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Port Access Fluidity Management during a Major Extension Project: A Simulation-Based Case Study

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Abstract: The increasing demand for freight services and the use of larger vessels to meet this demand has led to challenges related to storage space and logistics activities, highlighting the need for improvements in port infrastructure for better logistics management. At a crucial phase in its growth, the Port of Trois-Rivières in Canada is planning a major expansion, including the construction of a new terminal to enhance its hosting capacities and freight services. This expansion faces potential access congestion problems during the planned construction, exacerbated by the port's urban setting. In response to the needs identified by the port authorities for this event, the study's objective is to assess the implications of increased construction and freight truck flows on access gate fluidity and the impact of additional access infrastructure investment to mitigate potential congestion. These evaluations aim to define effective access management strategies throughout the construction period of the new terminal. To address these complexities, our approach is based on scenario analysis in variants co-constructed with the partner. These scenarios are evaluated using simulation models, configured according to parameters calibrated with a granularity that allows congestion detection. The results enabled an evaluation of the capability of existing and potential gates to manage access. Subsequently, recommendations were shaped in accordance with the expected objectives to manage access traffic effectively. These recommendations concern the optimization of construction activity planning, the layout and planning of access, and the importance of enhanced collaboration between municipal and port authorities for more controlled road traffic management. Recognizing the importance of synchromodality, road network centrality management, and the outsourcing of capacity through inter-port cooperation and with dry ports to manage congestion, these tools will be discussed in this work. The study proposes an approach that reconciles scientific rigor with the implementation constraints of the proposed solutions, allowing this study wider applicability in various port contexts facing challenges in this field of study.

Keywords: capacity expansion; fluidity access management; simulation modeling; scenario analysis approach

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1. Introduction

In the realm of global trade and industry, port expansion is a critical response to the escalating demands of a growing economy. This expansion typically entails challenges like accommodating larger vessels, increased cargo volumes, and intensified vehicular traffic, all of which can put considerable pressure on the existing port infrastructure. These general issues are prominently observed in the case of the port in Trois-Rivières, Canada. Here, the burgeoning industrial sector has significantly heightened the need for more robust freight services. Addressing these concerns, port authorities are planning a new maritime terminal, projected to boost operational capacity. The new terminal stands as a pivotal element in the port development plan. This terminal is set to increase the overall port's capacity by nearly 50%, a port already operating at its maximum capacity amid a growing demand from companies eager to utilize its services to access international markets. With the addition of 716 m of quays and nearly 100,000 m² of surface area located to the West of the existing facilities, as illustrated in grey in Figure 1, this project signifies a substantial expansion of the port's capabilities. This development, while crucial for expansion, raises issues of congestion and pollution during construction, necessitating thorough assessment of the port's access infrastructure (i.e., gates).

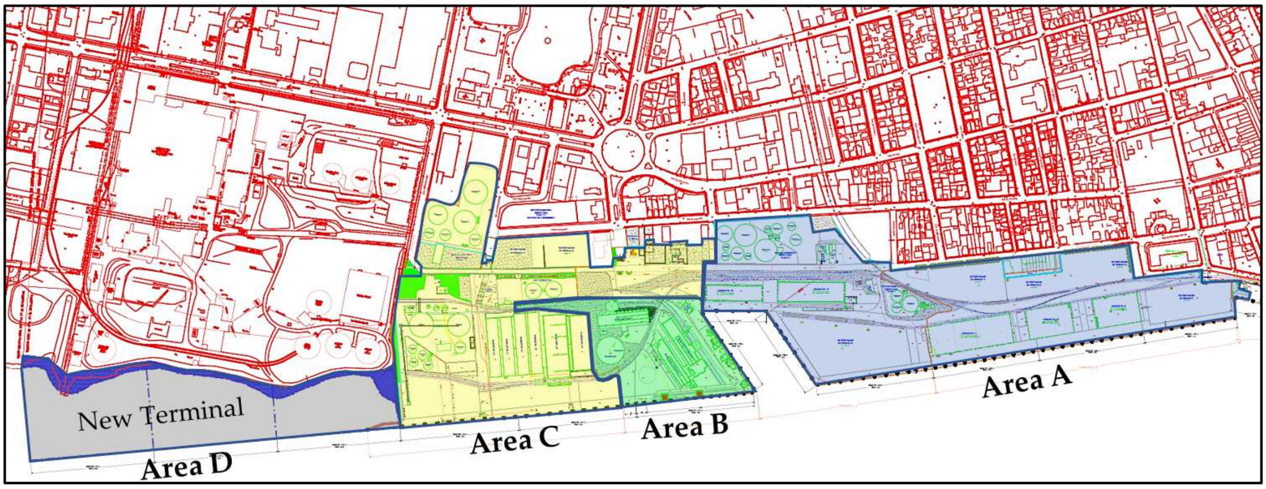


Figure 1. Overview of the Trois-Rivières port and its different areas (source: Port Authority of Trois-Rivières).

Responding to the specific requirements highlighted by the Port Authority, this study is meticulously crafted to thoroughly assess the implications of increased truck flows attributable to construction activities, as well as the impact of incorporating additional access gate infrastructure. The significance of such an evaluation cannot be overstated, as it is crucial for the formulation of efficient access management strategies, which are imperative during the construction phase of the new terminal. To navigate these complexities, our methodology employs a comprehensive integration of scenario analysis and simulation modeling, drawing on queuing theory. This approach leverages parameters extracted from real-world data with a level of granularity that significantly enhances the accuracy of congestion forecasting. Developed in close collaboration with the Port Authority, this framework is specifically designed to effectively address congestion management, ensuring that the terminal expansion project proceeds with minimal disruption to port operations and lays the groundwork for improved future capacity and efficiency.

This study elucidates two key findings: firstly, that access gate possesses the capacity to accommodate the surge in truck traffic during the construction phase, and secondly, that there is an imperative need to elevate the efficiency of unloading operations at the proposed new terminal as a strategic measure to alleviate urban congestion and diminish environmental impacts. Achieving this necessitates deploying optimization configurations tailored to the unloading timelines and the concurrent unloading capacity of trucks, derived from meticulously designed scenarios. To further enhance the accessibility and streamline traffic flow, the implementation of a peak-time appointment system is advocated, underscored by the necessity for enhanced collaborative efforts between city and port authorities to ensure more effective traffic governance. Our methodology integrates scientific research with practical applications to address a range of port-related challenges effectively. The discussion section emphasizes the pivotal role of synchromodality, road network centrality management, and capacity outsourcing in mitigating port congestion issues. Using sophisticated simulations and data analytics, our study presents actionable solutions for ports grappling with urban congestion, offering a cohesive strategy for enhancing access and logistics efficiency.

2. Literature Review

The history of the capacity expansion of the Trois-Rivières Port has been influenced by various events and developments due to various factors. Situated at the confluence of the Saint-Maurice and Saint-Laurent rivers, the port's fortunes have been closely tied to the economic conditions of the surrounding industries and forestry in the Mauricie region [1]. The port has faced competition from neighboring ports, such as Montreal and Quebec City, which have bigger infrastructure and serve larger and more prosperous demographic areas [2]. Moreover, the opening of the Saint Lawrence Seaway in 1959 increased the port's role in the transshipment of grains, but it now faces competition from ports better equipped for grain handling or benefiting from the expansion of Asian markets [3]. Detailed analysis of the port's traffic during the 1961–1970 period has been conducted, providing insights into its challenges and potential solutions [4]. The current port capacity increased from 400,000 tons in 1970 [4] to 4.3 million tons in 2022 (https://porttr.com/bilan-2023-un-tonnage-stable, accessed on 26 December 2023). These factors have shaped the capacity expansion of the Trois-Rivières Port over time.

Addressing congestion in ports often involves improving their capacity. This section looks at strategies to maintain smooth access and tools to assess and better these strategies. We conclude by sharing our unique insights, especially on how ports might face congestion when planning major construction projects.

Ports play a pivotal role in both global and local commerce, orchestrating the flow of a vast array of cargo types through complex operational frameworks. Fleming et al. [5] highlight the indispensable role that seaport terminals occupy within the supply chain ecosystem, emphasizing the significant impact of their operational efficiency on broader logistics networks. The capacity of ports is determined by several critical factors, including the availability of berths, the ports' ability to manage incoming truck traffic, the efficiency of access gate throughput, and the overall performance of freight services. In [6,7], the authors identified that port capacity is frequently constrained by the least efficient among these components. One of the foremost challenges in this operational milieu is the congestion experienced at access gates. This issue stems primarily from two factors: the lack of sufficient capacity to accommodate rising truck volumes and operational inefficiencies within port freight operations, as discussed in [8]. Moreover, the issue of landside access to cargo terminals presents a substantial obstacle for modern port planners, a concern that has been documented in [9]. In response to these critical bottlenecks, especially prevalent in urban ports, a plethora of studies have introduced various analytical tools aimed at dissecting congestion patterns and pinpointing their root causes. This analytical approach facilitates decision makers in devising strategies to mitigate the adverse effects of these congestive bottlenecks effectively.

Simulation stands as the predominant method in modeling flow systems within logistics, closely aligning with queueing theory principles. However, the accuracy and utility of the results hinge critically on the precise definition of parameters—to accurately mirror system behavior—and the thoughtful design of scenarios, ensuring the generation of meaningful outcomes. For analytical needs or parameter determination, simulation models can be part of complex frameworks that incorporate mathematical models, heuristics, or machine learning models. Dragovic et al. [10] identified, in the port industry, 226 articles on simulations, highlighting the extensive use of discrete-event simulation, particularly in containerized ports. Vadlamudi et al. [11] promote expanding research supporting a comprehensive strategy towards sustainable mobility and congestion issues.

Concentrating on the challenge of access fluidity, certain investigations demonstrate that enhancements can be achieved by making improvements directly at the access gates, while other studies suggest that issues with fluidity stem from inadequate levels of freight service. This nuanced understanding highlights the multifaceted nature of access issues, pointing towards a combination of gate-level modifications and service-level upgrades as potential solutions for improving overall system efficiency.

Chamchang and Niyomdecha [12] conducted a study at Songkhla Port, Thailand, employing a simulation grounded in queuing theory to investigate strategies for enhancing service in light of rising truck traffic. Evaluating five scenarios for gate performance and considering different vehicle types, they focused on metrics such as truck waiting times and queue lengths, demonstrating significant improvements over current operations. The results showed that gate sharing and the separation of certain processes effectively managed congestion at a lower cost, mirroring the benefits of lane expansion. Other studies examine the correlation between congestion at access gates and the level of service within the port. Li et al. [13] develop a hybrid simulation model, combining the Dynamic Geographical Model and Discrete-Event Queue Model, for landside port planning. This approach integrates traffic-flow modeling with discrete-event simulation to evaluate traffic conditions across different hypothetical scenarios. The study specifically addresses the complexities faced by real-world bulk cargo ports operating under constrained traffic regulation.

Palmer Jr et al. [9] pinpoint a research gap where traffic analysis and port efficiency are treated separately rather than recognizing their interdependence. They create a hybrid simulation that combines traffic flow with discrete-event models for integrated analysis. This innovation improves intersection management in complex settings, highlighting the vital connection between port operations and traffic conditions, and advocates for a unified strategy to enhance traffic and port efficiency. Furthermore, the authors advocate for more holistic modeling tools that encompass solutions derived from a thorough examination of all port environment components. In their research, they create TRUCKSIM, a dynamic model for analyzing port land access challenges. This hybrid tool evaluates transport policies and infrastructure enhancements by merging different analytical methods. Applied in Long Beach and Hawaii ports, TRUCKSIM assesses the effects of mixed traffic, trucking policies, and rail and road upgrades, proving its efficacy in boosting transport efficiency. Notably, it is a comprehensive simulation technology. Its use in comparing 2020 scenarios at the Port of Long Beach confirmed its value for port planning and operational improvement. Mark and Kemp [14], in the same vein, refine port capacity analysis by substituting traditional formulas with simulation models that encompass berth, yard, gate, and Automated Guided Vehicle operations, offering a detailed and accurate approach to evaluating port functions. These models simulate the entire port interaction cycle—from ship arrival to departure—offering precise insights into capacities, throughput, and operational efficiencies. This approach addresses the volatility of empirical methods, providing a dynamic and accurate framework for understanding port operations and capacity. Nevertheless, modern approaches are integrating advanced analytics to transition ports into intelligent, interconnected hubs by leveraging novel data sources for enhanced logistics simulation and planning. Lakhmas [15] introduces a simulation model for the Tanger Med Port to optimize vessel scheduling and minimize congestion, highlighting the use of Automatic Identification System data for predictive planning and smart technology integration to streamline port operations.

Beyond enhancing operational efficiency and gate infrastructure, as mentioned before, a major focus in the literature is on managing truck arrivals [16,17]. The literature emphasizes managing truck arrivals to improve port operational efficiency, especially in non-containerized ports, where unpredictable arrivals and long waiting times are common due to the challenges of handling bulk materials. The authors of [9,18] underline the complexity of planning in these ports, affected by varied cargo types, more unpredictable ship arrivals, weather conditions, and the need for diverse equipment, in contrast with container ports. Efforts to mitigate landside congestion focus on increasing port capacity and enforcing truck arrival policies, aiming to streamline operations and reduce congestion. Furthermore, research has evolved to create models for predicting truck arrival times and container pick-up schedules, employing multi-objective optimization strategies to enhance intermodal transport's contribution to port efficiency [19]. Kourounioti and Polydoropoulou [16] link unsystematic truck arrivals to increased seaport gate congestion. Meanwhile, Huynh, and Walton [20] recommend mitigating this by scheduling truck appointments. A shift towards static and real-time appointment systems has been shown to significantly ease gate queues [21]. This approach, validated in various global ports [8,22–24], demonstrates the effectiveness of appointment systems in reducing congestion.

In addressing landside congestion, a critical aspect is the assessment of port performance using various metrics. These include average and standard deviation of the truck queuing times, server utilization, maximum queue length, gate service time, gate utilization rates, and truck turnaround time [5,21,25]. Kim et al. [26] highlighted the waiting time of heavy vehicles as a key customer service indicator; however, truck turnaround time is considered as the most telling land-side performance metric [27,28]. Brooks and Schellinck [29,30] emphasized the need for reliability measures in port services, particularly regarding truck turnaround times, a gap that still exists in current research. These metrics are essential for a comprehensive approach to congestion management, providing a robust framework for evaluating the effectiveness of various strategies and solutions in improving port operations and mitigating congestion. Integrating these insights into our methodology ensures a nuanced and effective assessment of port performance during terminal construction.

The shortcomings highlighted in this review, especially in the nuanced modeling of non-containerized general cargo ports in urban settings and the identified scarcity of studies on truck congestion at bulk cargo terminals—an issue growing in importance due to its urban impact—have been noted [10,31]. Our study is focused on maintaining access fluidity during the construction of a new terminal, specifically examining access gates in a real-case context. Drawing on diverse research, we employ a spatio-temporal analytical approach that utilizes both finely tuned empirical parameters and simulations of dynamically constructed scenarios. This approach emphasizes our contribution to research on fluidity assessment amid significant disruptions in access flows.

The current study introduces three key advancements in port access management:

- Comprehensive Port Access Data Analysis: The work stands out by meticulously analyzing port access data, including vehicle type distinctions and the chronological sequencing of access operations. By capturing realistic time variations, we offer a detailed and accurate model for managing port access, particularly during construction phases.
- Refined Simulation Parameters: The approach used employs spatial and temporal dynamics in simulation configurations, allowing for an accurate representation of varying traffic and service levels across the port. This methodology effectively identifies peak and waiting times, enhancing the realism of truck arrival and departure simulations.
- Dynamic Scenario Design: This study leverages scenario-based planning coupled with stakeholder engagement to derive practical recommendations. This structured analysis progresses from basic assessments to complex scenario explorations, ensuring that recommendations are feasible and grounded in operational realities.

These streamlined points emphasize the study's innovative contributions to improving port access management through detailed data analysis, advanced simulation, and dynamic scenario construction. In the subsequent sections of the paper, Section 3 outlines the comprehensive methodology, Section 4 presents the results, and Section 5 concludes with key findings and actionable insights.

3. Materials and Methods

A comprehensive framework was developed to analyze access fluidity to the Port of Trois-Rivières during the construction of a new terminal intended to increase the port's capacity. Access fluidity, referring to the ease and efficiency with which vehicles, particularly trucks, can enter and exit a port, is a critical aspect of this study, as it directly impacts the operational efficiency and sustainability of the port. The framework combines simulation and a scenario-based analysis approach, which facilitates experimentation in various contexts of exploration, prediction, and optimization. Its components include data collection and processing, the design and implementation of simulation models, and design and experimentation with regard to scenarios. Factors influencing access fluidity include access infrastructure design, operational management within the port, the capacity to accommodate the number of trucks, and traffic management. To better understand the framework, it is important to first provide a brief overview of Trois-Rivières Port, as depicted in Figure 1. This port consists of a set of terminals that are categorized into different areas based on the types of goods they handle. These include the general cargo terminal (Area A), the grain terminal (Area B), and the liquid and solid bulk terminal (Area C). Currently, there are two access gates to the port: the main gate (MG), which has three entries and one exit, and the secondary gate (SG), which has one entry and one exit. Most cars and trucks pass through the MG and use the automatic entry mode with access cards either at the MG or SG. For those without access cards, a manual registration process is mandatory at the MG.

To increase the port's capacity, the port authority is planning a major expansion project through the construction of a new terminal over two years, which will result in a significant increase in traffic. To prevent construction trucks from waiting outside the port, a Kanban system has been implemented, capable of accommodating up to 15 trucks waiting for unloading in the construction area. Given this configuration of the port, we will tackle the components of the framework as described above.

3.1. Data Collection and Processing

Throughout this study, the port authority, referred to as "the industrial partner", actively participated in data communication and scenario design for evaluation.

3.1.1. Data Collection

Our industrial partner played a pivotal role in providing us with the necessary data to simulate the logistics activities related to freight and construction within the port. The data provided includes raw access data for entry and exit through the two active gates, such as the entry and exit time of trucks (time-stamped in 1 millisecond), truck and car IDs, maritime subcontractors, the destination terminal, and the type of goods handled by truck without automatic access cards, covering the period from 2015 to 2020. Furthermore, we requested additional data on the volume of freight and the total number of trucks per port area during this period. To forecast data on construction trucks, we relied on estimates provided by the industrial partner based on the civil engineering planning of such major works and experiences from previous construction projects held at the port. Surveillance videos from security cameras located at the MG and SG were utilized to perform time studies and measure service time for registering trucks and cars at the entry and exit of the access gates. Table 1 outlines the structure of the collected data.

Table 1. Summary of the collected data characteristics provided by the industrial partner.

Data Type	Observations and Attributes	Period
Vehicles access data	796,000 records with entry/exit time, vehicle type, destination, freight, subcontractors	2015–2020 (Selected period for analysis: 2017–2019)
Summarized activity data by port area	Tables with areas, load/unload quantities, truck count, and types of freight	
Access gate surveillance videos	96 h of streaming video from which was obtained the vehicle service time at gate	Four days of July 2019
Projected construction parameters	Civil engineering pre-feasibility study with a forecast of the number of construction trucks per day, unloading time, and the number of available unloading stations.	Construction period

3.1.2. Data Processing

The dataset showcased in Table 1 was subjected to a rigorous preprocessing phase aimed at eliminating outliers and records displaying anomalous values or inconsistencies. This was necessary to ensure the integrity of the analysis; as a result, data from periods affected by anomalies were discarded, focusing the study exclusively on the timeframe between 2017 and 2019. Utilizing this cleansed dataset, the port was subdivided into three distinct areas, each representing a specific destination area as explained above. This segmentation facilitated the tailored distribution of access data in alignment with these predetermined areas, from which simulation parameters were meticulously derived. This strategy, rooted in geographical analysis, sought to elucidate the dynamic fluidity inherent in each area's activities, offering insights into operational flow and efficiency.

Further, the study leveraged flow data targeted at each specific area to deduce relevant simulation parameters. These parameters included the Time in the System (TS) and the Inter-Arrival Time (IAT) as well as Access Registration Times (ARTs) for both entry and exit, derived accurately from surveillance footage of access gates for each vehicle type. This comprehensive approach not only enriches our understanding of port operations but also provides a nuanced framework for optimizing traffic management and operational planning based on real-world observations and data-driven insights.

- Segmentation of the Port into Four Areas

Historical data analytics revealed that only about a quarter of the accessed trucks had known destination areas, since this information is not registered for automatically accessed trucks. To overcome this limitation, a two-step approach was adopted. Firstly, the automatic trucks were manually assigned based on the maritime subcontractor's intervention area indicated in the historical access data. For trucks consigned by subcontractors operating in multiple areas (55%), Python programs were developed to randomly allocate them to areas A, B, and C based on the global annual truck allocation flow provided by the industrial partner. This process was repeated 50 times to generate 50 random allocation vectors. The percentage distribution of trucks according to the data provided by the industrial partner was 32%, 36%, and 32%, respectively, for areas A, B, and C. Area D corresponded to the new terminal scheduled for construction. Based on the cleaned data, historical records showed an average of 43,189 trucks and 107,890 cars per year. Table 2 illustrates the data structure by vehicle type (truck or car), by area, and by year.

Table 2. Distribution of vehicles (trucks and cars) by area and by year.

Area	2017	2018	2019	Total	%
A	13,511	13,493	14,918	41,922	32%
B	13,600	17,506	15,126	46,232	36%
C	14,845	15,366	11,202	41,413	32%
Total trucks	41,956	46,365	41,246	129,567	100%
Total cars	100,219	117,963	105,488	Avg: 107,890	-

- Time in the System

Given that our data were determined by area, exploring the distribution of TS by area and by hour proves that there were different profiles, as illustrated by Figure 2. This finding highlight spatio-temporal variabilities revealing intrinsic information that must be considered to better represent the vehicle behavior based on type, area, and entry time.

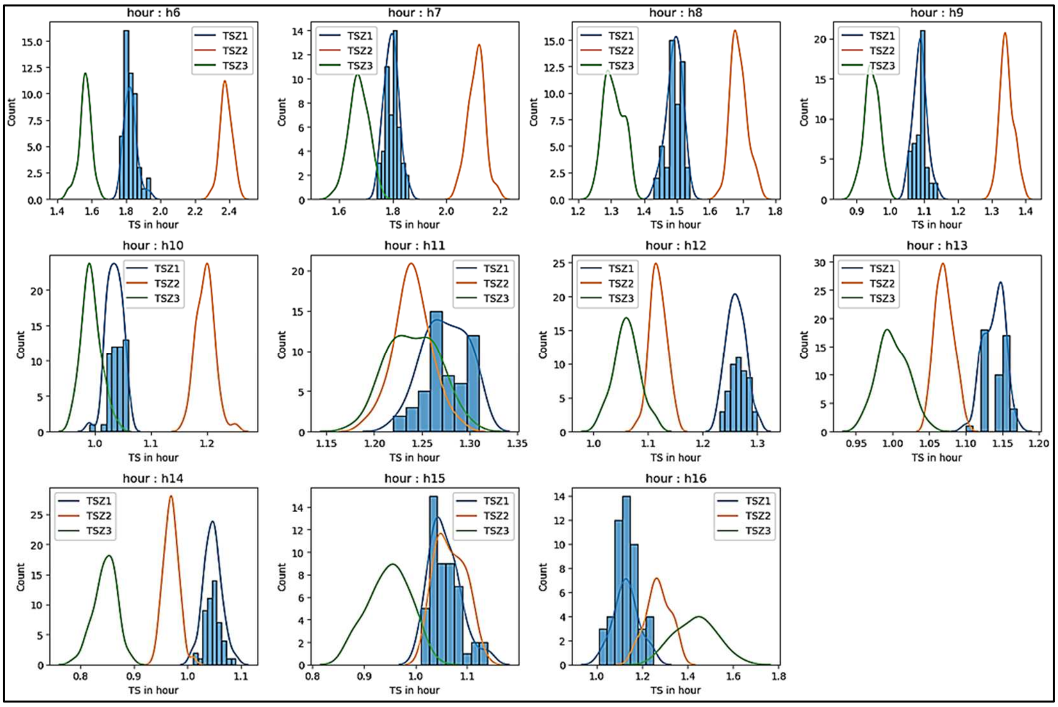


Figure 2. Hourly variability of TS across different areas from 6:00 to 17:00 (X h means the elapsed time between X and X + 1 h, TSZ1, TSZ2, and TSZ3 means TS in areas A, B, C).

It is worth noting that the shape of the distribution of TS varied in terms of amplitude and variability by hour and by area. To control this effect, a distribution of TS by hour and by area was chosen, and statistical transformations were applied to the data to fit the normal distribution when the initial distributions were beta, gamma, lognormal, or Weibull.

Figure 3 illustrates the relationship between TS and IAT, showing a slight tendency of decreased service levels (high TS) when arrival rates are high (low IAT). These insights are essential for understanding vehicle fluidity in relation to the service level of each area. This figure reveals two distinct patterns, distinguished by varying concentrations of data points. Observations with a TS of less than 5 h correspond to weekday freight operations, from Monday to Friday. In contrast, observations with TS times exceeding 5 h, up to 15 h, are attributed to trucks arriving overnight or to operations conducted on Saturdays and Sundays, as depicted in Figure 4. To mitigate the effect of this correlation, we retain the TS by hour, by area, and by vehicle type (trucks/cars) to accurately detect congestion at the access level.

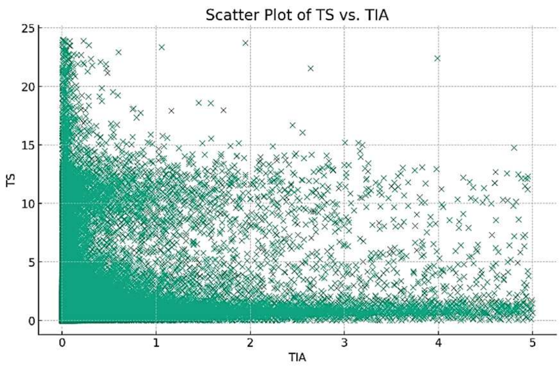
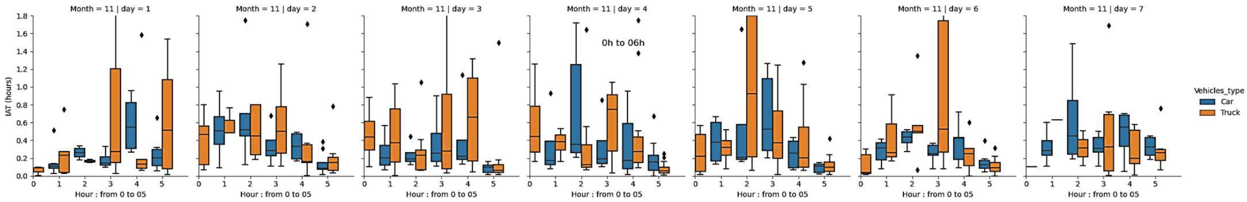
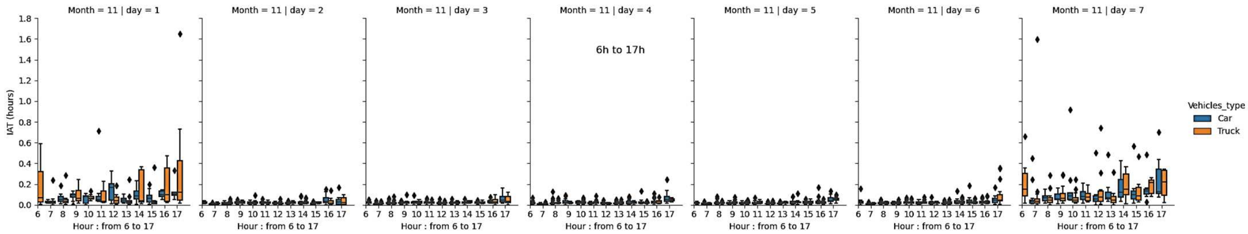


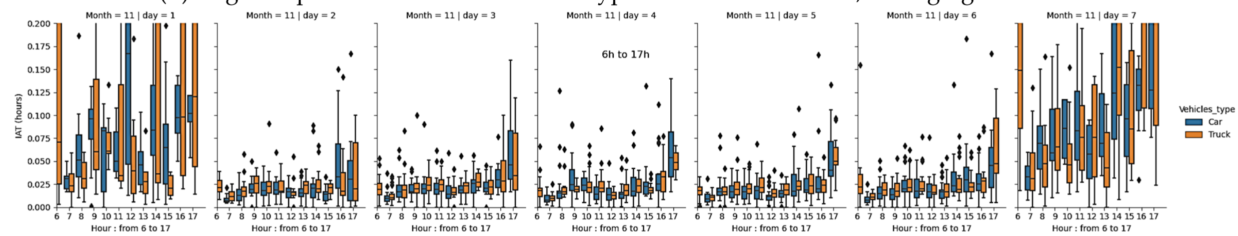
Figure 3. Correlation between TS and IAT for the period 2015–2019.



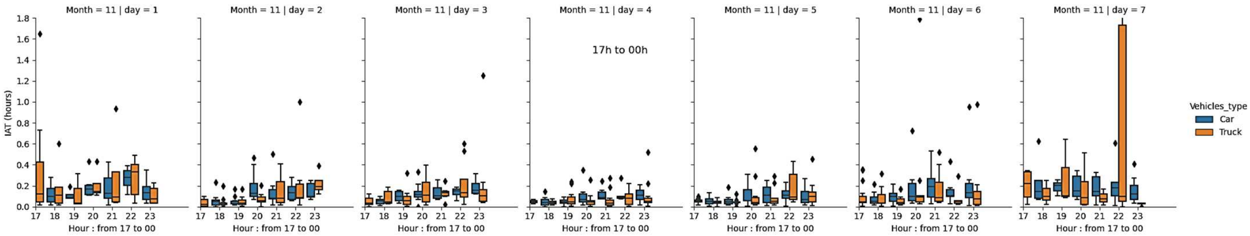
(**a**) Avg. IAT during 0:00–6:00 for a typical week in month 11 across 2017–2019.



(**b**) Avg. IAT per hour at 6:00–17:00 for a typical week in month 11, averaging 2017–2019.



(**c**) Zoom of Avg. IAT during 6:00–17:00 for a typical week in month 11 across 2017–2019.



(**d**) Avg. IAT during 17:00–00:00 for a typical week in month 11 across 2017–2019.

Figure 4. Selection of the Simulation Period: Monday through Friday, Based on TIA Variation as Illustrated in the Box Plot.

- Inter-Arrival Time

The analysis distinguishes between weekdays and weekends, and working hours versus off-hours, for the crowded month of November during 2017–2019. Through this analysis, we pinpointed a critical congestion risk between 6:00 AM and 5:00 PM. This timeframe is therefore the focal point of our traffic flow investigation, given its high congestion likelihood, as demonstrated in Figure 4. This figure uncovers three distinct traffic patterns throughout the day: a smooth flow from midnight to 6:00 AM, illustrated in Figure 4a; moderate fluidity observable from 5:00 PM to midnight, shown in Figure 4d; and a period of intense activity from 6:00 AM to 5:00 PM, depicted in Figure 4b, with a more detailed zoomed view provided in Figure 4c.

To refine our simulation, the analysis concentrates on weekdays during the 6:00 AM to 5:00 PM window, capturing the peak congestion times. Given the significant variability in the IAT across different hours, the study evaluates IAT in fifteen-minute increments, enhancing the accuracy of congestion detection. This approach adjusts the probability of vehicle arrivals to reflect the real traffic flow observed in historical data, ensuring a nuanced and precise simulation of daily traffic dynamics.

On the basis of these trends, a model with relevant parameters was developed to evaluate fluidity. This model processes each vehicle entering the system according to characteristics such as its type, entry and exit registration time, destination area, entry time for TS, and entry quarter-hour for IAT. The simulated period selected, as mentioned earlier, is from Monday to Friday from 6:00 am to 5:00 pm, when the risk of congestion is high.

- Access Registration Time

The ART for entry and exit, extracted from surveillance videos of various vehicles, was analyzed with 300 observations per parameter to establish probability distributions, as summarized in Table 3.

Table 3. Vehicle entry and exit ART distributions.

Vehicle Entry and Exit Modes	ART Distributions	Avg. Times (Seconds)
Automated truck entry	JohnsonSB (0.16, 0.70, 12.00, 59.27)	33.65
Manual truck entry	JohnsonSB (1.19, 0.59, 69.20, 390.37)	133.29
Automated truck exit	Norm (17.444, 5.0472)	17.42
Manual truck exit	JohnsonSB (1.79, 0.57, 27.76, 243.13)	50.26
Car entry	JohnsonSB (7.70, 0.94, 4.90, 28.00, 610.99)	18.59
Car exit	JohnsonSB (7.96, 1.21, 4.52, 4975.24)	14.3

- Parameters related to area D (new terminal)

The industrial partner supplied essential parameters for the new terminal, drawing from civil engineering plans and the port's past experiences; these were vital for defining the service level in the construction area. Key parameters include the daily truck visits to the port, simultaneous unloading capacity (4 trucks), estimated unloading time per truck (15–20 min), and the port's holding capacity for trucks awaiting unloading (up to 15 trucks). Truck arrivals are consistently distributed throughout the working day.

3.2. Simulation Model Design and Validation

To model logistics systems in the port context, we use the IAT/ART/c/K queue theory, where IAT represents the inter-arrival time distribution, ART the access registration time at entry/exit, c the number of servers (entry/exit lanes), and K the queue capacity (assumed as infinite in the case study). Additionally, managing exit flow requires the TS parameter, which includes both entry and exit ART. Excluding the new terminal, the existing system is abstracted as a black box, focusing on optimizing vehicle flows through arrival pacing and the TS. Vehicle type allocation to gates relies on historical patterns: over 70% of trucks and 90% of cars use the MG, with the rest processed through the SG.

The simulation models were developed using version 14 of the Simio software. Various objects and processes from the Simio library were utilized to configure flows, entry/exit gates, areas (A, B, C, and D), and the Kanban zone. Specific statistics were implemented to align with fluidity performance criteria. The simulation models took into account the following object implementations and parameters:

- Four flow sources for various vehicles types (manual access trucks, automatic access trucks, construction trucks, and cars), connected to current and potential access gates;
- A rate table is utilized to generate a flow of entities every 15 min, based on historical flow data. This table allows for the simulation model to capture the variability of IAT accurately, ensuring that the flow of entities aligns with historical trends;
- Stochastic entry and exit ART specific to each vehicle type, as illustrated in Table 3;
- Allocation of each vehicle to a destination area based on a stochastic flow and a specific stochastic TS;
- A Kanban zone designed to hold up to 15 trucks awaiting unloading. This Kanban system increases as incoming trucks find no available unloading service and decreases using the FIFO (First In, First Out) method whenever an unloading station becomes available in the construction area;
- After completing their stay, vehicles leave the port through a specifically designated exit gate based on the exit flows drawn from historical data of the reference period;

- The simulated period is from 6:00 am to 5:00 pm daily, with a replication of 44 days to achieve a state of convergence for stochastic parameters;
- Construction trucks that exceed operational capacity are purged from the system and recorded for analysis.

Two models were developed: one with two access gates (MG and SG), and the other incorporating new access infrastructure with one entry and one exit. These models were validated with low uncertainty (less than 2%) and applied to our case study, leading to substantial recommendations for decision support aimed at improving access fluidity during the construction period. Figure 5 depicts the conceptual model featuring two access gates, while Figure 6 presents the model's implementation using Simio objects.

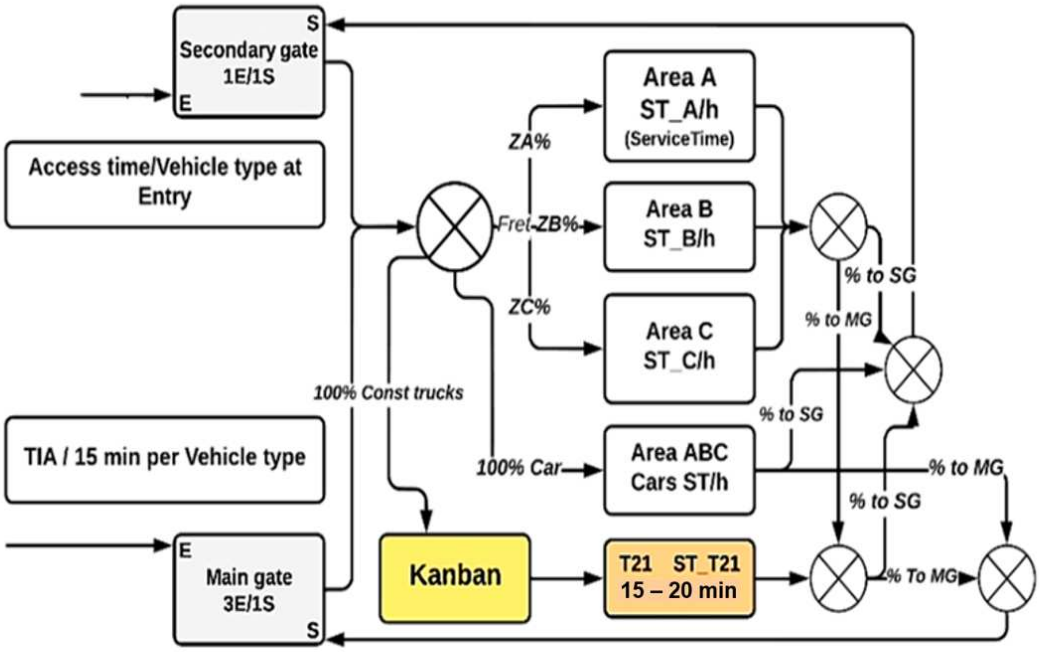


Figure 5. Design of the two-gate simulation models.

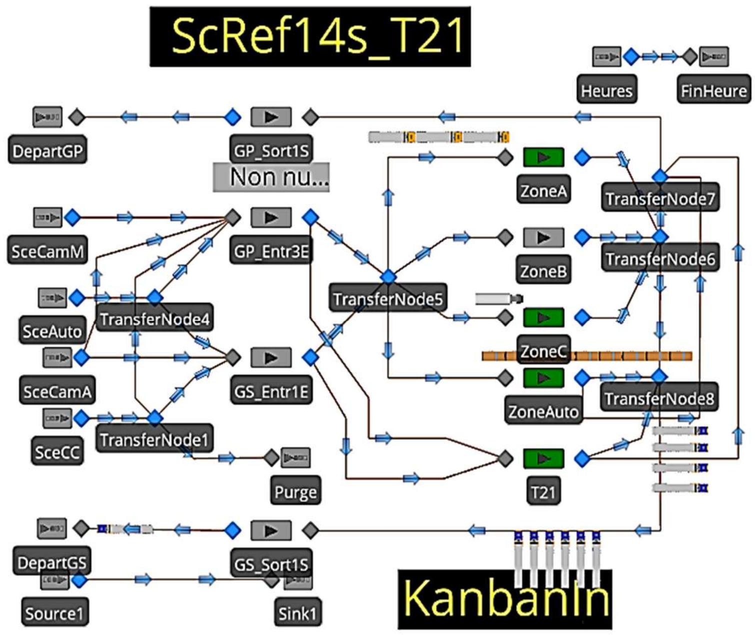


Figure 6. Implementation of the two-gate simulation models using Simio objects.

3.3. Performance Indicators

The performance indicators adopted in this study are the most commonly used in queueing theory to measure access fluidity to stations within a system. The focus is on the gates under investigation and the parameters that accommodate construction trucks within the port. The assessment involves evaluating the number of trucks waiting for access or encountering difficulties accessing the port due to inadequate service levels, as well as the waiting time and the capacity utilization of the gates.

3.4. Scenario-Based Analysis Approach

By designing parameters and simulation models that take into account time and space, potential congestion can be detected for specific contexts. The model's ability to predict such congestion, combined with the scenario-based approach, highlights the effectiveness of the methodology presented in this framework. To conduct scenario-based analysis, a four-step approach is employed. Figure 7 provides an overview of the scenario design approach detailed in next subsections. As described, each scenario design phase was generated based on the analysis of the previous phase's results, hence the dynamic label attached to the scenario design. This approach aligns well with the study's objective and with the industrial partner's desires, who acknowledged the importance of our recommendations for access logistics management during the construction period.

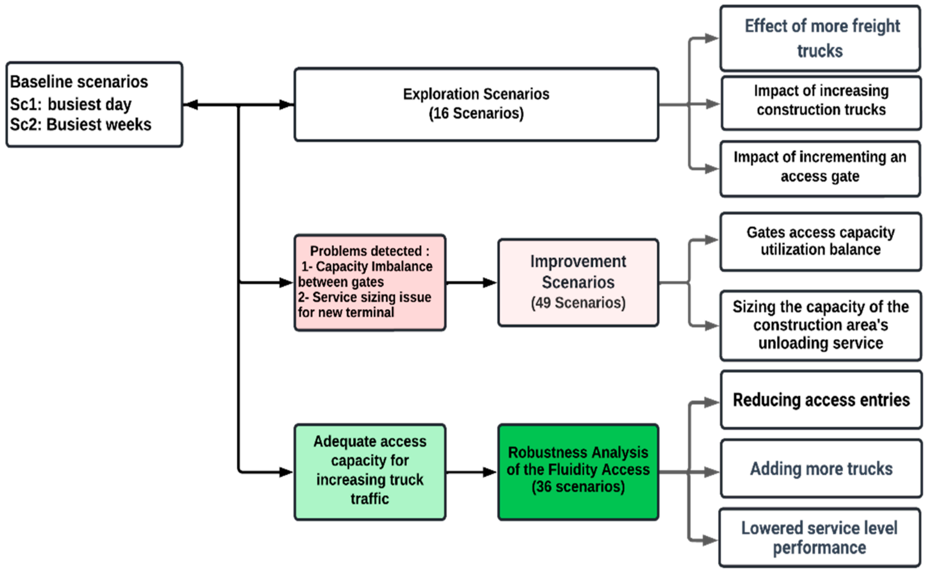


Figure 7. Scenario design approach.

3.4.1. Reference Scenarios

To address potential inaccuracies in actual queue times due to assuming registration time as arrival time, this study employs scenarios focused on the port's busiest periods rather than averaging historical traffic. This approach aims to better represent peak and moderate congestion levels. The analysis is grounded in two specific baseline scenarios: one derived from the single busiest day, and the other from the 14 busiest weeks during the reference period of 2017–2019. This selection, informed by a detailed examination of the traffic flow, ensures a focus on critical congestion periods. These periods correspond to spring, marking a resurgence in agricultural and construction activities, and winter, associated with maintenance needs. This method, validated with our industrial partner, captures key traffic dynamics during essential operation times, as depicted in Figure 8, providing a more accurate framework for analyzing access fluidity and infrastructure impacts.

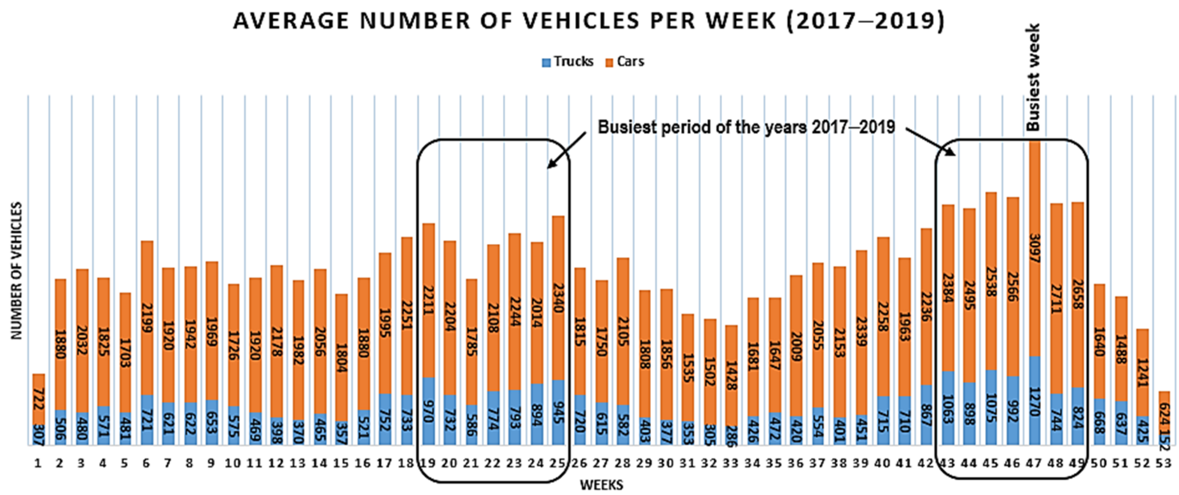


Figure 8. Reference period selection for baseline scenarios.

3.4.2. Exploration Analysis

This study assesses access fluidity during construction and investigates the potential benefits of additional access infrastructure on port accessibility. The current phase of analysis evaluates the capacity of existing access gates to manage traffic during the construction of a new terminal and the impact of incorporating an extra gate. Through scenario analysis, two main concerns regarding fluidity were identified: an imbalance in traffic distribution between the existing gates and a lack of operational capacity for construction activities, leading to considerable congestion outside the port and impacting urban traffic flow. In response, optimization and improvement analysis was formulated to bolster traffic management and increase operational efficiency.

3.4.3. Improvement Analysis

The improvement scenarios are designed to address two critical capacity challenges identified in the exploratory scenario analysis. These initiatives aim to achieve a more balanced utilization of the existing access gates and tackle additional issues concerning the service level design for construction activities. Following the evaluation of improvement scenarios and discussions with our industrial partner, the decision was made against investing in new access infrastructure due to the satisfactory utilization rates of the current gates. Consequently, we developed a series of scenarios to assess the primary gate's resilience to disruptions. This assessment focuses on the gate managing the bulk of traffic, in order to study the robustness of this infrastructure and determine its service capability limits.

3.4.4. Robustness Analysis of the Main Gate Access Fluidity

For the robustness analysis, scenarios were crafted to assess the effects of significant disruptions, aiming to understand the access system's resilience and capacity thresholds to inform operational recommendations. This method aligns with the "capacity drop" concept, as delineated in the research of [32], which utilized scenario analysis and simulations to examine capacity reductions at highway bottlenecks and underscored the critical role of targeted scenarios in influencing traffic control system design. Similarly, Ambrosino and Sciomachen's [33] study applied this concept, investigating capacity drop effects on traffic flows and overall sustainability costs. Their findings highlight how the design and management of the analyzed multimodal logistic network significantly impact sustainability-related external costs. To achieve this final analysis step, several scenarios were proposed to evaluate the impact of different factors, including the duration and frequency of slowdowns as well as the number of entrances and trucks visiting the port.

4. Results and Interpretations

Before analysis and interpretation, all simulation results across various scenarios were validated for parameter convergence. This section presents an analysis of the baseline, exploratory, improvement, and fluidity robustness scenarios, evaluated against different criteria. The following are the configurations and results of various scenario types, as per the previously presented framework.

4.1. Results Analysis

4.1.1. Baseline Scenario Analysis Results

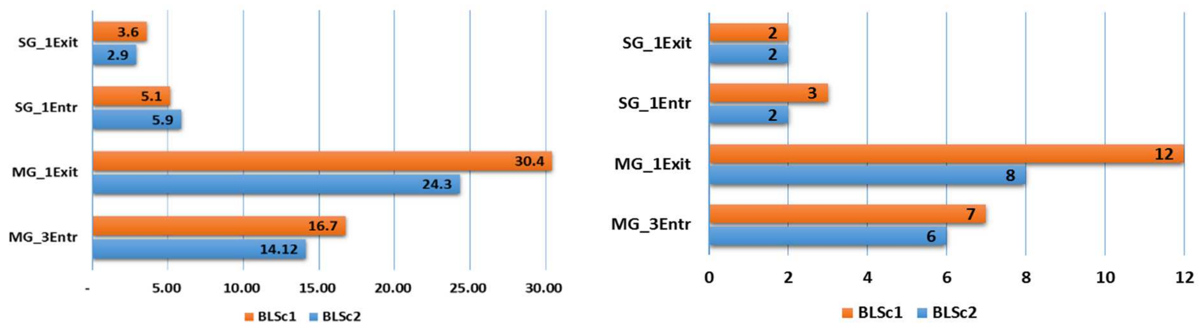
As delineated in the methodology section, the baseline scenarios are predicated upon two distinct periods of the year, characterized by varying levels of traffic flow. Specifically, baseline scenario 1 (BSc1) corresponds to the average day (2017–2019) with the highest congestion of the year (bd: busiest day), which occurs on Day 5 of Week 47. Meanwhile, baseline scenario 2 (BSc2) pertains to the most congested period of the year, encompassing Weeks 19–25 and 43–49. The parameters for both scenarios are itemized in Table 4.

Table 4. Baseline scenario parameters.

Baseline Scenarios	Gate Number	Data	Truck Flow MG	Truck Flow SG	Reference
BSc1	2	2017–2019	78%	22%	Busiest day
BSc2	2	2017–2019	67%	33%	14 busiest weeks

The used capacities of the access gates according to historical data are shown in Figure 9. The main interpretations of the baseline scenarios are presented as follows:

- The access capacity is largely underutilized, especially in the case of the SG, where the entry/exit used capacity does not exceed 4% to 6%. The crowding observed in practice is primarily attributable to inadequate planning of truck arrivals;
- The used capacity between the MG and SG is imbalanced. Figure 9a depicts the utilization capacity of the two access gates. The historical capacity shows that the port can accommodate more than 300 cars and 76 trucks at the same time;
- The time system is 1.23 h on average and 2.87 h as a maximum for freight trucks, while the TS is 3.38 h on average for cars;
- Regarding the MG, queues at the entrance can reach up to 6 to 7 vehicles, while the maximum number of vehicles at the exit is 8 to 12 for scenarios 1 and 2. As for the SG, the maximum number of vehicles waiting to access does not exceed three, as illustrated in Figure 9b.



(**a**) Percentage of capacity utilization (**b**) Maximum waiting queue lengths

Figure 9. Capacity utilization and maximum waiting queue lengths at access gates (MG and SG) under baseline scenarios (BLSc1 and BLSc2).

The exploratory scenarios will be analyzed in relation to these two baseline scenarios.

4.1.2. Results of Exploratory Scenario Analysis

Two Access Gates

Table 5 presents the parameters of this exploratory scenario, which aim to investigate the impact of an increase in the number of freight trucks. ExpSc1 and ExpSc2 reference historical data for flows BLSc1 and BLSc2 for two access gates. In addition, the impact of construction truck (CT) flows is explored, taking into account the increase in the number of freight trucks (FTs). These exploratory scenarios (ExpSc3–6) are intended to assess the effect of increased FT and CT traffic on the flow of existing access gates. These scenarios utilize forecasted data for the construction period and take into account the unloading of four trucks simultaneously, with an unloading time of 15 and 20 min.

Table 5. Design settings for exploratory scenarios.

Exploratory Scenarios	Number of Gates	Unloading Time for CT in min	Reference Flow	Impact to Be Evaluated
ExpSc1	2	-	BSc2	Increase in FTs
ExpSc2		-	BSc1	
ExpSc3 ExpSc4		15 20	BSc2	Increase in FTs and CTs
ExpSc5 ExpSc6		15 20	BSc1	

Figure 10 depicts the impact of an increase in freight and construction trucks on the utilized access capacity as compared to the baseline scenarios. Based on the forecast period data, an increase in 20% in freight trucks along with construction trucks has a moderate impact on the utilized capacity of access gates. However, the average number of waiting trucks at the end of the shift day is around 25% of the total number of construction trucks, potentially reaching a maximum of 50%. When the unloading service time is 20 min, the issue does not arise at the access level but rather at the operational capacity level in the new terminal, which negatively affects traffic flow on the city side. The utilized capacity increases significantly at 15 min of unloading time, without significantly compromising the access fluidity. In this case, the number of waiting trucks is, on average, 10% and, at most, 30% of the number of construction trucks, as illustrated in Figure 11. This situation still remains unfavorable for traffic flow on the city side, where an average of 25 trucks wait for access to the port. Further experiments with shorter unloading times showed that 2.5% additional utilized capacity was observed at the two gates when all the construction trucks are purged in the case of two-gate scenarios.

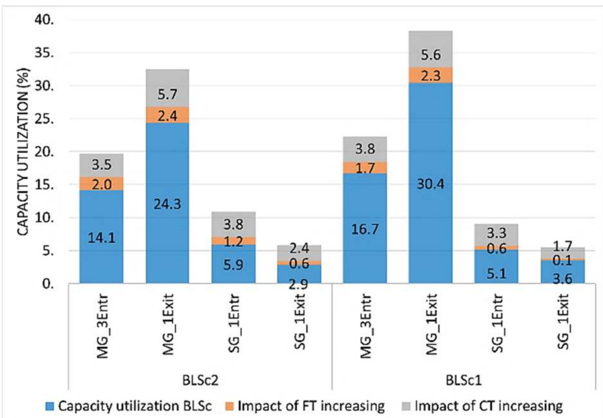


Figure 10. Impact of increased truck volume on access capacity in two gates scenario.

Figure 11. Total number of trucks in the system, including those waiting for access, with an unloading time of 15 min.

Three Gates Exploratory Scenario Analysis Results

Within this set of scenarios, we are exploring the impact of adding an access gate, designated as New Gate (NG), with one entrance and one exit, which serves a specific destination, as illustrated in Table 6.

Table 6. Impact of adding an access gate with one entrance and one exit.

Exploratory Scenarios	Number of Gates	Unloading Time for Construction Truck	NG (Truck Destination)	Reference Flow
ExpSc7 ExpSc8	3	15 20	Area B	BLSc2
ExpSc9 ExpSc10		15 20		BLSc1
ExpSc11 ExpSc12		15 20	Area B and 20% Area A	BLSc2
ExpSc13 ExpSc14		15 20		BLSc1

In comparison to the two-gate scenarios, an increase in freight and construction trucks in the three-gate scenarios reveals that the addition of a new gate dedicated to automatic trucks destined for area B eases the load of the two existing gates, as shown in Figure 12. This observation is particularly noticeable when the new gate is dedicated to automatic trucks destined for area B and 20% of the traffic to area A. The utilized capacity for the new access gate ranges from 6.1% to 6.8% at entry and 3.2% to 3.6% at exit, on average.

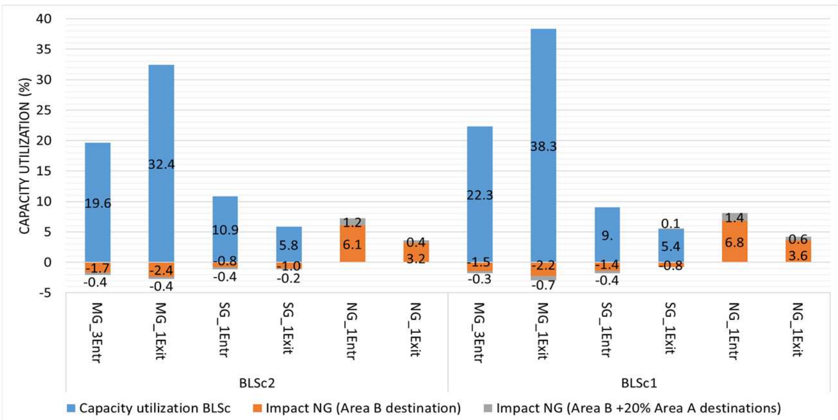


Figure 12. Impact of adding a new access gate to the capacity utilization with an unloading time of 15 min.

In the case of scenarios with two and three gates, the average and maximal number of construction trucks waiting for access due to insufficient operational unloading capacity is quite noticeable. This context is illustrated in Figure 13.

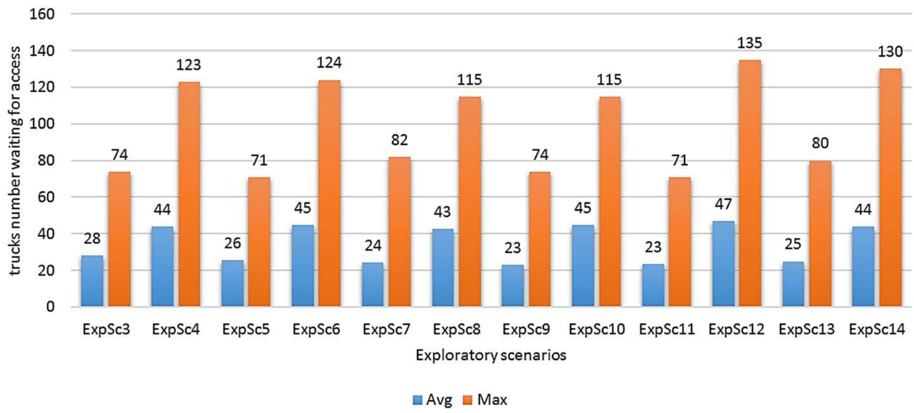


Figure 13. Average and maximum number of construction trucks waiting for access.

Figure 14 shows that 41 trucks (23 on average) remain on the city side after 11 h of running simulation time for the scenario ExpSc9.

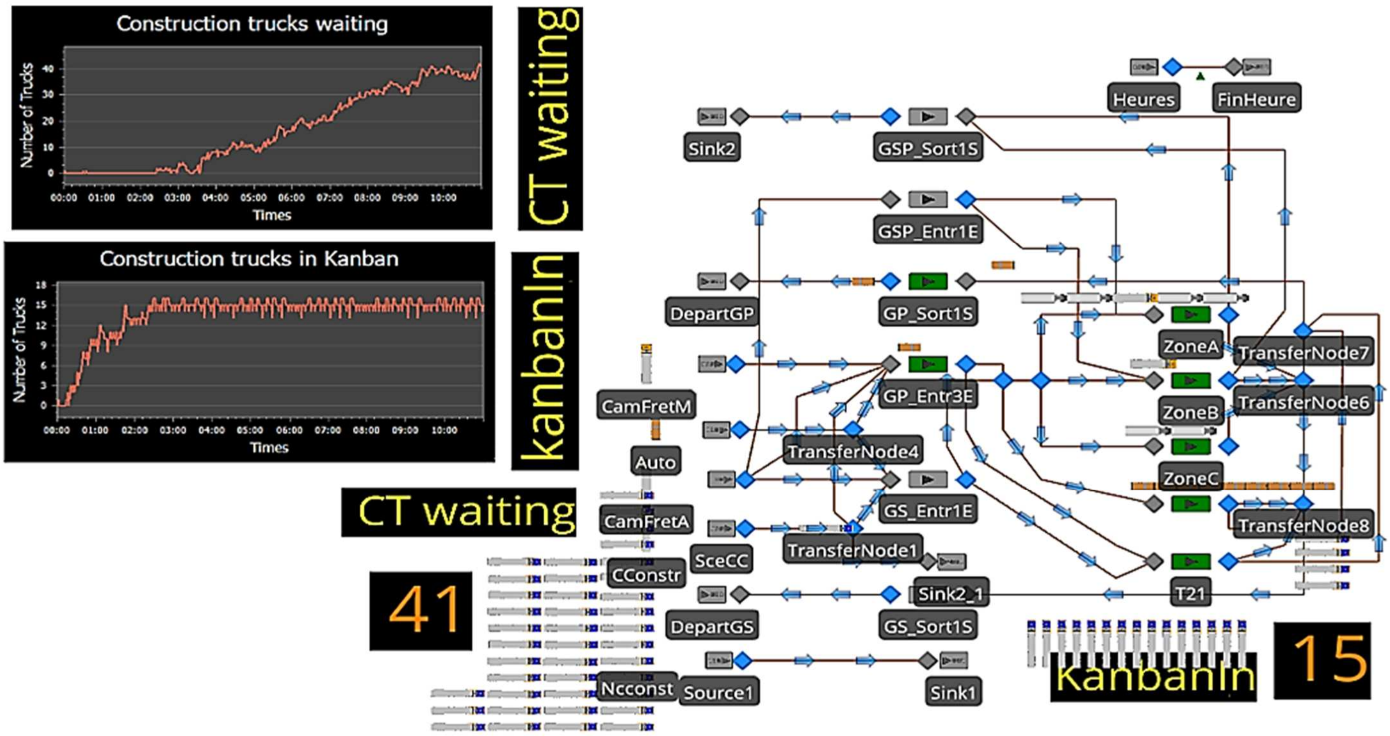


Figure 14. Scenario with three gates after 11 h of simulation time.

After conducting the first set of exploratory scenarios, it was observed that access gate capacity was not a significant problem. However, the number of construction trucks waiting caused significant traffic issues on the city side. Additionally, it was found that the flow of trucks, based on historical data, did not allow for an equitable distribution between the different gates. To address these issues, improvement scenarios were designed to optimize, on the one hand, unloading service time at the new terminal and, on the other hand, access flow between the existing gates.

4.1.3. Analysis Results of Improvement Scenarios

The improvement scenarios target anomalies identified during the assessment of operational access capacity at the port, particularly in response to increased truck traffic and inadequate unloading service levels for construction activity at the new terminal. In the first set of scenarios, aimed at achieving a balanced flow between the access gates, flows ranging from 10% to 90% for the MG and their complementary values for the SG were explored. These flows pertain to both automatic access freight trucks and construction trucks. However, manual freight trucks exclusively use the MG, while car flows remain consistent with historical data. The second set of scenarios focuses on optimizing unloading service time at the new terminal by varying the number of trucks unloading simultaneously and the unloading time, which ranges from 15 to 25 min. The objective is to minimize trucks' waiting time outside the port as much as possible. Table 7 provides a summary of the parameters for the improvement scenarios.

Table 7. Summary of the parameters for the improvement scenarios.

Scenarios	Number of Gates	No. of CTs Unloaded Simultaneously	Unloading Time	NG Flow	MG Flow	SG Flow	No. of Scenarios
ImpSc1	2	4	-	-	0.1–0.9	0.9–0.1	9
ImpSc2			15	-			
ImpSc3	3			ZA			
ImpSc4				ZA + 20% ZB			
ImpSc5	2	4/5/6		-	0.67	0.33	3
ImpSc6		4/5/6/7/8	20	-			5
ImpSc7		5/6/7/8/9	25	-			5

To enhance the strategy for optimizing traffic management and minimizing wait times, it is crucial to meticulously plan the distribution of traffic among the Main Gate (MG), Secondary Gate (SG), and a third access gate. Considering the preference for the MG by manual access trucks and most cars, it is advisable to allocate only 30% of the remaining traffic (automated access freight trucks) to the MG when construction trucks are absent, directing 70% towards the SG to alleviate congestion. With the inclusion of construction trucks, an adjustment in traffic distribution becomes necessary: up to 50% can be routed to the MG in two-gate scenarios, as depicted in Figure 15, and a range of 40% to 50% in three-gate setups.

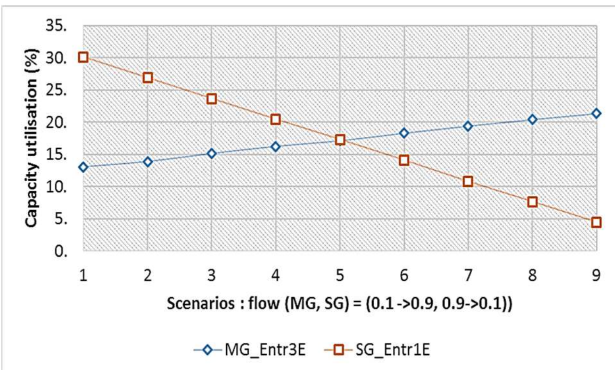


Figure 15. Balancing the flow between the MG and SG in the two-gate scenario case and construction trucks in scenario ImpSc2.

For the NG, the traffic flow should be set between 24% and 29%, depending on whether this gate exclusively serves Zone A or Zone A and 20% of Zone B. In this context, the SG manages the excess flow. This precise calibration of traffic through each gate ensures smoother operations and significantly reduces delays, effectively addressing potential bottlenecks and facilitating more efficient access and egress for all vehicle types.

Improving upon the optimization of unloading services in construction areas, it is clear from the analysis that careful planning around the number of trucks unloading simultaneously is crucial to minimizing waiting times for trucks queuing for access. The findings highlight a direct correlation between unloading times and the optimal number of trucks required to maintain efficiency and prevent congestion. For instance, a setup allowing for five trucks to unload simultaneously with a 15 min unloading period results in an average of five trucks waiting. However, by increasing the capacity to six trucks, the waiting queue is significantly reduced to an average of just one truck. Moreover, for a 20 min unloading window, the optimal arrangement involves eight trucks unloading concurrently, though seven trucks can serve as a viable alternative. This balance shifts as the unloading time extends to 25 min, necessitating nine trucks unloading in parallel to achieve optimal flow and minimize waiting times.

These insights underscore the necessity for precise scheduling and resource allocation in construction planning. It is imperative that construction contracts explicitly include these logistical considerations to pre-emptively address potential bottlenecks. In Figure 16, we see the impact of unloading times and capacities on the average and peak construction truck presence on the land side.

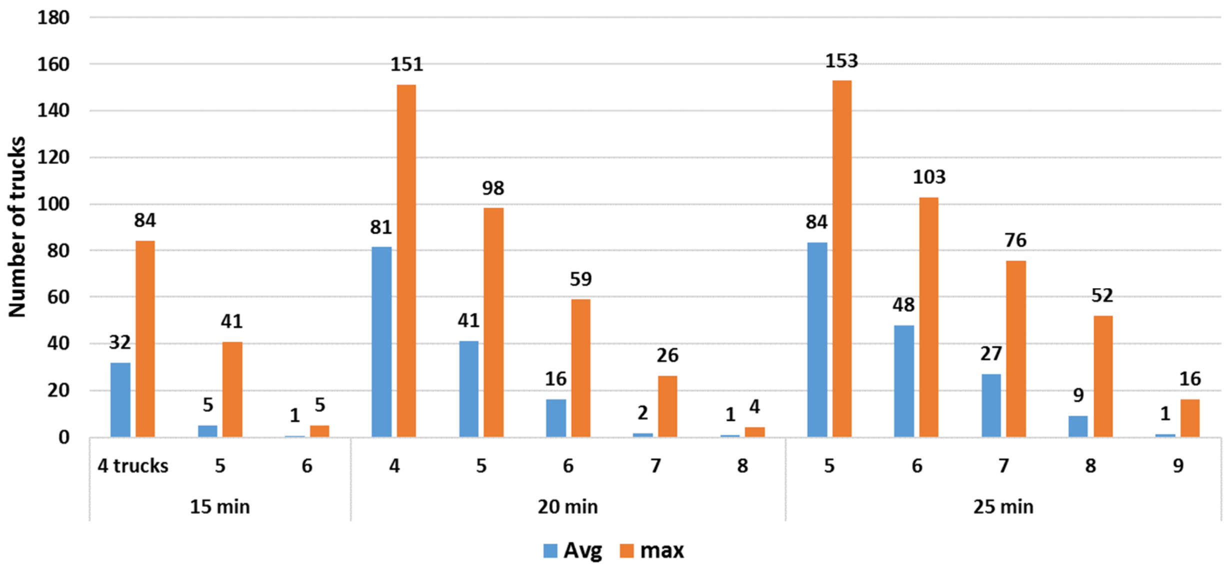


Figure 16. Comparative analysis of construction truck presence, showing average and peak numbers on the land side, affected by unloading service duration and simultaneous unloading capacities.

4.1.4. Assessing the Resilience of Main Gate Access Flow

Based on traffic flow predictions with an increase in trucks during the construction period, the current access setup (which includes two gates with four entrances and two exits) can handle the additional truck flows, even during historically busiest periods of the year. Since the SG is least affected due to the low flow it manages at the entry/exit, we proceed with further experiments to test the impact of access service slowdown at the MG. In addition to the parameter related to the number of entrances (historically three entrances), several parameters were established to constrain the service level at the MG, such as the slowdown factor of the registration service (number, duration, and frequency) and the increased truck flow. Table 8 summarizes the parameters of the experimental scenarios. Khondaker [32] presents a comparable design approach, detailing the creation of various scenarios based on crucial factors, including traffic flow variations (from congestion to free flow), accident duration, the car-to-truck ratio, and the number of available lanes. This methodology is designed to meticulously simulate a wide range of real-world conditions.

Table 8. Parameters of the experimental scenarios.

Batch Sc	Slowdown Duration	Slowdown Factor	Slowdown Freq. per Hour	Entrance Number	Outlook Number of Trucks	Number of Scenarios
1	10 min	20% and 30%	1, 2, 4, 6	1–2–3	construction period	24
2	10 min	40% and 50%	1, 2, 4, 6	1	construction period	8
3	10 min	40%	6	3	construction period + 20 to 50%	4

In our case study, the daily vehicle count is approximately 873, divided into 395 cars, 201 trucks with automatic access mode, 55 trucks with manual access mode, and 222 construction trucks. There is a 15 min service time for unloading construction trucks, and four trucks are unloading simultaneously.

The robustness analysis was structured around three main sets of scenarios to assess the impact of various factors on the fluidity of access to the port:

- Access Service Degradation Scenarios (Sc1 to Sc24 in Table 9): This set aimed to explore the effects of potential service degradation—due to adverse weather conditions, delays, registrar training, or technological failures—across 24 scenarios. By varying the degree of slowdown (from low to high) and the number of entrances (from one to three), the study sought to understand how different levels of service impairment, their frequencies, and the availability of simultaneous entrances influence access fluidity.
- Extreme Access Condition Scenarios (Sc25 to Sc28 and Sc33 to Sc36 in Table 9): Focused on evaluating the system under extreme conditions, this batch of eight scenarios considered operating with only one entrance available and slowdown factors of 40% and 50%, with frequencies of occurrence ranging from one to six times per hour. The objective was to examine the resilience of the access system under severe restrictions on entrance availability, high slowdown rates, and varying frequencies of these slowdowns.
- Increased Truck Volume Scenarios (Sc29 to Sc32 in Table 9): The last four scenarios were designed to assess the effects of an unpredictable increase in truck volumes—from 20% to 50%—while dealing with significant, continuous service degradation (40%) and operating with three entrances. Given the unpredictable nature of construction activities and the potential fluctuation in truck numbers depending on the subcontractor involved, it is essential to consider how changes in truck volume could affect port access fluidity. These scenarios specifically aim to understand the potential effects of varying truck volumes on port operations and efficiency.

The experimental simulation was conducted over a period of 440 h, equivalent to eleven-hour workdays (from 6 AM to 5 PM) replicated 40 times across 10 replications, including a 10 h warm-up period to ensure more accurate measurements. A 95% confidence interval was applied to the experiment outcomes. The results of these various scenarios are concisely summarized in Table 9, providing insights into the port's ability to maintain fluidity under varying conditions of access service degradation, extreme access constraints, and fluctuations in truck volumes.

Table 9. Results of scenario-based robustness analysis.

Sc	MG Capacity	Delay Factor	Delay Frequency (h)	Avg. No. Vehicles Waiting	Max. No. Vehicles Waiting	Avg. Waiting Time (min)	Max. Waiting Time (min)	Scheduled Utilization (%)	Processing Time (%)
Sc1	1	0.2	1	1.82	32.1	1.80	15.8	57	57
Sc2			2	2.56	38.2	2.56	19.4	60	60
Sc3			4	2.82	39.7	2.76	23.7	61	61
Sc4			6	3.40	44.5	3.35	26.8	66	66
Sc5	2		1	0.10	9.7	0.09	3.3	29	43
Sc6			2	0.12	8.4	0.11	3.6	30	45
Sc7			4	0.11	8.3	0.11	4.3	30	45
Sc8			6	0.16	10.6	0.16	4.5	33	48
Sc9	3		1	0.01	4.3	0.01	1.1	19	42
Sc10			2	0.01	4.2	0.01	1.2	21	45
Sc11			4	0.01	4.5	0.01	1.3	20	44
Sc12			6	0.02	4.7	0.02	1.5	22	47
Sc13	1	0.3	1	1.96	34.6	1.93	17.4	57	57
Sc14			2	3.44	47.5	3.39	27.9	62	62
Sc15			4	3.46	45.4	3.41	27.2	63	63
Sc16			6	4.88	50.8	4.80	30.1	71	71
Sc17	2		1	0.10	9.5	0.10	3.1	29	43
Sc18			2	0.15	10.0	0.15	4.1	31	45
Sc19			4	0.17	11.5	0.16	5.3	32	46
Sc20			6	0.18	10.6	0.18	4.9	36	51
Sc21	3		1	0.01	4.5	0.01	1.3	19	42
Sc22			2	0.01	4.5	0.01	1.3	21	45
Sc23			4	0.02	4.5	0.02	1.4	21	44
Sc24			6	0.03	5.5	0.03	2.0	24	49
Sc25	1	0.4	1	1.61	25.0	1.59	13.4	58	58
Sc26			2	4.15	47.1	4.10	32.6	64	64
Sc27			4	4.38	47.5	4.36	32.7	64	64
Sc28			6	7.99	57.0	7.83	41.7	76	76
Sc29	3 (*)	0.4	6	0.05	7.6	0.04	2.3	27	54
Sc30			6	0.07	8.3	0.06	3.0	29	56
Sc31			6	0.06	7.4	0.05	2.8	30	58
Sc32			6	0.06	6.8	0.05	2.7	31	59
Sc33	1	0.5	1	1.82	29.9	1.80	16.6	58	58
Sc34			2	6.26	58.4	6.08	45.2	67	67
Sc35			4	6.34	58.6	6.26	47.0	67	67
Sc36			6	11.53	70.2	11.42	51.1	81	81

(*) Increase in the number of trucks by 20%, 30%, 40%, and 50%, respectively, for scenarios 29 to 32.

The analysis of results for each group of scenarios unfolds as follows:

Batch 1 (Scenarios 1–24): This group investigates the operation of the MG with one to three entrance capacities and slowdown factors of 20% and 30%, at frequencies of one, two, four, and six times per hour.

- Reducing the entrances from three to two increases capacity utilization by 50%, and decreasing to a single entrance triples the capacity used. This has a substantial impact on system fluidity, especially during peak times. Both the extent of the slowdown and its frequency lead to higher capacity use. A rise in slowdown factor from 20% to 30% results in a 5% boost in capacity utilization, as depicted in Figure 17 for a 20% delay factor.
- The adjustment from two entrances to one critically effects and can significantly disrupt access fluidity. Figure 18 shows that the peak number of waiting vehicles quintuples when comparing one entrance to two. Conversely, the quantity of waiting vehicles doubles when the number of entrances is reduced from three to two. Slowdowns in service also have a marked impact on the system's performance.

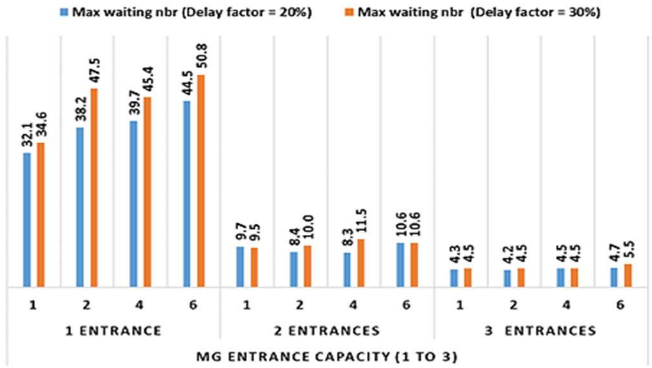


Figure 17. Peak vehicle queue length for access.

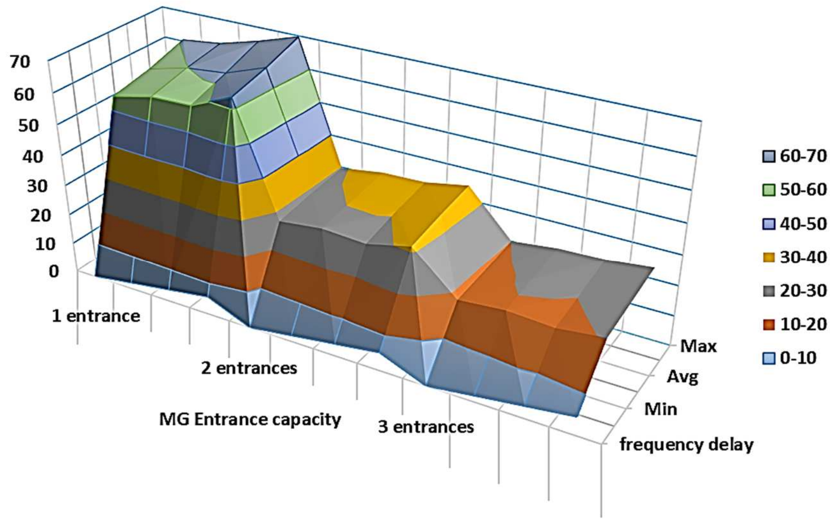


Figure 18. Percentage utilization of MG capacity with a 20% slowdown factor at various frequencies.

Batch 2 (Scenarios 25–28 and 33–36): This group examines the operation of the MG under the constraint of having only one entrance and encountering significant slowdown factors of 40% and 50%, with slowdown frequencies of one, two, four, and six times per hour.

- As shown in Figure 19, with just one entrance and high slowdown factors of 40% and 50%, the peak queue of waiting vehicles becomes notably large. An increase in the slowdown factor from 40% to 50% has a pronounced impact on the peak number of waiting vehicles, adding up to 13 more vehicles in scenarios with frequent slowdowns.
- The capacity utilization in these scenarios falls short of adequate. At a 58% utilization rate, the gate faces congestion for a significant portion of the operational time. Notably, the peak number of waiting vehicles reaches 25 with a 40% slowdown occurring once every hour for a duration of 10 min. Figure 20 highlights the utilization rates of the MG.

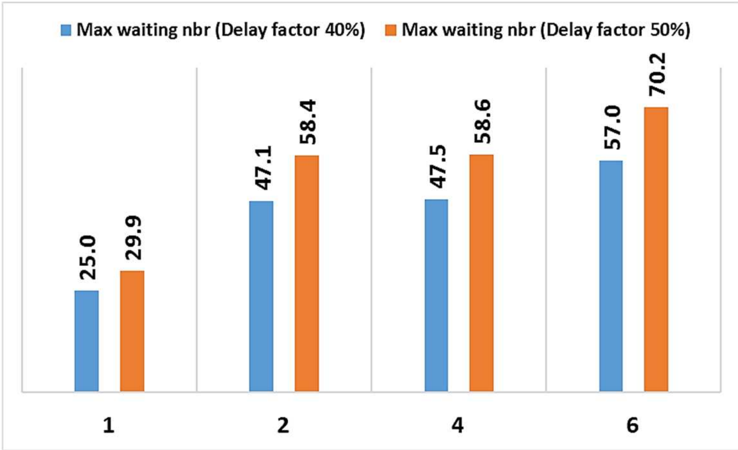


Figure 19. Peak queue length for access by delay frequencies: 1, 2, 4, and 6.

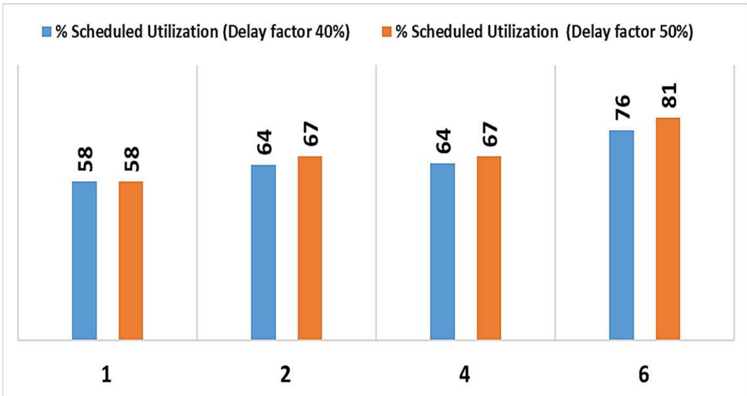


Figure 20. Utilization rates of the MG across delay frequencies: 1, 2, 4, and 6.

Batch 3 (Scenarios 29–32): This group examines the effects of operating the MG with three entrances, a 40% slowdown, and truck volume increases of 20%, 30%, 40%, and 50%:

With three entrances operating under a consistent 40% slowdown, the system shows a low sensitivity to increases in truck volumes ranging from 20% to 50%, in terms of both peak waiting vehicle numbers and overall capacity usage. On average, there is a 1.24% increase in capacity utilization for every 10% rise in truck volume. The peak number of waiting vehicles sees minimal variation, as illustrated in Figure 21. The system's fluidity is maintained effectively with three entrances, even with truck volume surges up to 50%.

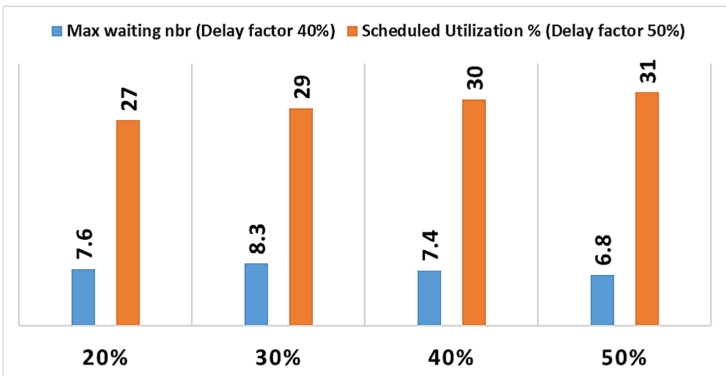


Figure 21. Impact of truck volume increases from 20% to 50% on peak vehicle queue and MG capacity utilization.

4.2. Discussion

4.2.1. Summary of Key Findings in Relation to the Study's Objectives

Our scenario-based analysis, evaluated through discrete-event simulation modeling, demonstrates that traffic flow is not generally compromised by increased construction truck flows or freight truck flows during the construction period. The exploration scenarios identified two main issues: significant service level problems in the construction zone, leading to noticeable waits for construction trucks on the city side, and an imbalance between the two existing gates, with the MG bearing a higher load than the SG.

Optimization and improvement scenarios streamlined the distribution of traffic between the two gates, accounting for their handling of different vehicle types and the varied configurations in terms of entry and exit lane numbers. For the unloading service at the new terminal, multiple optimal configurations were developed to minimize queues at the port's entrance. Building upon this foundation of efficiency, it becomes crucial to extend such strategic planning to the legal frameworks that govern construction activities within the port. The negotiation of clauses in construction subcontracting contracts must meticulously address the organization of construction operations to maintain the port's capacity to accommodate incoming trucks, including a strategic provision for a holding area for 15 trucks within the port's boundaries.

While investing in new access infrastructure could strategically enhance long-term access fluidity, this is not a short-term priority. To aid decision makers, we tested the MG's resilience to additional stress conditions in the context of robustness scenarios, finding significant resilience except when access lanes were reduced. Although the experiments show that the capacity of the two existing gates is sufficient to accommodate both construction and freight trucks, scheduling truck arrivals during specific hours of the day and peak traffic seasons is necessary as a preventative measure in these cases.

Recommendations based on our analyses include scheduling freight truck arrivals from 7 to 8 AM and 12 to 1 PM, delaying construction truck arrivals until after 9 AM, extending evening work hours for construction trucks, and using an entry lane as an exit after 3 PM to alleviate port congestion. These recommendations were presented to and discussed with our industrial partner, who actively engaged in the scenario design and parameter setting for the terminal construction. Figure 22, produced by simulation software, illustrates the daily occupation levels of the Main Gate (MG) during a typical workday, showcasing entry traffic through three lanes and exit traffic through one. This visualization provides insights into the flow dynamics and potential bottlenecks at critical points of the day.

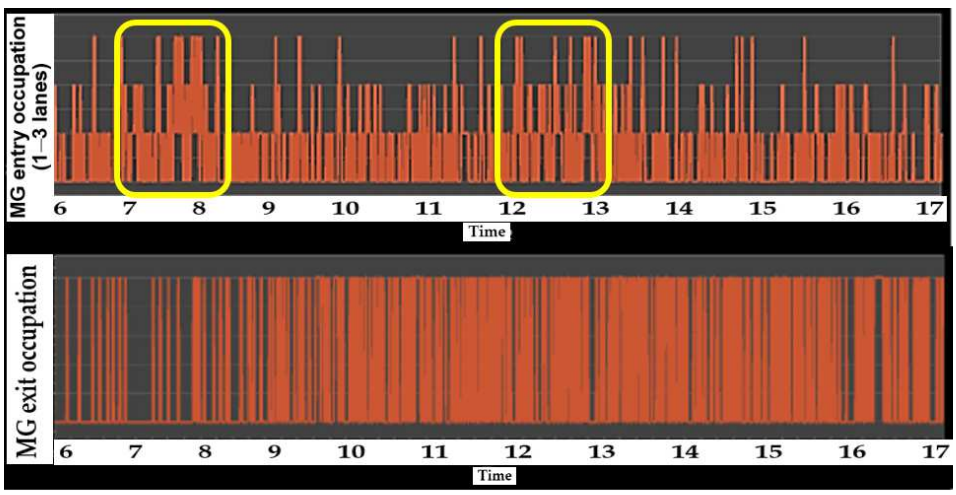


Figure 22. Daily MG occupation at entry (3 lanes) and exit during a workday.

4.2.2. Discussion of Study Limitations and Methodological Challenges

The study's limitations encompass methodology aspects, including data processing, assumptions, the assessment of simulation uncertainties, and other limits related to solution selection.

- Regarding the data, selecting the historical period between 2017 and 2019 may not accurately reflect the current traffic behavior at the port. However, the projection of an increase in the number of freight trucks during the construction period was provided by the industrial partner based on an internal study.
- The distribution of trucks between zones is historically accurate in terms of the overall number provided by the partner. However, the allocation of 55% of the trucks to zones was approached randomly, using a significant number of replications to minimize errors. Applying more sophisticated models, especially Machine Learning or Deep Learning models that can perform supervised classification by training on the 45% of well-categorized data, could improve this.
- Assuming the truck's registration time in historical data as its arrival time may obscure actual queue times at the moment of registration. While addressing this issue may not be straightforward, we used reference scenarios relative to the busiest contexts to mitigate the effects of this assumption. The queue time and number results were confirmed by the industrial partner as being close to reality, lending further confidence to our findings.
- The freight truck TS negatively correlates with the IAT, as previously demonstrated. This context was corrected by adopting TS per hour to reflect this correlation. However, the experiments focusing on scenarios with an increased number of trucks did not consider how this increase affects the throughput TS. Yet, the industrial partner believes that profitability constraints, aimed at reducing the trucks' dwell time in the port, ensure that the service level remains managed. This uncertainty may create a slight shift in truck exit times. An AI-based model could more accurately determine the correlation between TS and service level, which would allow for better management of truck exit times.
- Our simulation model validation involved 44 replicas, meaning a day would be simulated over 44 days for the simulation parameters to converge towards their average. However, we did not set a Seed for the experiments, which could slightly increase the uncertainty of the results. This increase should not compromise the analyses, especially since the stochastic parameters converge to an uncertainty of less than 2%. Similarly, during validation, we carried out 44 validation replicas in the experiments for each of the 10 replicas allocated to each scenario, with a warm-up time of 10 h before starting the experiments. Khondaker [32] incorporates the Seed factor into the study to mitigate the impact of randomness on the simulation outcomes. Using different Seed values and averaging results help stabilize outcomes and reduce the impact from stochastic parameters, particularly when some converge with notable uncertainty.
- Another limitation related to the proposed solutions arises from the nature of our research (applied research). Being practically oriented and aimed at addressing a specific issue through active collaboration with our industrial partner, our focus was on devising solutions that are not only feasible but also align with the partner's constraints and capabilities to ensure implementability.

One specificity of this study is that it aims to assess the fluidity in a particular context, such as during the construction of a new terminal. However, the methodological approach can be applied to any other similar case, as it follows a structured process of baseline, exploration, improvement, and robustness assessment. This adaptability makes the methodology valuable for addressing various fluidity challenges in different contexts.

4.2.3. Comparative Analysis with Recent Studies

In this subsection, we will compare the results in terms of recommended solutions versus current trends to alleviate congestion issues in urban port access. We will address the two main areas of our study: investment in new access infrastructure and operational layout improvements for existing access gates.

- Regarding Infrastructure Investment

Two studies highlight that decisions on infrastructure investments should follow the optimal use of current facilities. White [34] suggests that expanding a capital-intensive facility is viable when occupancy rates exceed roughly 70%. Joao [35] found optimal utilization at 85% enhances port capacity by 62.5%, concluding investments should focus on operational efficiency before considering new infrastructure.

- Regarding the Management of Access from Existing Infrastructure

Similar studies have proposed several solutions to manage congestion at port access gates. We will discuss these solutions and their validity in our context.

- Truck Arrival Scheduling or Appointment System

Truck appointment systems have been widely examined and implemented in several ports worldwide to reduce congestion at access gates, as demonstrated in [13,15]. These studies have shown the effectiveness of appointment systems in reducing truck waiting times and improving overall port efficiency. However, implementing this solution is more difficult in non-containerized ports, where service times are neither standard nor predictable. Indeed, Palmer Jr et al. [9] underscored the operational planning complexity inherent in bulk ports. Unlike container ports, bulk ports face challenges such as diverse cargo, unpredictable ship arrivals, weather-dependent loading/unloading, and the need for varied equipment, all of which affect port performance. The industrial partner deems the applicability of this solution for the specific case inefficient.

Several traffic management strategies, such as reallocating an entry lane to serve as an exit to alleviate port congestion when the exit queue is crowded, draw inspiration from [12], where the authors suggest to occasionally repurpose an exit as an additional entry lane, as shown in Figure 23. This method, which has been discussed and deemed viable with the port authority for the case study, aims to reduce congestion during peak workday periods, according to the configuration presented in Figure 24.

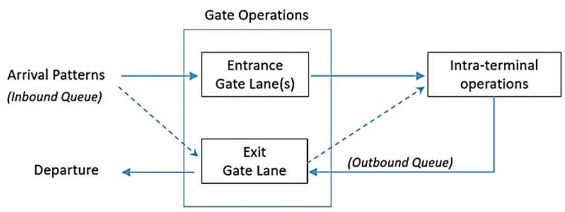


Figure 23. Repurposing an exit as an additional entry lane [12].

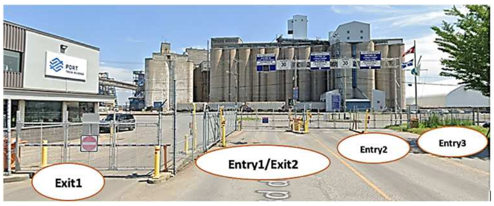


Figure 24. Repurposing an entry as an exit lane during peak workday periods (Google maps).

- Cooperation and Synchromodality

Fostering collaboration between neighboring seaports and enhancing their links with inland ports, along with the establishment of internal customs zones, offers a strategic approach to mitigating capacity constraints and reducing traffic flows, as indicated in [5,36]. Further, encouraging partnerships with additional ports and leveraging the capabilities of dry ports for capacity outsourcing present an effective solution to redistributing cargo operations, thus alleviating pressures on coastal port infrastructure. The concept of synchromodality further highlights the critical need for flexible and efficient integration of different transportation modes. As per the findings in [9,37], facilitating multimodal connections between road and rail transport can significantly mitigate congestion issues stemming from road traffic. Palmer Jr et al. [9] advocated for prioritizing multimodal strategies beyond just operational planning, addressing the inherent complexities within bulk port operations and underscoring the importance of innovative solutions to boost port operational efficiency.

- Collaboration Between Urban and Port Authorities and Road Network Centrality Management

Some studies collectively suggest that integrated planning, encompassing sustainable development, technological innovations, and collaboration between urban and port authorities, is essential for effective congestion management. This approach is underlined in [38], where the authors advocate for a shift towards more sustainable maritime transport systems. Further research in [39,40] delves into how road network centrality and land use intensity interplay to affect urban congestion, indicating the need for careful urban and logistical planning. Frémont [41] categorizes urban centers by their logistics characteristics, emphasizing the critical role of ports in efficient distribution and the broader supply chain. Lehmacher et al. [42] highlight the potential of data analysis, simulation, and AI in streamlining traffic flow and enhancing the quality of life in port cities. Additionally, Jugović et al. [43] stress the importance of synchronized efforts between cities and ports to manage congestion efficiently, showcasing the collective push towards a more integrated, technology-driven, and collaborative approach in tackling the complexities of port city congestion. Vadlamudi et al. [12] highlight the intricate nature of landside congestion management and the critical need to involve diverse stakeholders, including trucking firms and port terminal operators, in formulating thorough congestion mitigation strategies. Effective management of land-side transportation provides a competitive advantage to port terminal operators in improving services and making efficient use of the limited space in an urban port [13].

Indeed, the recent shift in the literature towards landside congestion underscores the necessity for expansive research, encompassing varied geographic contexts and the impacts on different stakeholders [2,4]. Some studies suggest that working in cooperation with stakeholders at all levels is necessary to increase internal and external operational and geographical capacity to align with future capacity needs. Islam and Olsen [44] identified a significant gap between the current and forecasted capacity utilization versus the actual volume at major ports, urging for extensive capacity expansions. This underscores that various factors driving capacity needs are outpacing the ability of ports and stakeholders to adapt. The paper suggests broad strategies, including engaging all transport network stakeholders and implementing productivity enhancements, physical expansion, and off-site solutions, to accommodate the expected doubling of container volume in the next decade.

- New Trends in Logistics Planning

Port logistics research is shifting towards AI and internet of things (IoT)-based models for smarter data acquisition and service management, aligning with Industry 4.0 principles. This includes integrating truck scheduling into smart port operations and developing analytical tools as part of a technology ecosystem that supports decision making through real-time analysis and simulation, known as digital twins (DTs). Facing congestion and environmental concerns, digital twins emerge as key in optimizing port operations and reducing ecological impact. These technologies simulate port activities in real time, enabling effective, sustainable solutions. Metcalfe et al. [45] discuss DTs' maturity levels, emphasizing their role in strategic decision making and innovation. Bedogni et al. [46] introduced an

IoT-based framework for creating and controlling DTs, enhancing machine learning-driven control. Klar et al. [47] highlighted DTs' benefits for port efficiency and sustainability, highlighting their ability to integrate diverse data for improved management. In the same vein, Bergeron et al. (2023) [48] utilize digital shadow simulation to enhance visibility in Canadian port operations, addressing challenges through technological advancements and better data strategies.

5. Conclusions

This in-depth study provides valuable insights into the challenges and strategies associated with managing port access fluidity during the construction of a new terminal at the Port of Trois-Rivières. Through a detailed analysis of various scenarios using discrete-event simulation models, it identifies effective access management strategies to mitigate potential congestion during critical construction phases. The study highlights the ability of existing access gates to manage increased truck flows and emphasizes the importance of optimizing unloading operations at the new terminal to reduce urban congestion and environmental impacts.

Key recommendations include strategic truck arrival planning, implementing peak-time appointment systems, and enhancing collaboration between city and port authorities to ensure efficient traffic management. The study also showcases the potential of synchromodality, road network centrality management, and capacity outsourcing through cooperation with other ports and dry ports as essential elements for addressing capacity and congestion issues.

Furthermore, the study acknowledges the significance of integrating technological advancements such as AI and IoT-based models, in line with Industry 4.0 principles, to enable smarter data acquisition and service management. Digital twins emerge as a promising tool for optimizing port operations and reducing ecological impacts by simulating port activities in real time.

In conclusion, this study not only addresses the immediate challenges faced by the Port of Trois-Rivières but also provides a blueprint for other ports facing similar challenges. It bridges scientific rigor and practical implementation strategies, offering a balanced approach to port management and expansion projects. Future research should continue to explore the interplay between technological innovations and operational strategies to further enhance port efficiency and sustainability, taking into account the evolving global trade landscape and environmental concerns.

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