between the two approaches is evident when examining how services are distributed to the windows. The minimum pull model completes all activities sooner but experiences substantial fluctuations in the number of trucks delivering to customers, which occur sporadically and unevenly, as shown in Figures 11 and 13. This indicates that windows are served in an unequal and sequential manner. In contrast, the guided pull model, illustrated in Figures 12 and 14, distributes trucks more evenly across the windows.

This analysis highlights the key factors that influence the minimum pull method, its effects on port activities, and its advantages and disadvantages compared to the guided pull model. While the minimum pull method is more efficient regarding operational time at the port, it often leads to idle periods and results in uneven fulfillment of port activities.

5 CONCLUSIONS

The results from the simulation of truck flow during ship unloading at the Port of Itaqui highlight the significance of effective resource management in reducing operational bottlenecks. Variations in factors such as the number of trucks at docked ships and the availability of scales and loading arms directly affect the unloading rate and the time trucks spend at the port. It was observed that an overload of trucks, delays, and poor distribution of activities within the port significantly worsened congestion, negatively impacting logistical flow and overall operational efficiency. The simulation proved to be an effective tool for predicting and adjusting critical variables, allowing for developing strategies that enhance operational capacity without compromising efficiency and safety in port operations.

For future improvements, it would be beneficial to include interruption events in the simulation, such as equipment failures or adverse weather conditions, as these factors can significantly affect the efficiency

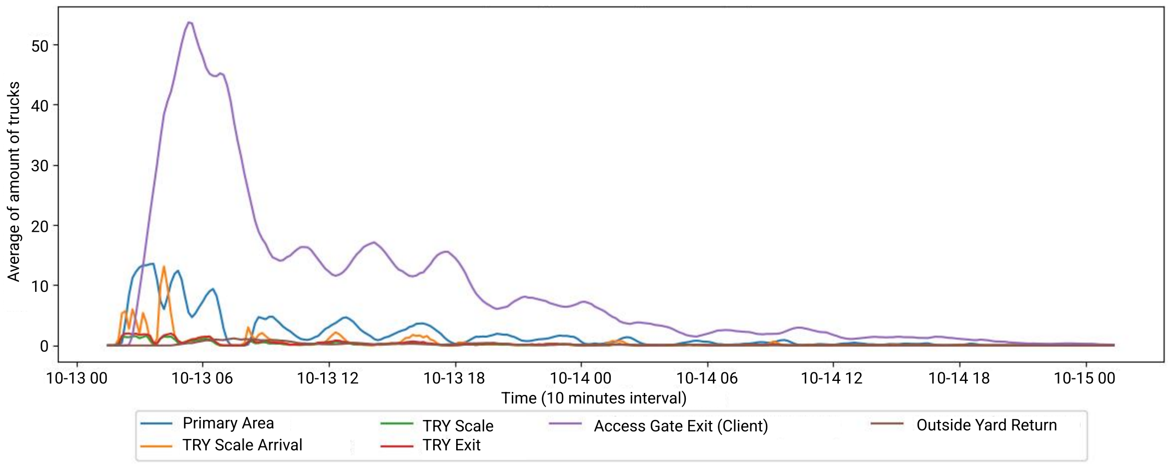

Figure 11: Average of the number of trucks per region through time for minimum queue size equals 1 for the pull min model.

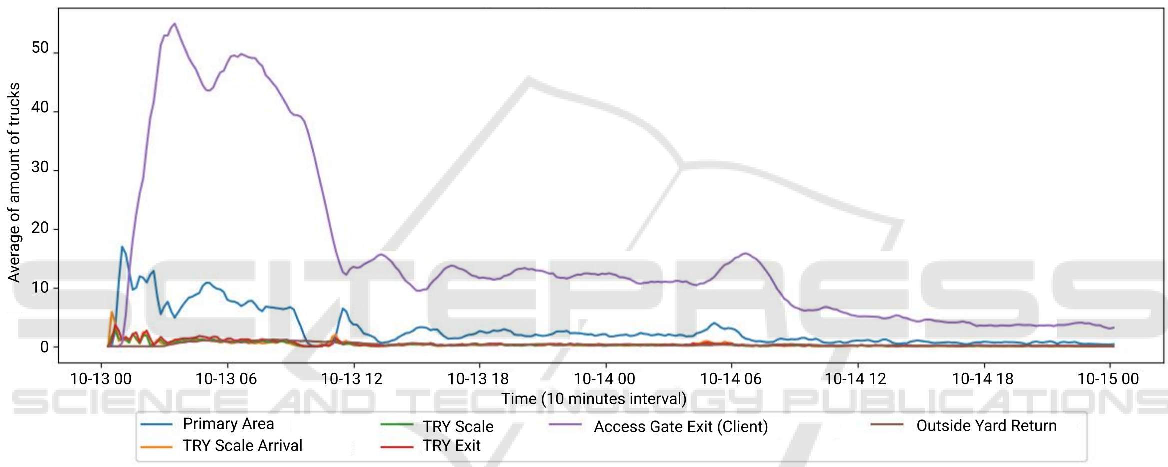

Figure 12: Average of the number of trucks per region through time for minimum queue size equals 1 for the guided pull model.

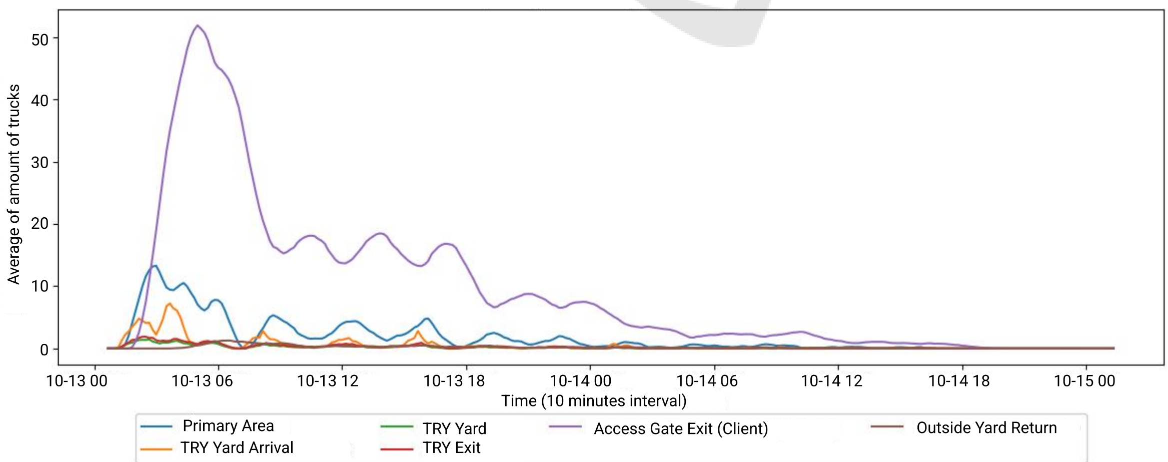

Figure 13: Average of the number of trucks per region through time for minimum queue size equals 10 for the pull min model.

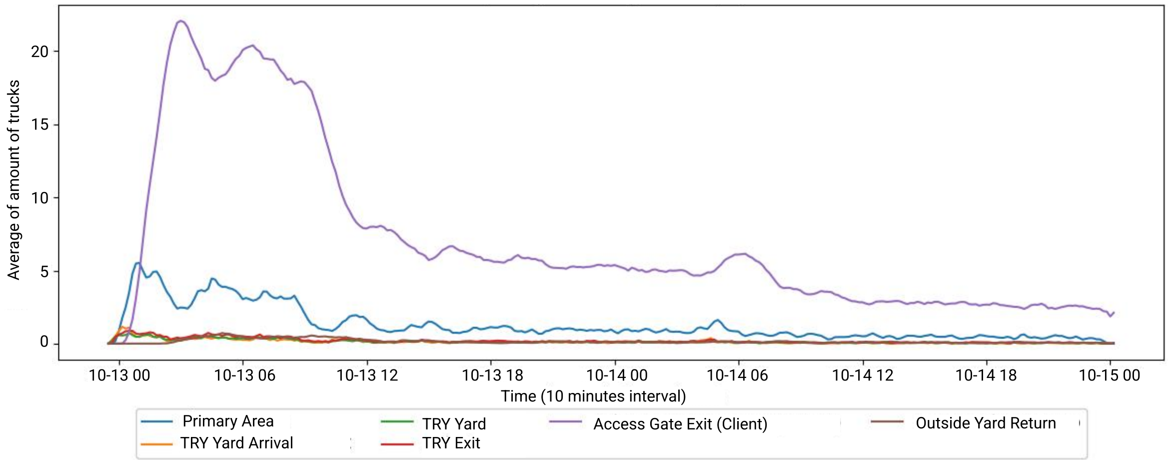

Figure 14: Average of the number of trucks per region through time for minimum queue size equals 10 for the guided pull model.

of port operations. Additionally, an important advancement would be to develop an interactive simulation with a graphical interface that allows operators to monitor progress in real time and adjust operational variables as needed. Expanding the guided pull concept to accommodate more ships and multiple operating windows would also enhance the model's applicability in more complex scenarios.

Additionally, it would be helpful to expand the pull operation models to include various strategies that can address different scenarios, such as changes in truck demand and new allocation policies. Another important consideration is integrating additional metrics into the simulation. This should encompass operational costs, environmental impacts (like pollutant emissions), and maintenance expenses to analyze port operations comprehensively.

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