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Preliminary investigation of the sea-rail intermodal system's efficiency using a simulation approach: case of the Port of Trois-Rivieres

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Abstract

Sea-rail intermodal transportation around the globe faces complex challenges that affect the satisfaction of shippers' needs. An efficient cargo flow between the port and its hinterland depends particularly on efficient connectivity between the seaport and rail. Sea-rail intermodal can be a cost-efficient and green alternative to unimodal road transportation. Inefficient sea-rail connectivity in the seaport slows cargo flow and affects port capacity. Various factors could affect the system's efficiency and create bottlenecks in the system. A case study adopts a discrete event-based simulation approach to assess bottlenecks in the sea-rail connection that affect cargo flow and generate congestion. The data were collected from the Port of Trois-Rivières, the focus of our investigation. Our objective is to identify bottlenecks in the sea-rail intermodal system in the port, identify strategies to mitigate bottlenecks and accelerate cargo flow. To this end, we examined various scenarios, including an increase in the share of trains for cargo transportation and an increase in the number of daily train convoys. The findings underscore that elevating the train share to 40% and introducing two daily train services yield significant enhancements in key performance indicators. Noteworthy advantages encompass a reduction in the average time ships spend in the port, a decrease in the average waiting time for trains to depart from the port, an overall improvement in cargo handling efficiency within the port, and a notable alleviation of bottlenecks within the system.

Keywords: Sea-rail intermodal, Simulation, Port capacity, General cargo port

Introduction

Port authorities primarily aim to increase the annual throughput of handled cargo in the port to avoid building new facilities until existing facilities are fully utilised (Bassan 2007). Scholarly research has identified various port reform drivers that can lead to better port performance, including efficiency measurements and investment in port capacity and infrastructure (Doctor 2016; Bergqvist and Cullinane 2017). Terminal throughput capacity is defined as the estimated total cargo that can be processed or put through a terminal in a year, with TEU per year for containers, tons, or pallets per year for bulk cargoes and autos per year for Ro-Ro cargoes. Insufficient port capacity increases ship waiting time, resulting in lost clients and shipping lines (Balliauw 2020). According to a survey by Langen et al. (2018), approximately 70% of requested investments in European ports from 2018 to 2027 involved capacity investments. Owing to increasing ship size, terminals have become a bottleneck in the intermodal transportation system, and any delays or inefficiencies in terminal operations can adversely affect the supply chain (Amir Gharehgozli 2019). Minimising ship dwell time at the terminal is essential to improve port operations, which can be achieved through the right investment channel in infrastructure and terminal superstructures. A short time spent in a port indicates port efficiency and competitiveness (Nations 2019).

Transporting cargo from the seaport to its next destination using sea-rail intermodal transportation is a complex system that requires careful planning to perform operations efficiently. Inefficient terminal operations can slow cargo flow and increase ship dwell time in the port, leading to increased costs. Storage facilities and open storage areas at seaports serve as temporary storage points for cargo, facilitating the exchange of transportation modes to reach their final destination (Cullinane and Wilmsmeier 2011). However, minimising cargo dwell time at seaports is a key challenge, as long-term cargo storage in the port negatively impacts port capacity (Ng and Talley 2020).

An integrated rail network with an accurate schedule and proper synchronisation between trains and ships can enhance a port's ability to meet increasing demand for port services and enable shipping firms to offer reliable service at a competitive rate. However, in our case study, The Port of Trois-Rivieres is grappling with substantial obstacles that hinder operational efficiency and the achievement of strategic goals. The challenges identified in technical reports and the port's strategic plan are linked to the limitations of the current rail network. Efforts to increase rail share are impeded by critical issues at specific intersections, leading to delays in wagon movement. Congestion is exacerbated by restrictions on the number of wagons in each convoy passage to storage facilities, resulting in a bottleneck and a slowdown in cargo flow. The port's urban surroundings constrain its capacity expansion, compounding challenges related to rail network flexibility, cargo handling, and transport. The Port of Trois-Rivieres faces a particular challenge because of its location, which is surrounded by a city. Rail track between the port and its hinterland crosses a number of city streets; train operations block many streets during the day, causing congestion and negatively affecting the city. Despite plans for a new terminal in the western part of the port, connecting it with the existing port and eliminating bottlenecks remains a major challenge for ensuring smooth cargo flow and addressing capacity issues.

To overcome this challenge, there is a need for new methodologies and technologies that guarantee enhancements to increase port capacity and performance. Port operators must find solutions that balance the port's needs with the city's interests and guarantee enhancements to increase port capacity and improve performance. The study is prompted by identifying a bottleneck in the targeted port in a previous study (Bergeron 2022). Even though the previous study identified a bottleneck in cargo flow in the port, it did not investigate the bottleneck created by the movement of wagons in depth. Therefore, this study investigates the bottlenecks caused by the movement of wagons in the port in depth.

To the best of our knowledge, most of the current research focuses on issues of the exchange of cargo between ships and trains in container ports. However, there is a scarcity of research investigating the issues of exchange cargo in general cargo ports. In other words, this paper focuses on the detailed movement of wagons between the train yard and the loading/unloading point in the general cargo port to investigate system bottlenecks. The main research question is: To what extent can we mitigate bottlenecks in the sea-rail intermodal transportation system within the port, thereby reducing cargo dwell time in the port and accelerating cargo flow to their destinations?

This research provides significant insights for port management, highlighting the effectiveness of simulation techniques in diagnosing issues in the wagon network within the port. The study will help decision-makers in the seaport to evaluate investment decisions in terminals and make proper decisions by understanding bottlenecks in transferring general cargo within the port through the simulation approach. In addition, port authorities could use the study to evaluate port performance.

The study analyses the movement of wagons in a Canadian general cargo port, identifies areas where operations can be improved, and evaluates the impact of these improvements on port capacity. To successfully mitigate bottlenecks and accelerate cargo flow, the study employed discrete event simulation to explore various scenarios. These scenarios included increasing the proportion of cargo transported by trains and increasing the number of train convoys per day.

The remainder of the paper is structured in the following manner: Sect. 2 provides an overview of previous research related to the problem. The research methodology is discussed in Sect. 3, whereas Sect. 4 presents the simulation results. Section 5 evaluates the proposed scenarios. Section 6 concludes the study.

Literature review

Port-rail connectivity is a strategic element of port development in an economic context, as well as the reduction of negative externalities on the community and the environment. Proper rail connectivity not only expands the port hinterland but also promotes capacity growth without affecting the port-city relationship by linking "spatially" fragmented processes without congesting the urban environment around the port (Matamala and Salas 2012). This interest aligns with the goals of the Trois Rivieres port, aiming to establish connections with the hinterland while ensuring minimal negative impact on the city surrounding the port. Additionally, Shan et al. (2014) found that port cargo throughput positively affected the host city's economic growth based on their data analysis from 41 major port cities in China from 2003 to 2010. Since the port of Trois Rivieres is a general cargo port and there is no possibility of expanding the port area, it is essential to use space effectively to maximise efficiency and economic benefits. Stacking order, method, cargo characteristics, shape, and volume significantly impact yard space utilisation. As noted by Hongwei Tian (2018), the general cargo yard serves as a short-term storage location, and proper use of the space is vital to optimising its functionality.

Sea-rail intermodal

Efficient cargo transportation from the port to its destination is critical due to the high cost associated with transportation activities, such as shipping and port activities. Therefore, it is imperative to carefully consider the transportation system to ensure it is cost-effective and efficient. Thus, an effective and efficient transportation system is required (Putra et al. 2018).

Due to the high frequency and flexibility of the road transportation mode (Bouchery et al. 2020), its market share is steadily growing worldwide (Hanssen et al. 2012). In the port of Trois Rivieres, about 70% of cargo is transported by trucks, and 30% is transported by train; the port plans to increase the train share by improving the current rail network within the port and delimiting the bottleneck in the port. In the context of a climate emergency, moving from trucks to trains is urgent since rail is considered a more sustainable transportation mode (Ng and Talley 2020). Various countries are planning to mitigate congestion and environmental effects, especially from urban traffic, including port-related trucking transportation. For example, Rotterdam Port has planned to reduce its traffic by 20% during city peak periods; the Los Angeles and New York ports also have their own strategy (Fan et al. 2020). Port of Trois Rivieres has an initiative with the collaborative partnership announced in 2022 between the ports of Montreal, Quebec City, and Trois-Rivières, aimed in particular at greening their facilities, operations, and supply chains. It also supports the three ports' efforts to join Canada's government's carbon–neutral challenge. Nowadays, road congestion is a serious problem in urban port cities worldwide, causing major delays in shipments and disturbing the entire supply chain (Selmoune et al. 2020). Recently, many researchers have been studying sea-rail intermodal transportation because of its lower cost and carbon footprint compared to other transportation modes. Many container ports are trying to enhance connectivity between the terminal and hinterland by investing in a rail terminal located at seaports. Efficiently accelerating container flow between container ships and trains is one of the significant problems that must be addressed (Yan et al. 2020). The entrance to and exit from the train area clogs because trains arrive, depart, or are processed on the same tracks. A common solution to this problem would be to increase the facility size. However, in many cases, expansion is not feasible due to a lack of available land near the port (Hdrinc 2021). This challenge represents just one of the many issues the Port of Trois-Rivières faced. Fang (2016) pointed out two main reasons for the lack of smooth sea-rail connections: lack of connecting conditions between railway container yards and ports and incomplete sea-rail intermodal transport information system construction.

Examining the research perspective on sea–rail intermodal transportation, Liu and Wang (2023) conducted a study aimed at assessing the service capacity of port-centric intermodal transhipment hubs. The evaluation was categorised into three dimensions: radiation scale capacity, transportation connection capacity, and resource integration capacity. Utilising the fuzzy matter element method, the service capability of these hubs was evaluated, and the results were quantified through the Euclidean closeness degree. The findings indicate that Tianjin Port possesses the highest service capacity, followed by Ningbo Zhoushan Port. The dedicated rail line mileage is a critical area that requires attention in Ningbo Zhoushan Port and Qingdao Port. Tianjin Port should enhance its container sea–rail transportation volume, while Guangzhou Port and Xiamen Port should focus on improving sea–rail container handling capacity.

The aforementioned studies distinctly underscore the significance of enhancing sea-rail intermodal operations within the terminal to facilitate cargo flow and mitigate the adverse effects of cargo transportation between the port and its hinterland.

Benefits of sea-rail intermodal transportation

Despite their vital role in the global supply chain, ports have a significant negative environmental impact, primarily stemming from terminal operations and activities (Hossain et al. 2019). Consequently, mitigating this impact and enhancing terminal performance sustainability is imperative (Vacca 2010). Reducing the carbon footprint associated with transport logistics at seaports is a complex challenge. Meng (2018) analysed the overall benefits of sea-rail intermodal transportation and the status of combined rail and water transport in containers in China.

The increase in container traffic and environment rules in the recent decade have forced the involved parties to pay more attention to the negative influence on their operational activities. Recently, considerable attention has been paid to the sea-rail intermodal container transportation sector because of its cost and environmental benefits (Ashrafi et al. 2019; Di Vaio and Varriale 2018; Acciaro 2015; Roh et al. 2016; Sislian et al. 2016; Kang and Kim 2017; Langenus and Dooms 2018; Oh et al. 2018).

Sea-rail intermodal transportation is a crucial component of international trade, gaining global recognition because of numerous benefits, including the ability to handle large volumes, low cost, and low energy consumption. Liu (2020) proposed a route optimisation model for container sea-rail intermodal transport by minimising the total cost as the objective function. In the Zhao et al. study (2020), a multi-objective optimisation model was established to reduce the total cost of the transportation process, which meant maximising resource utilisation and ensuring it was environmentally friendly. Most studies conducted in the field of intermodal transportation have primarily emphasised the reduction of operating costs as a primary objective (Ghane-Ezabadi and Vergara 2016; Hanssen et al. 2012; Ishfaq and Sox 2011; G. Chen et al. 2013).

The better environmental performance of sea-rail intermodal versus road transport is often presented as evidence by policymakers to encourage the modal shift to sea-rail intermodal. Because low-carbon emissions and mass capacity are major benefits, sea-rail combined container transportation has been believed to be a promising way to mitigate air pollution and traffic congestion (Yan and Xu 2021). In that regard, the study of Zhang et al. (2021a, b) assesses the environmental benefits of the modal shift of port-connecting freight transportation by increasing the use of sea-rail intermodal in Shenzhen. Abu Aisha et al. (2020) compared GHG emissions produced by different modes of transportation to increase train dependence on transport containers in sea-rail intermodal.

Transshipment operation efficiency

Although sea-rail intermodal is a tremendous opportunity to improve seaport competitiveness, various factors determine their efficiency. Factors affecting the port container sea-rail transportation system, as described in (Chen and Zhang 2021), can be divided into internal and external factors. The interior sea-rail intermodal transport factors compositions in the container port are infrastructure, production equipment, resource scheduling, and transmission service subsystem. In contrast, the external compositions are geographical location, economic level, transport policy changes, and weather characteristics. The impact of most of these factors is notably evident in our case study, which is the port of Trois Rivieres. The system's infrastructure is considerably aged, and the rail network is characterised by numerous intersections, impeding the smooth flow of wagons within the port, prompting a closer examination of its existing infrastructure and potential improvements needed to enhance efficiency.

Additionally, the port's geographical location, surrounded by the city of Trois Rivieres, constrains train movements through the urban area during daylight hours to prevent street blockages. Understanding and addressing these constraints is crucial for enhancing sea-rail intermodal operations within the port. The study by Zhang et al. (2021a, b) demonstrated that logistics facility location and layout can significantly affect seaport connectivity with other transportation modes. The study further has shown that location rationality and logistics facility layout reduce costs by delivering an economy of scale and maximising transportation efficiency and service quality by planning efficient multimodal networks.

Similarly, Naiyu Wang and Wei (2020) summarised factors affecting rail-sea intermodal transportation handling equipment configuration and put forward the principles that should be considered when configuring the equipment. In another research, the model of Zhao et al. (2018) considered many factors, such as transshipping capacity, network capacity, and the importance of containers, to minimise total container hours in the coordination area, reflecting the efficiency of inbound container distribution organisation.

Feng et al. (2014) defined dry bulk's key sea-rail intermodal transport factors. Dynamic system and modelling software VENSIM were used to establish a dynamic system model of sea-rail intermodal transport of dry bulk. The case of sea-rail intermodal transport of dry bulk at Meizhou Bay Port in Fujian was used to simulate and check the model; the result showed that the model was feasible and effective.

Han et al. (2020) analysed vital factors influencing the level of multimodal transportation development from a sea-rail intermodal transport perspective. He concluded that the volume of intermodal container transportation and railway mileage were the core factors affecting the level of multimodal transportation development. The evaluation model results can objectively reflect the level of multimodal transportation development and problems in each city in China.

The main operations of the chain's rail-sea link are train transfers between the railway station and the maritime terminals, train loading and unloading, and the storage management of goods in dedicated yards. Trains approaching the area may sometimes have to split into cars depending on specific ports; these cars are then transferred to destination terminals (and vice versa for the import cycle).

Grishin et al. (2022) addressed the problem of optimising cargo transfer from ships to trains at the sea-rail terminal in Russia, aiming to reduce the overall delivery time to the destination and minimise the cost associated with train formation. Two models were formulated for this purpose: a binary model and an integer model, both of which were compared. These models were executed using the Gurobi optimiser.

Yan et al. (2020a, b) conducted a study on the sea-rail transhipment operation problem regarding seaport rail terminals, which included two key sub-problems involved in sea-rail intermodal container transportation: namely, train schedule templates and inbound container transhipment plans. In another study, Yan et al. (2020a) investigated transhipment operations between vessels and trains in seaport rail terminals. Results showed that handling capacity significantly affected transfer plan performance, and an increase in the storage cost of import containers led to a more effective transhipment plan. Pingping et al. (2013) analysed the challenges of Ningbo sea-rail combined transport in China. These challenges included connecting the port with the hinterland and expanding the expected hinterland of rail-sea intermodal transportation in Ningbo. Canadian ports respond to record cargo volume growth through major expansions and far-reaching transformation of their facilities (Zatylny 2020). One example of investigating rail-seaport intermodal issues in a Canadian port is studied by Gillen et al. (2018), demonstrating that enhancing train services and increasing train frequency is the best way to improve port performance.

Although the principle of dry port is not new, its implementation and proficient operations have been only recently exploited and implemented. In this respect, Borruso et al. (2023) conducted an analytical study to highlight the importance of railway connections between the seaport and its hinterland, particularly in terms of the reconstruction of the rail links among the Port of Trieste and its major inland destinations. However, it is essential to emphasise that the research has focused almost exclusively on the geographical aspects of evaluation.

Various authors have investigated numerous strategies to improve sea-rail intermodal efficiency. For example, Abu Aisha et al. (2020) suggested changing the container terminal layout and connecting it to a dry port with a rail track to enhance sea-rail intermodal efficiency. This suggestion was approved according to results by Tadić et al. (2021). The study concluded that the best intermodal transportation system development scenario referred to establishing dry port terminals for Danube River ports with improved network connectivity between terminals via rail transportation mode. Another strategy to improve sea-rail intermodal, suggested by Li and Ye (2009), was to develop a management information system for railway-sea intermodal transportation. The synthetic logistic information platform, including information on railway-sea intermodal transportation, should be established to execute information sharing among the railway, port, customs clearance, three inspections, intermodal transport companies, ship-owners, and consigners. Jarašūnienė and Čižiūnienė (2021) covered the need for applying information systems in the field of maritime and rail transport. Insights from these studies could be beneficial in developing strategies for the Port of Trois-Rivieres that promote efficient cargo transfer, minimise overall delivery times, and reduce associated costs.

Many container ports worldwide are trying to enhance connectivity between railway transportation and the shipping area by investing in rail terminals located at seaports. Due to the multi-management of combined railway and port operations, a series of problems may cause low operation efficiency. While the studies in the literature review provide a broader understanding of sea-rail intermodal systems, applying these insights to the specific context of the Port of Trois-Rivieres would require a detailed analysis of the port's current situation, operational challenges, and goals. It serves as a valuable resource for identifying relevant factors and potential strategies that could contribute to improving sea-rail intermodal operations in Trois-Rivières.

Although many studies have been carried out to assess and improve port operation efficiency, most research has emphasised the container terminal. However, non-containerised cargo has specific characteristics and needs to be transported in general cargo ships or bulk carriers. Despite the prevalence of general cargo ports handling raw materials, there is a notable absence of research investigating these specific types of ports. The Port of Trois-Rivières, situated in Quebec, is one of the general cargo ports, and it is a case study of this research. This study aims to fill the research gap and contribute valuable insights that can benefit ports throughout Quebec. Particularly, these insights can support the alignment of Quebec's ports with the provincial government's plan to achieve a substantial 37.5% reduction in greenhouse gas emissions below 1990 levels by 2030 (Québec 2022).

Most of the previous research focused on addressing the impact of particular factors on the performance of the system within the container terminals, and mathematical models were widely used to solve these problems. However, the current study focuses on general cargo ports, and complexity is characteristic of these types of ports. Since handled cargo in general cargo ports is different in shape, condition, and size, the operations in general cargo ports are more critical and complex than those in container ports. Therefore, the simulation approach will be the proper tool for the current study to solve problems in the complicated system of the port of Trois Rivieres. Leveraging a simulation model, we aim to discern factors contributing to bottlenecks and propose viable enhancements for the intricate system.

Based on the literature review, no comprehensive research has been conducted to analyse how wagons operate within ports and increase rail share in any ports. Therefore, this study aims to examine operations of moving wagons between rail tracks and handling points in an actual general cargo port to identify improvement points and analyse their impact on the port operation using discrete event simulation in the ARENA simulation software, version 16.0. In this study, one of the most active general cargo ports along Canada's St. Lawrence River has been selected to be analysed in railway cargo functioning. Although the Port of Trois-Rivieres has a railway system infrastructure and the benefits of using this transportation method are clear, its railway performance seems to have potential for improvement.

Research methodology

Because of the significant intricacy of the processes involved and the considerable expense associated with implementing real-world modifications, the study used a simulation to model the current situation and proposed scenarios. The simulation provided an opportunity to explore the real world without the high cost and interference with real-world systems. Additionally, by adjusting the study variables, researchers can observe the global impact of changes.

Data collection

Three sources of information were employed during this research to understand all cargo operations and wagon movements in the port. The first source was field visits to the Port of Trois-Rivieres in July, August 2022, and February 2023. During each visit, all operations were investigated and scheduled, including loading and unloading cargo, transferring cargo to storage facilities, loading trucks and wagons, and sending wagons to the train yard in the port to leave the port.

During the port visits and sharing files with the port authority, we obtained data files such as maps and port layout, historical data of ship arrival and associated data, as well as types and amounts of cargo. Other data was related to trains, such as arrival and departure times and dates, as well as amounts and types of cargo. Some of the data was taken from the port's statistical reports. Additionally, many meetings were scheduled with the port authority to discuss the format and required data and clarify some port operations. Some meetings took place at the port, and others were held via Zoom.

Moreover, security cameras installed in the port were used to observe the time to transport wagons between the train yard and the loading point. The recorded video was meticulously transferred to the laboratory for in-depth analysis and time study. Given the exploratory nature of our study, as stated in the title, we had limited observations from video records to determine the time it takes to transport wagons between the train yard and the loading point. Therefore, we decided to model this transportation time using the normal distribution. This choice was influenced by findings from our literature review, which showed that transportation and transhipment times often follow this distribution pattern (Xu et al. 2021). The accuracy and consistency of data were verified using the base scenario.

Case study

The Port of Trois-Rivieres is the case study used in this work. This port is strategically located halfway between Montreal and Quebec City and has been an active Canadian port since 1882. The port plays a crucial role in local, national, and international economic development, particularly in major industrial sectors such as aluminium, forestry, and agri-food. The Port of Trois-Rivieres is a general cargo port that receives more than 200 ships from over 100 different ports in more than 40 countries worldwide. The port has ten berths with a length of 1458 m. The port also receives 11,000 wagons and 55,000 trucks annually. In all, more than 3.5 million metric tons are handled by the port. The Port of Trois-Rivieres is a medium-sized urban port specialising in the storage and multimodal transport of a wide variety of bulk products and general cargo. We visited the port many times to build a model of the Port of Trois Rivieres; the port layout is shown in Fig. 1.

Once the ship arrives at the port and is berthed, ship unloading operations to the storage facility or ship loading from the storage facility begin. The ship leaves the port after ending these operations. Trucks and trains transport cargo between the port and the hinterland. Trucks arrive at the port based on the availability of cargo that needs to be picked up by trucks. The train entry has been restricted to only 7 a.m. and 11 p.m. to minimise potential disruptions to public roads within the city.

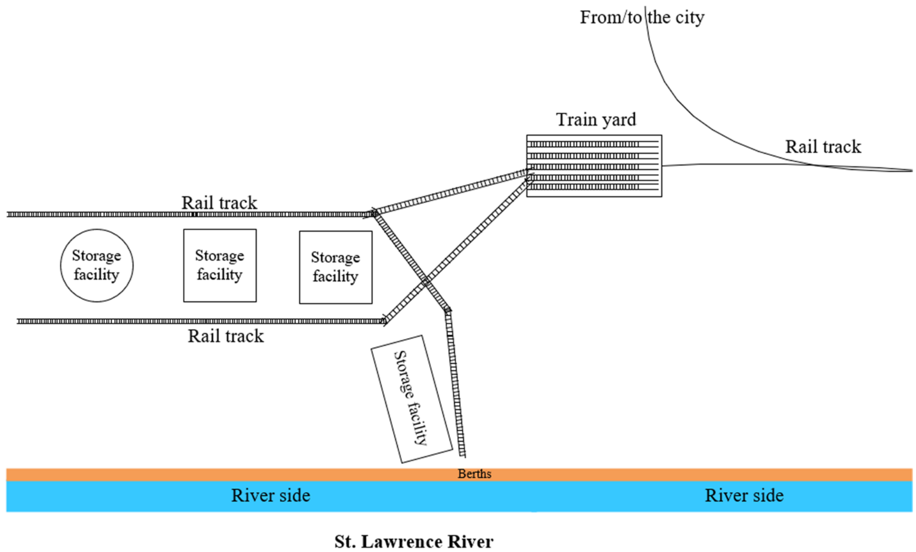

Fig. 1 Rail track network sketch in the port

The train arrives at the port vertically with the berths and runs parallel to the berth, as shown in Fig. 1. The wagons stop in the train yard located inside the port. From the train yard, wagons are sent to storage facilities to load or unload the cargo in groups of wagons.

Simulation model

Since a general cargo port is a complex system consisting of many subsystems and various overlapping operations that undoubtedly affect outputs, a model that simulates such a system could provide a significant analytical benefit. A complex, large-scale, discrete event-based simulation model was developed to implement and validate the developed framework. The model was created after a comprehensive understanding of the actual system and all operations related to handling and transporting the cargo in the Port of Trois-Rivières. While the simulation code is not included in the supplementary materials, it is available upon request for researchers. We modelled wagons and cargo flow movement, starting from the ship's arrival at berth to unload or load its cargo and the truck and train arrival to load or unload the cargo and leave the port, as shown in Fig. 2. Since this study is a preliminary investigation, the model of this study does not consider seasonality in cargo flow; it will be our focus of attention in the next port project.

Entities that move through the simulation model include ships, cargo, trucks, and wagons. Resources include six berths, two loaders to load/unload the ship, one loader to load/unload trucks, one loader to load/unload wagons, and a storage facility. The processes are created to represent port operations for loading and unloading cargo and moving wagons in the terminal. In this context, four key system parameters were selected based on their significant impacts on the system performance: (1) ship arrivals, (2) train arrivals, (3) truck arrivals, and (4) the amount of cargo, in addition to (1) time to move wagons from train yard to storage facility and (2) time to load and unload wagons. Including these parameters reflects their critical roles in evaluating

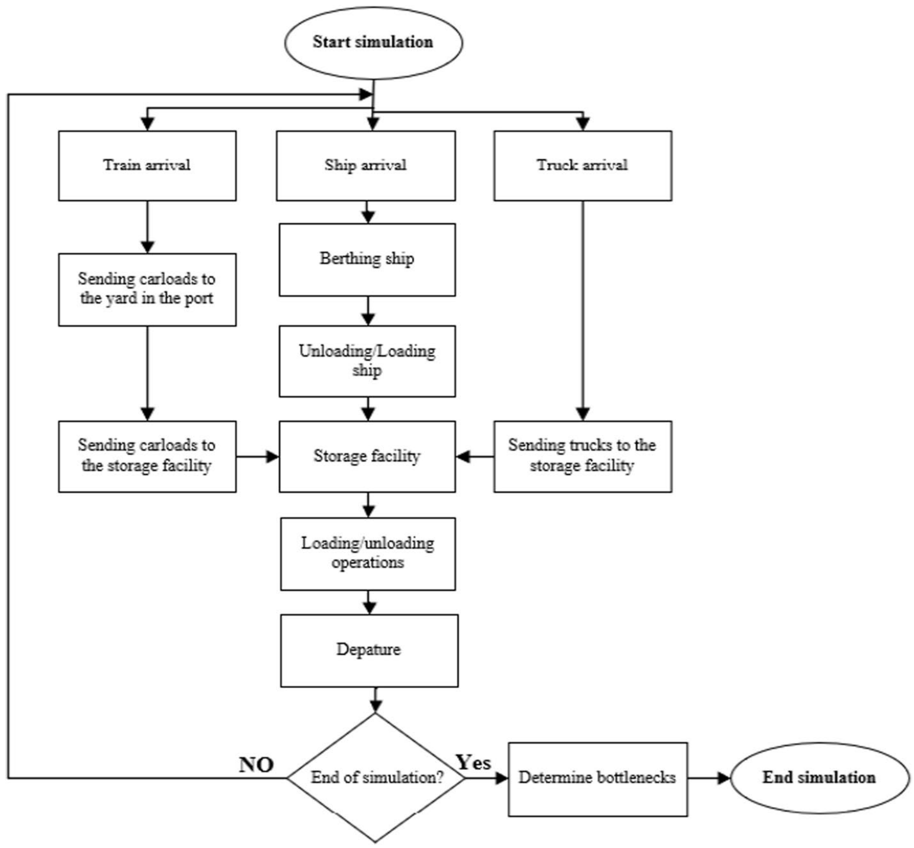

Fig. 2 Simulation model

port congestion, resource utilisation, and overall cargo flow efficiency. The initial values of ship, train, and truck arrivals are zero, but during the simulation run, these values are subject to change based on real data, which is correlated to the day and time of the year. We assumed a consistent load of 15,000 tons per ship for cargo volume, derived from the average cargo capacity observed in ships visiting the port. The initial values for the time required to move wagons from the train yard and for loading and unloading wagons are set at zero. Still, they are susceptible to real-data adjustments throughout the simulation run. Table 1 presents justifications to clarify the rationale behind the parameter selection and to emphasise their relevance to real-world port operations.

The cargo operation flow chart in the port is illustrated in Fig. 2. With the help of this chart, the model was used to test various scenarios to accelerate cargo flow between the port and the hinterland.

A discrete simulation model was developed using the SIMAN simulation language and implemented through the ARENA software application. We used this software to structure the conceptual and simulation model for the port layout, including ship arrivals, cargo operations, truck movement inside the port, and train operations. The objective of the model is to reflect the system's functioning and assess its performance

Table 1 Justifications of parameter selection

Parameters	Justification
Ship arrivals	Crucial for assessing the flow of vessels, impacting port congestion and overall cargo handling capacity
Train arrivals	Essential to understand the frequency of trains, influencing the rail transport aspect and its integration with other modes
Truck arrivals	Signifies the arrival frequency of trucks, affecting ground transport logistics within the port
Amount of cargo	Represents the volume of cargo being processed, influencing storage facility occupancy and overall system load
Time to move wagons from the train yard	It reflects the efficiency of transferring wagons from the train yard to the storage facility, which is a critical factor in cargo flow
Time to load and unload wagons	Measures the duration required for loading and unloading wagons, impacting the overall speed of cargo movement within the port

to discover bottlenecks that negatively affect port capacity and assess various scenarios to improve port efficiency.

System performance consists of calculating the number of trucks, wagons, ships, and the amount of cargo transported by many modes of transportation to discover bottlenecks in the system. These can be defined based on the average number of wagons in the system, the average waiting time to enter the port, and the amount of cargo remaining in the storage facility that needs to be transported out of the port or loaded on the ship for export.

In order to analyse and evaluate system performance, we conducted a variety of simulation tests aimed at demonstrating bottlenecks in the system. The model has three components: ship movement and activity, truck movement, and wagon movement and activity in the terminal. Each component has many operations, and each operation performs a specific task or event in the system (for example, ship arrival and departure, truck arrival and departure, truck loading/unloading, train arrival and departure, wagon grouping and separation, transport, loading, and unloading cargo). The study will focus on analysing the movement of the wagons in the terminal.

The simulation model considered the Port of Trois-Rivieres business hours, i.e., 8 a.m. to 5 p.m., Monday to Friday. In other words, loading and unloading operations and truck movement to and from the port take place from Monday to Friday from 8 a.m. to 5 p.m., whereas the trains arrive and leave the port at 7 a.m. and 11 p.m. However, the simulation model was developed to model generic port operations as well as ship, truck, and train movement in the port.

Because of uncertainties such as random truck, train, and ship delays, separate simulation replications were needed to determine the necessary time for the system to reach its steady state. If we consider only a single replication, the results may be influenced by specific or unusual events within the system, such as the arrival of trains, trucks, or ships, as well as loading/unloading and time of sending wagons to storage facility. However, these events are stochastic in nature, meaning they are subject to randomness and variability. To ensure the accuracy and generalizability of the results over multiple years, it is essential to conduct multiple replications of the simulation. By running numerous replications, we can better capture the variability inherent in the system and obtain a more robust understanding of its behavior. Consequently, the duration of simulation runs was set to 365 days. On average, each run takes 2.65 min on a computer with a 2.00 GHz CPU. In 2019, the port handled 217 ships, 159 imported ships, and 58 exported ships. The port can receive 150 trucks and handle 40 wagons daily, but the number and arrival of trucks and trains are based on ship arrival. The processing time to load and unload modes of transportation was calculated based on the number of each mode the port can handle per day, considering weekends and business hours.

After implementing the system in ARENA software, many steps are conducted to assess and validate the simulation model's accuracy, including model operation monitoring, animation displays, and debug features in the simulation software. Model operation monitoring involves observing and analysing a simulation model's performance while running to ensure that it behaves as expected, represents the real-world system, and identifies any issues. Animation displays visually represent the simulation model, allowing you to observe the system's dynamic behaviour over time. As the simulation ran, we observed the movement of entities through the system and the utilisation of resources in real-time. In addition, we observed whether resources were appropriately assigned, whether queues were behaving as expected, and whether resources were idle or busy as per the model logic to ensure that entities moved through the simulation model according to the defined logic and that there were no unexpected delays, blockages, or other issues. Also, the ARENA software's debug features were used to monitor the value of specific variables, and the breakpoints feature was used to inspect the model and variables at a given breakpoint. Therefore, This helped identify the cause of unexpected behaviour. System bottlenecks appeared after the simulation run ended. The block diagram representation of the simulation model is illustrated in Fig. 2.

Simulation results

The results presented in this paper stem from an extensive one-year simulation of the port operations, meticulously accounting for business days and hours and incorporating five replications to ensure robustness. Over this period, the port successfully managed a total cargo volume of 3,197,000 tons.

Breaking down this comprehensive cargo volume, the imported cargo accounts for 2,342,000 tons, imported by the arrival of 156 ships, with an additional three ships in the queue awaiting entry into the port. Meanwhile, the total exported cargo amounts to 855,000 tons, exported by 57 ships.

Examining the impact of capacity conditions on the maximum number of wagons within the port, the simulation results, spanning one year, reveal intriguing patterns. After this duration, the average volume of imported cargo remaining in the storage facility stands at 21,335 tons, highlighting the challenges associated with managing cargo storage within the port. Similarly, the average volume of exported cargo still present in the storage facility is 10,719 tons. The level of handled cargo in storage facilities can affect the overall port capacity, the number of vessels entering the port, the flow of vessels, and the punctuality of arriving ships. Consequently, this can give rise to bottlenecks within the port's operations.

This underscores a critical operational challenge. Wagons are needed to transport the stored cargo out of the port and bring new cargo to the export storage facility to meet the loading requirements for outgoing ships. However, the simulation highlights bottlenecks in the system due to restrictions on the maximum capacity of wagons allowed in the port and the limitation on entry and exit times, set exclusively at 7 a.m. and 11 p.m. These constraints collectively contribute to the hindrance of wagon entry into the system, exacerbating the formation of bottlenecks within the port's logistics network. The study focuses on this aspect because there are many factors that need to be investigated in the preliminary investigation that impact the number of wagons entering the port.

Given that 70% of the cargo is transported by trucks and the remaining 30% by train, we anticipate respective shares of 1,639,400 tons and 702,600 tons. However, simulation outcomes in terms of imported cargo, under the condition of a daily capacity of 150 trucks and 40 wagons entering the port, reveal that truck transport amounts to 1,627,500 tons, while trains handle 679,860 tons.

In the realm of exported cargo, the total stands at 855,960 tons, with trucks responsible for 609,000 tons and trains for 246,960 tons. One ship remained idle in the system, awaiting cargo, as trucks and wagons have reached the maximum capacity of the number that can enter the port, precluding further entry. The average count of wagons in the port is 64. Table 2 summarises these results, and Table 3 provides a comprehensive breakdown of the transportation modes used in transporting the total cargo at the port.

Since this study analyses wagon movement in the port, Table 4 illustrates train and ship times. Our simulation model has a relationship between the wagons and the ship because arrival time and the number of wagons are based on ship arrival.

Strategies to mitigate bottlenecks in the port

After defining system bottlenecks, some strategies were proposed and evaluated to mitigate the bottlenecks in the port and utilise the port's unused capacity. In addition, these strategies encouraged port operators to use rail transport since it is a more environmentally friendly alternative.

The proposed solution led us to increase the train share, but increasing the rail transportation share by up to 50% of total cargo could increase the number of wagons in the port even though the port has a limited capacity for wagons. The proposed solution is

Table 2 Amount of cargo carried by modes of transportation

Items	Basic scenario 70% trucks and 30% train	
	Import (tons)	Export (tons)
Total tons carried by ships	2,342,000	855,000
Average cargo in storage facility	21,335	10,719
Total tons carried by trucks	1,627,500	609,000
Total tons carried by train	679,860	246,960
Maximum cargo level reached in the storage facility	64,220	
Average of maximum cargo level reached in the storage facility	32,055	
Total cargo handled in the port	3,197,000	

Table 3 Number of vehicles for each transportation mode in the system

Items	Basic scenario 70% trucks and 30% train	
	Number in	Number out
Number of ships	217	213
Number of loaded ships	159	156
Number of empty ships*	58	57
Number of trucks to load	54,600	54,250
Number of trucks to unload	20,300	20,300
Number of trains	259	257
Number of wagons	10,360	10,280
Average number of wagons in the port	64	

*Empty ships mean the ship that arrived empty at the port to be loaded with cargo

Table 4 Time of transportation modes in the system

Items	Basic scenario 70% trucks and 30% train
	Time (min)
Average time of ships in the port (imported cargo)	6644
Average time of ships in the port (exported cargo)	5475
Average waiting time of empty ships for enough cargo to load*	4995
Average waiting time of trains for enough space to enter the port	4397
Average waiting time of trains for a particular Time (7 a.m., 11 p.m.) to enter the port	575
Average waiting time of trains for a particular Time (7 a.m., 11 p.m.) to leave the port	602
Average time of wagons in the port	3257

*Empty ships for enough cargo to load" means the ship that arrived empty to the port to be loaded with cargo

based on two arguments: increase the percentage of rail share in transporting imported and exported cargo through the Port of Trois-Rivieres and add another train service.

Currently, trains operate only at 7 a.m. and 11 p.m. because they intersect with many public roads, negatively affecting the city. Adding another train service at 11 p.m. will reduce wagon turnover time in the port.

To implement the proposed solution, we created three scenarios for testing and evaluation. In the first scenario, we kept the percentage of train and truck shares as they are, but we added another train service at 7 a.m. and 11 p.m. In the second scenario, the train share increased by 40% and two train services were added at 7 a.m. and 11 p.m., whereas in the third scenario, the train share increased by 50% and two train services were added at 7 a.m. and 11 p.m. The proposed solution could help reduce cargo turnover time in storage facilities at the port, consequently increasing the use of existing capacity in the port. The simulation results of these comparisons are shown in Table 5.

The total tons of cargo imported and exported by ships are presented for each scenario. These values indicate the overall volume of cargo handled by the port in different scenarios. Across all scenarios (Basic, Scenario 1, Scenario 2, Scenario 3), the total tons imported by ships increased between the basic scenario and the other three scenarios, and they remained constant at 2,342,000 for the three scenarios. Similarly,

Table 5 Scenario comparison and amount of cargo by modes of transportation

Items	**Basic scenario 30% train and one train service**	**Scenario 1 30% train and two train services**	**Scenario 2 40% train and two train services**	**Scenario 3 50% train and two train services**
	Amount of cargo (tons)	**Amount of cargo (tons)**	**Amount of cargo (tons)**	**Amount of cargo (tons)**
Total tons imported by ships	2,342,000	2,380,000	2,380,000	2,380,000
Total tons exported by ships	855,000	855,000	855,000	855,000
Average cargo in storage facility (import)	21,335	17,033	14,855	16,460
Average cargo in storage facility (export)	10,719	12,619	12,889	12,396
Total tons picked up by trucks (import)	1,627,500	1,659,000	1,422,000	1,185,000
Total tons picked up by train (import)	679,860	694,620	934,560	1,173,870
Total tons drop off by trucks (for export)	609,000	609,000	522,000	435,000
Total tons drop off by train (for export)	246,960	255,780	344,520	433,260
Maximum of cargo level reached in the storage facility	64,220	50,760	50,280	52,800
Average of maximum cargo level reached in the storage facility	32,055	29,653	27,745	28,857

the total tons exported by ships remain consistent at 855,000 since there is no change in the number of ships.

Additionally, the average cargo inventory in the storage facility for both imported and exported goods provides valuable insights into the levels of cargo maintained within the port's storage facilities throughout the simulation time. For imported cargo, the average cargo in the storage facility decreases as the percentage of train share increases. Scenario 2, with 40% train share and two train services, has the lowest average import cargo in the storage facility at 14,855 tons. Conversely, for exported cargo, the average cargo in the storage facility fluctuates across scenarios. Scenario 2 has the highest average export cargo at 12,889 tons. This is because, in scenario 2, the port still has enough capacity to accommodate the trains. In contrast, in scenario 3, the port does not have enough capacity to accommodate the trains; consequently, the average of imported cargo in the storage facility was increased.

The total tons of cargo picked up by trucks and trains for imported cargo reflects the distribution of transportation modes and their impact on cargo movement. The total tons picked up by trucks for imported cargo decrease as the train share increases. Scenario 3, with 50% train share, has the lowest total tons picked up by trucks at 1,185,000 tons. In contrast, the total tons picked up by trains for imported cargo increased with a higher train share. Scenario 3, with 50% train share, has the highest total tons picked up by trains at 1,173,870 tons. This information is crucial for understanding the impact of the mode of transportation on cargo movement.

Similar to the import category, these values represent the total tons of cargo dropped off by trucks and trains for exported goods. It provides insights into the outbound cargo distribution. The total tons dropped off by trucks for exported cargo decrease as the train share increases. Scenario 3, with 50% train share, has the lowest total tons dropped off by trucks at 435,000 tons. The total tons dropped off by trains for exported cargo increase with a higher train share. Scenario 3, with 50% train share, has the highest total tons dropped off by trains at 433,260 tons.

The maximum and average maximum cargo level in the storage facility indicates the peak level of cargo stored in the facility at any given time during the simulation. It helps in understanding the maximum capacity utilisation of the storage facility. The maximum cargo level reached in the storage facility in scenario 2 decreases as the train share increases. Scenario 2, with 40% train share and two train services, has the lowest maximum cargo level at 50,280 tons. The average maximum cargo level in the storage facility follows a similar trend, decreasing with a higher train share. Scenario 2 has the lowest average at 27,745 tons. The average of the maximum cargo levels reached in the storage facility across the simulation provides a more generalised view of the storage facility's capacity utilisation over time.

Figure 3 illustrates the simulation results of the three scenarios compared with the basic scenario regarding the total cargo transported by each mode of transportation (import or export).

Figure 4 demonstrates the comparison in terms of average time and capacity. Comparing the three scenarios in Tables 5 and 6 shows that the amount of imported cargo increased from 2,342,000 tons to 2,380,000 tons because three ships were waiting to enter the port in the basic scenario. Due to the port capacity constraints, wagons were unable to enter the port and pick up cargo from the storage facility. Exported cargo is still the same for the basic scenario and the three scenarios, which is 855,000 tons, whereas the difference was noticeable in average cargo in the storage facility waiting to reach full shipload. In contrast with the basic scenario, average cargo in the storage facility waiting to reach full shipload increased in the first and second scenarios, while it decreased in the third. This difference is because the average number of wagons in the port reached 66 compared to the other scenarios, and the average waiting time of trains for enough

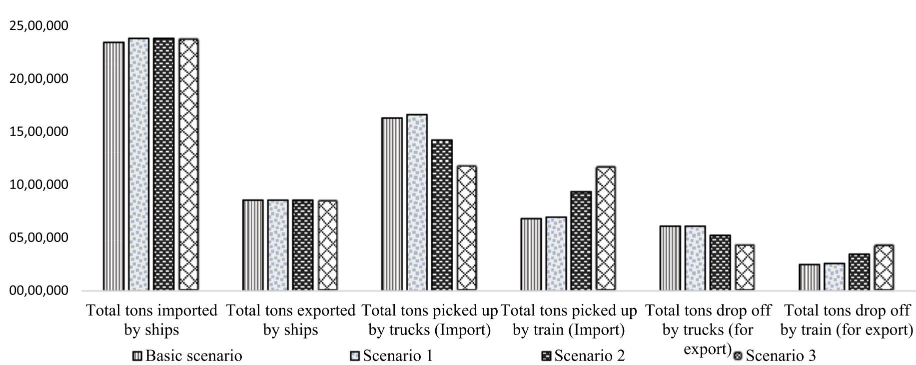

Fig. 3 Comparison between scenarios

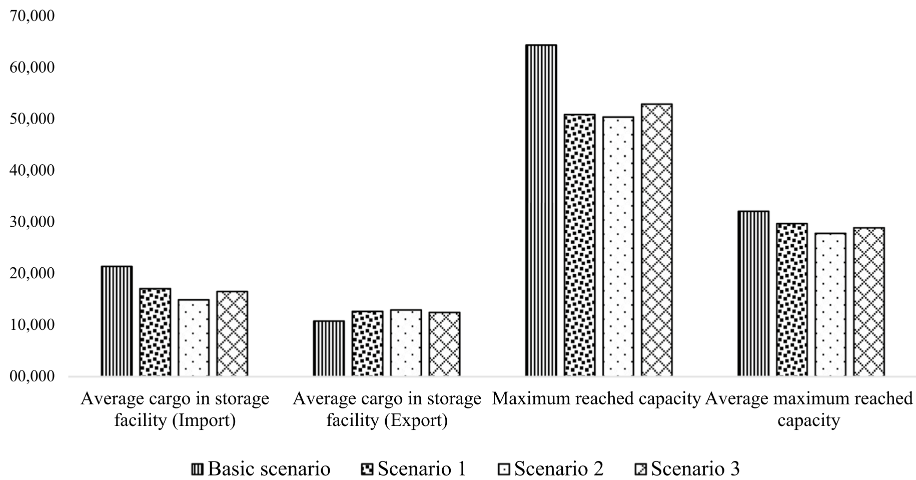

Fig. 4 Comparison between scenarios (storage facility, capacity)

Table 6 Scenario comparison by the number of transportation modes

Items	Basic scenario 30% train and one train service		Scenario 1 30% train and two train services		Scenario 2 40% train and two train services		Scenario 3 50% train and two train services	
	Number in	Number out	Number in	Number out	Number in	Number out	Number in	Number out
Number of ships	217	213	217	215	217	215	217	215
Number of loaded ships	159	156	159	158	159	158	159	158
Number empty ships	58	57	58	57	58	57	58	57
Number of trucks to load	54,600	54,250	55,300	55,300	47,400	47,400	39,500	39,500
Number of trucks to unload	20,300	20,300	20,300	20,300	17,400	17,400	14,500	14,500
Number of trains	259	257	264	264	356	355	448	446
Number of wagons	10,360	10,280	10,560	10,560	14,240	14,200	17,920	17,840
Average number of wagons in the port	64		39		51		66	

space to enter the port increased to 2909 min compared to 338 min and 942 min in the first and second scenarios. Also, the average of imported cargo in the storage facility was improved; the minimum value was in the second scenario. The average minimum capacity in the simulation was reached in the second scenario. It is clear from Table 6 that the number of wagons increased from the basic scenario to the third scenario because of increased train share, reflecting a positive result for the environment because of the benefits of rail transportation. In addition, the average number of wagons in the port was 64 in the basic scenario but decreased to 39 in the second scenario because of additional train service. The average number of wagons was 51 in the second scenario, whereas that number increased to 66 in the third scenario.

As illustrated in Table 7, the average time of imported ships in the port was improved in the second scenario (3960 min) compared with the first and third scenarios, which was 6644 min in the basic scenario. Also, the minimum average time of the exported ship in the port was in the second scenario, which was 5268 min. Similarly, the average time of the exported ship in the port was the minimum value of 5268 min. Unlike the basic scenario, the average waiting time of empty ships for enough cargo to load was decreased in the first and second scenarios, while time increased to 5187 min in the third scenario. The average waiting time of empty ships for enough cargo to load implies the average time it takes for an empty ship to wait until a sufficient amount of cargo is available to load the ship to its full capacity. It was clear that the proposed solution was effective with respect to train wait times for enough space to enter the port and train wait times to enter and exit the port.

The average wait time was 4397 min in the basic scenario, while it was respectively 338 min and 942 min in the first and second scenarios. The average waiting time decreased from 575 min in the basic scenario to 213 min in the second scenario. In terms of wait time for leaving the port, the average time decreased from 602 min in the basic

Table 7 Scenario comparison by average activity time of transportation modes

Items	Basic scenario 70% trucks and 30% train and one train service	Scenario 1 70% trucks and 30% train and two train services	Scenario 2 60% trucks and 40% train and two train services	Scenario 3 50% trucks and 50% train and two train services
	Time (min)	Time (min)	Time (min)	Time (min)
Average time of ships in the port (importing cargo)	6644	3961	3960	4086
Average time of ships in the port (exported cargo)	5475	5269	5268	5667
Average waiting time of empty ships for enough cargo to load	4995	4789	4789	5187
Average waiting time of trains for enough space to enter the port	4397	338	942	2909
Average waiting time of trains for particular time (7 a.m., 11 p.m.) to enter the port	575	300	213	211
Average waiting time of trains for particular time (7 a.m., 11 p.m.) to leave the port	602	421	394	408
Average time of wagons in the port	3257	1916	1917	1937

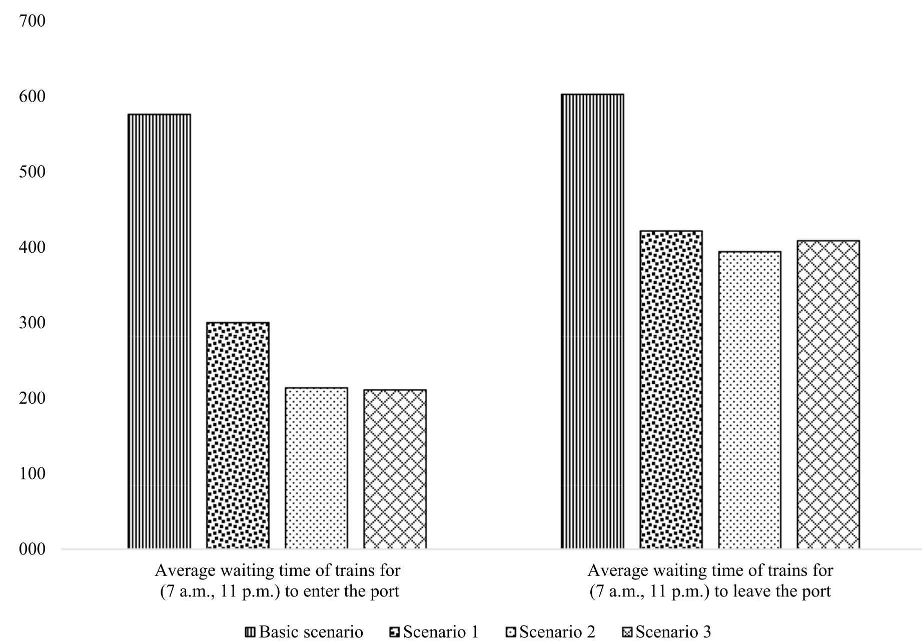

Fig. 5 Times comparison between scenarios

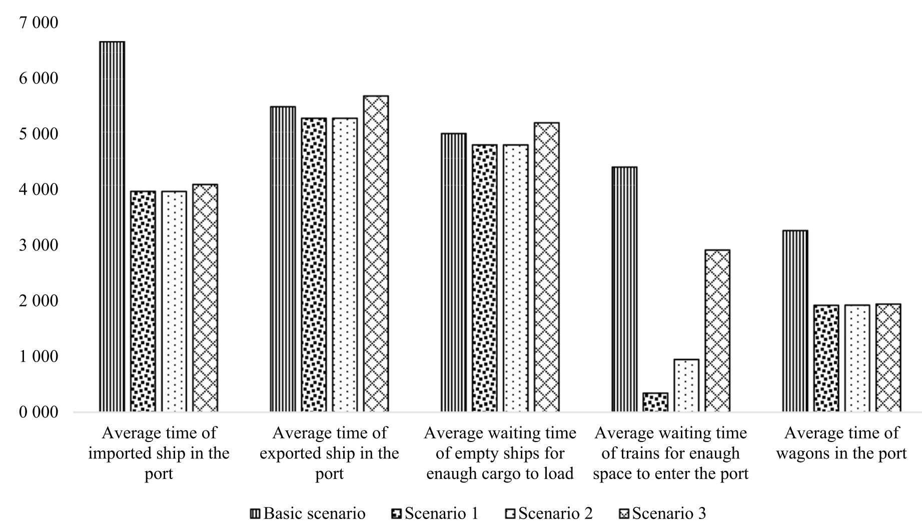

Fig. 6 Comparing average wait time for trains between scenarios (7 a.m., 11 p.m.)

scenario to 394 min in the second scenario. The indicator of the average time that wagons spend in the port was almost the same in the first and second scenarios (1917 min), while it was 3257 min in the basic scenario.

In contrast with other scenarios, the average number of wagons in the third increased to 66 because of increased train share, but the loading and unloading times were the same. Figures 5 and 6 illustrate these comparisons.

Based on the results of the three scenarios, the second could be more effective than the others. The second scenario emerges as the most effective. It involves a 40% increase in rail transport share, the addition of two train services, and demonstrates improvements in various key performance indicators. Notable benefits include reduced Average Time of ships in the port, Average waiting time of trains for a particular time to leave the port, and enhanced overall cargo handling efficiency in the port. The second scenario led to decreased train wait times for enough space to enter the port and train wait times to enter and exit the port. This reduction in wait times is crucial for overall port efficiency. These findings highlight the second scenario's positive impact on port operations and its potential to improve existing capacity.

However, in evaluating each scenario, the maximum capacity reached in the storage facility emerges as a critical metric with significant operational implications. When the storage facility reaches its maximum capacity in the given scenario, it signals potential challenges in handling additional cargo, potentially leading to operational bottlenecks. The operational consequences of reaching maximum capacity include the risk of delays in cargo operations, increased waiting times for incoming vessels, and potential disruptions in the overall flow of goods within the port. These challenges may compromise the efficiency of cargo handling operations, adversely impacting the port's performance metrics. It is imperative to consider proactive measures to address these operational concerns and ensure sustained efficiency. Recommendations for managing or expanding capacity could include Implementing efficient storage practices, such as prioritising the movement of high-priority cargo or regularly clearing space for incoming shipments, which can help make the most of existing storage capacity. In addition, robust forecasting mechanisms should be developed to predict increases in cargo volumes, allowing the port to adjust its operations and prevent reaching maximum capacity proactively. Since the city surrounds the port, expanding storage facilities or investing in additional infrastructure to accommodate growing cargo volumes is not an option, but enhancing existing facilities could be another option. By considering and implementing these recommendations, the port can better manage its operational capacity, mitigate potential bottlenecks, and maintain a seamless flow of cargo, thereby enhancing overall efficiency.

Conclusion and future work

The paper analysed the sea-rail intermodal transportation system in general cargo ports from the perspective of a large system. General cargo ports are complex systems because each cargo type has specific characteristics requiring particular storage facilities and handling equipment. Thus, the overlapping between operations and resources used in cargo operations makes analysing the system more complex. In this respect, simulation modelling is a very efficient approach to assessing and analysing complex systems. This research examined the current status of the general cargo port in Trois-Rivières to discover bottlenecks that slow cargo flow down and affect port capacity. The result of this research demonstrated that bottlenecks limit port capacity and the number of transportation modes in the port at all times. To mitigate bottlenecks, we propose to increase train share in transporting the cargo between the port and its hinterland and increase daily train service. The study could provide valuable assistance to decision-makers in the seaports industry, offering insights not only for the Port of Trois Rivieres but also for seaports in general. Decision-makers can utilise the findings to assess investment decisions related to sea-rail intermodal infrastructure within their respective ports. Additionally, port authorities can leverage the study's findings to evaluate and enhance overall port performance.

In addition, the findings of this research offer valuable insights that can be applied to improve operational efficiency and address bottlenecks in sea-rail intermodal transportation systems across various general cargo ports. By implementing the proposed strategies, such as increasing train transportation share, enhancing daily train service, and appropriate balance between the share of trains and trucks, ports facing similar challenges can effectively mitigate bottlenecks and optimise their capacity utilisation. Moreover, the methodology employed in this study provides a blueprint for conducting comprehensive analyses of port operations and identifying areas for improvement. By leveraging these insights, other ports can enhance their operational performance, reduce cargo dwell times, and ultimately improve the overall efficiency of their transportation networks. Furthermore, the study results will help obtain more effective solutions for intermodal transportation to create more balance between the conflicting objectives, such as increasing the train service and imposing restrictions on the city. Implementing the proposed scenario will lead to increased use of the port's capacity, which is correlated to increased train service between the port and its hinterland. While our simulation model successfully investigated the bottleneck in the system and suggested scenarios to mitigate the bottlenecks within the port, it is important to acknowledge certain limitations in our study.

Our model does not account for seasonality in cargo flow. This limitation implies that the simulation does not consider variations in cargo movement patterns that may arise due to different seasons or external factors. As a result, seasonality in cargo flow could potentially result in increased bottlenecks. Therefore, the current study depicts minimal bottlenecks, offering a more optimistic perspective. Prospective studies could gain greater insights by developing a more comprehensive model that integrates seasonality, offering a nuanced understanding of the operational dynamics within the whole port. Furthermore, upcoming research endeavours should consider the implications of greenhouse gas (GHG) emissions, particularly concerning congestion, and explore the possibility of changing the layout of the port by making some changes to the rail tracks within the port. Our future work will be dedicated to a detailed and comprehensive simulation model and detailed input parameters for the entire port while considering seasonality in cargo flow.

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Author contributions
JF and MO proposed the idea of the paper, which was approved by authors. TA built the simulation model and analyzed the results. The manuscript written by TA and intensively reviewed by the other authors. All authors have read and agreed to the published version of the manuscript.

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The data are not publicly available due to restrictions and confidentiality agreements.

Declarations

Competing interests
The authors declare that they have no competing interests.

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