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Evaluation of railway operations efficiency within a port using simulation: a preliminary study

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***Abstract* – Cargo transportation between the ports and their hinterland is facilitated by rail transportation. The seaport's performance largely depends on how well the rail system operates inside the port. The increased time spent by the wagons in the port ultimately affects the delivery time of goods to the recipients. The article focuses on the issues concerning the interaction of seaports with rail transportation, particularly with several seaport terminals, and how they affect the effectiveness of port operations. This paper investigates wagons' processes and their movements on the rail network in a port. A simulation approach is first used to diagnose the actual situation of the movement of the wagons in the port. The results indicate that the system is experiencing a bottleneck, and there is an opportunity for enhancing its performance. In order to mitigate the bottlenecks within the system, two scenarios were evaluated and analyzed.**

***Keywords* – rail track, simulation, rail terminal, system performance.**

1 INTRODUCTION

Seaports have a complex and strategic role and essential function, not just for domestic trade and the import and export of goods but also as a key hub for connecting with other modes of transportation, especially land-based networks that cover all types of transport. Due to the increase in the ships' size, the terminals have become a bottleneck in the intermodal transportation system; thus, any delay and inefficiency of operations in the terminal may affect the supply chain (Amir Gharehgozli 2019). Therefore, inefficiently operating the terminal can slow down the flow of cargo to their destination as well as increase the dwell time of the ships in the port, which leads to an increase in the total cost and affects the whole supply chain. Consequently, there is a need for new methodologies and technologies that guarantee enhancements of terminal performance, increase capacity, and mitigate negative impacts on the environment. In many cases, the seaports are surrounded by cities, and there is no possibility of expanding the port. One of the most critical recent problems in railway transport is the railway infrastructure's lack of throughput and carrying capacity (Abramov et al., 2018). Insufficient port capacity increases ship waiting time, consequently losing clients and shipping lines (Balliauw, 2020). According to a survey by Langen et al. (2018), about 70% of investments in European ports in the period of 2018–2027 involve capacity investments. The enterprises that are involved in the marine terminal are various: carriers, port authorities, terminal operators, stevedores, labor, shippers, railways, truckers, and government. Each enterprise affects the terminal throughput. A major port authority goal is increasing the annual throughput of cargo per area in order to avoid building new facilities until all current facilities are fully exploited (Bassan, 2007).

Due to the low cost and environmental benefits of sea-rail intermodal transportation, many countries are promoting the sector and investing in seaport rail terminals to improve the link between maritime and railway transport. Ports are critical gates for Canada's imports and exports since they guarantee distribution and deliveries inside the country and to markets outside the region and abroad. The port's connectivity with rail tracks is necessary to be genuinely successful. Rail terminals in ports are essential in transshipping cargo between rail wagons and port storage facilities. The primary purpose of rail terminals is to exchange freight transportation modes. As sea-rail intermodal transportation is receiving increasing attention because of its cost and environmental advantages, many countries are propelling the industry and investing in seaport rail terminals to enhance the connectivity between shipping and railway transportation. One main problem that needs to be studied is how to effectively transfer containers between vessels and trains (Yan et al., 2020b) and, more broadly, to any non-containerized cargo. However, connecting different systems in the port causes congestion, consequently slowing the cargo flow. About 65% of maritime transportation delays are due to port congestion (ElSayed, 2012). Such congestion causes inefficient use of port capacity, harms the environment, and affects the whole supply chain (Amir Gharehgozli, 2019). One way to accelerate the port unloading process is to use rail for fast and large handling. As trains can bring considerably more goods than trucks, delivering cargo via the railway system increases ports' handling capacity. In addition, trains are more environmentally friendly and keep roads clear of large dangerous vehicles (Sadeghi et al., 2021). Port congestion often occurs at the gate or the terminal's yard. Although truck queues can be reduced by increasing gates and enlarging storage space, the bottleneck will move from one place to another. Meanwhile, the required investments are usually significant, and land space availability often constrains capacity expansion (Zhang et al., 2017).

The general cargo yard is the place for short-term storage of goods, and the effective use of the space directly impacts the general cargo terminal's efficiency and economic benefits. Characteristics, types of cargo, shape, and volume largely influence the space utilization of the yard. The stacking order and method will directly affect the space utilization of the yard (Hongwei Tian, 2018). Considering the limited space available in the port areas, the challenge is to optimize the use of resources in order to decrease the total cycle time needed to forward goods from and to the ports; this would allow to reduce the global costs and achieve high standards of service, imposed nowadays by the high level of international competitiveness (Caballini et al., 2012). The efficiency of the internal rail network in the port plays a significant role in ensuring port performance and is considered as the port's strengths or weaknesses. The performance of seaports largely depends on how well the rail network in the port operates and how well they work together. The aim of this research was set within the framework of a project involving the Trois Rivieres port, which focuses on utilizing simulation techniques to diagnose and enhance rail operations at the port. For this goal, the current work seeks to investigate bottlenecks in the rail operations in the port's internal rail network and test different strategies to improve the efficiency of the rail network within the port. This paper applies a simulation technique to mitigate the bottlenecks in rail terminals at the seaport and compares the results of the proposed alternative scenarios. Section 2 introduces the related descriptive literature review. The simulation model and data collection are covered in Section 3. In section 4, the performance of the system and the simulation results are discussed. Section 6 concludes the paper.

2 LITERATURE REVIEW

The general cargo yard is the bottleneck for developing the whole port logistics system, and the yard is the most complex part of the terminal. The location of the general cargo yard and its internal structure are keys to the system's efficiency. Therefore, it is necessary to use advanced technology to study the general cargo yard (Li, 2015). Due to the expensive nature of transportation tasks involved in port operations, such as the movement and delivery of goods to their final destinations, it is essential to consider the port's transportation infrastructure. Therefore, an effective and efficient transportation system is required (Putra et al., 2018). Sometimes the investment in port infrastructure is not the proper option to accelerate the cargo flow and increase the capacity. Recent evidence (Lee et al., 2018) and (Taner et al., 2014) highlight that the way of storage containers in the yard impacts the efficiency and flow of the cargo. In a recent advance (Abu Aisha et al., 2021) analyzed the effect of the layout on the efficiency of the intermodal transportation systems and cargo flow. Nevertheless, some interesting and relevant solutions (strategies) still have to be investigated in this proposal.

2.1 The connectivity between the port and modes of transportation

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). Therefore, there is an urgent need to move from trucks to trains since rail is considered a more sustainable transportation mode (Ng &Talley, 2020). Various countries are planning to mitigate congestion and environmental effects. Rotterdam Port has planned to reduce congestion by 20%, and the port of New York in the United States has gradually moved the real port away from the city (Fan et al., 2020).

Recently, many researchers have been studying sea-rail transportation because of its low cost and low carbon footprint compared to other transportation modes. Many container ports are trying to enhance the connectivity between the terminal and the hinterland by investing in a seaport rail terminal. One of the significant problems that must be addressed is how to accelerate container flow between container ships and trains efficiently (Yan et al., 2020b). The area where trains enter and exit clogs because trains arriving, departing, or being processed cross the same tracks. The common solution to this problem is to increase the facility size, but in many cases, there is no possibility of expanding the facility size due to a lack of land near the port (HDRINC, 2022).

The Canadian ports respond to record cargo volume growth through major expansions and far-reaching transformation of their facilities (CanadianSailings, 2020). One example of investigating rail-seaport intermodal issues in the Canadian ports is studied by (Gillen &Hasheminia, 2018), which has demonstrated that enhancing train services and increasing train frequency is the best way to improve port performance. The increase in container traffic and the rules for the environment in the recent decade have forced the involved parties to pay more attention to the negative influence on their operational activities. Although several studies have been carried out to assess and improve the operations efficiency of ports, most of these researches focus on container terminals. Port-rail connectivity is a strategic element of port development, both in economic and competitive terms, and to reduce negative externalities on the community and the environment. Proper rail connectivity not only expands the port hinterland but also promotes growth in capacity without affecting the port-city relationship by linking "spatially" fragmented processes without congesting the port's urban environment (Matamala & Salas, 2012). Shan et al. (2014) investigated the impact of the seaport on the host city's economic development Based on data from 41 major port cities in China from 2003–2010. His analysis showed that port cargo throughput positively affects the economic growth of the host city. In addition, the competing ports in the neighborhood have an even more significant positive association with the local port city. Rodrigue et al. (2016) and Bermúdez et al. (2018) affirmed that investments in port infrastructures directly impact national economies.

2.2 Transshipment operations in the port

The main operations in the rail-sea link of the chain are the transfer of trains between the railway station and the maritime terminals, the loading and unloading of trains, and the storage management of goods in dedicated yards. Depending on the specific ports, sometimes, to reach the wagons' loading/unloading area, trains have to be split into subset of wagons, then these wagons are transferred to the terminals of the destination (and vice versa for the import cycle). Unfortunately, this passage, from the rail network to the maritime terminals and vice versa, has rarely been addressed in the literature; therefore, this paper aims to attract the researcher's attention to this topic where there is room for improvement. In this regard, Filina-Dawidowicz & Kostrzewski (2022) investigated the issues connected to the complexity of logistics services offered by transshipment terminals. The aim was to develop a decision-making approach to assess the complexity of logistics services provided by these terminals.

Similarly, Yan et al. (2020a) investigated the transshipment operations between vessels and trains in seaport rail terminals. The results report that the handling capacity significantly affects the transfer plan's performance, and increasing the storage cost of import containers leads to a more effective transshipment plan. In another study, Yan et al. (2020b) studied the sea-rail transshipment operation problem of seaport rail terminals, which includes two critical sub-problems involved in sea-rail intermodal container transportation, namely, train schedule template and transshipment plan of inbound containers.

Thus, several articles have assessed the importance of service quality attributes that the shippers consider and play an essential role in mode choice decisions. In this respect, Yan & Xu (2021) studied the improvement possibility of the operation efficiency of sea-rail terminals by adjusting the yard layout and equipment deployment plan. Fang (2016) pointed out two main reasons for the lack of smooth sea-rail connections. One is the lack of connecting conditions between railway container yards and ports, and the other is the incomplete construction of a sea-rail intermodal transport information system.

Yan et al. (2020a) proposed a mixed integer programming model to synchronize the vessel and train operations from the container terminals' perspective, in which the service time window and unloading time requirement of trains are considered. Then, extensive experiments were conducted to analyze the influence of several factors, including the handling capacity, yard capacity, and unit cost value. Ge et al. (2020) conducted a questionnaire survey and content analysis to investigate the various parties involved in sea-rail intermodal in China. The main problems are a lack of institutional design and system regulation, resistance from the rail sector, insufficient cooperation and investment, and a fragmented information system. Policy recommendations are addressed through a three-step administrative framework: (a) unification of international regulations and standards; (b) rail sector reform for better alignment with other transport sectors; (c) incentive policies for enterprises instead of direct subsidies.

2.3 Evaluating port performance using a simulation approach

Performing a simulation is a popular approach for evaluating port performance, and simulation has proven to be an extremely valuable tool for decision support in port operations. Thus, research has been conducted to evaluate the container terminal performance by building a simulation model, as discussed in (Kotachi et al., 2013); (Osman Kulak 2011). Similarly, Zhuo et al. (2012) have developed a simulation model to evaluate a seaport container terminal's operational capability and efficiency. Simulation models are significantly different in terms of their objectives and their levels of detail in modeling the real system (Osman Kulak 2011). In this manner, Park et al. (2012) have presented an approach that combines the importance of simulation models with an optimization model for evaluating the performance of the container terminal. Sadeghi et al. (2021) aimed to define the bottlenecks in a port’s rail container transport process and simulated proposed scenarios. The results showed that the rail container terminal warehouse is a significant bottleneck for the port. Also, the study reduced time and costs by up to 20%.

Although rail and maritime transportation receives increasing attention, to our knowledge, just a few studies have focused on investigating the movement of wagons between the rail tracks in the port. This study focuses on investigating the operations related to the movement of wagons, starting from the train yard located in the port to sending them to their loading points for loading operations at port storage facilities, then sending them back to the train yard using the locomotive. It is concluded that it is necessary to develop a simulation model for the interaction between the port facilities and railways to increase their capacity and reduce the downtime of wagons and locomotives at stations to reduce the congestion and cost of rail transportation within the port.

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 the bottlenecks in the system. This research aims to narrow the gap in this field of research, which is the main contribution of this paper. Besides, the results of this research reveal significant managerial insights, such as the advantages of using simulation techniques in diagnosing the issues in the wagons network in the port. The study will help decision-makers in the seaport to evaluate investment decisions in terminals. In addition, the study could be used by port authorities in evaluating port performance.

3 THE SIMULATION MODEL

Since a general cargo port is a complex system consisting of many sub-systems and different overlapping operations, which undoubtedly affect outputs, a simulation model that simulates precisely such a system could provide a significant analytical benefit.

The port rail cycle is examined in this research, with a focus on the movement of wagons within the port's rail tracks. Additionally, the analysis in the current study is restricted to dry products and bulk cargo. We modeled the movement of wagons between the rail tracks (TLAU1, TLAU2, and TWSECT19) in the port of Trois Rivieres. The model boundaries are shown in Figure (1), i.e., wagons will be modeled from the moment they arrive at the train yard in the port; they are stored temporarily in the yard until they leave the train yard.

The movement of wagons in the port starts once the wagons arrive at the train yard located in the port. Next, the wagons are sent to the rail tracks (TLAU1, TLAU2, and TWSECT19), where they are loaded with cargo. Then the operation of sending the wagons back to the train yard will take place. The rail tracks in the port have many intersections with each other, which causes the movement of a limited number of wagons on each rail track to avoid blocking the tracks. For example, only five wagons can send on the rail tracks TLAU1 and TLAU2 to avoid blocking track TWSECT19, while only 12 wagons can pass on track TWSECT19 to avoid blocking tracks TEL1 and TEL2. The capacity of the train yard is another constraint in the model.

A complex, large-scale discrete event-based simulation model was developed in ARENA software to implement and validate the developed framework. The model was utilized to examine the influence of different factors on the movement of wagons among the rail tracks at the port. After a comprehensive understanding of the real system and all operations and events related to the movement of wagons in the Port of Trois Rivieres, a conceptual model was created. The entities that move through the simulation model are the wagons, and the resources include berths, locomotives to move wagons, and loaders to load/unload the wagons and ships. The processes represent operations of loading and unloading wagons and ships. Figure (2) illustrates the flow chart of the model.

The primary data were collected from the Port of Trois Rivieres through various visits to the port and sharing files with the port authority.

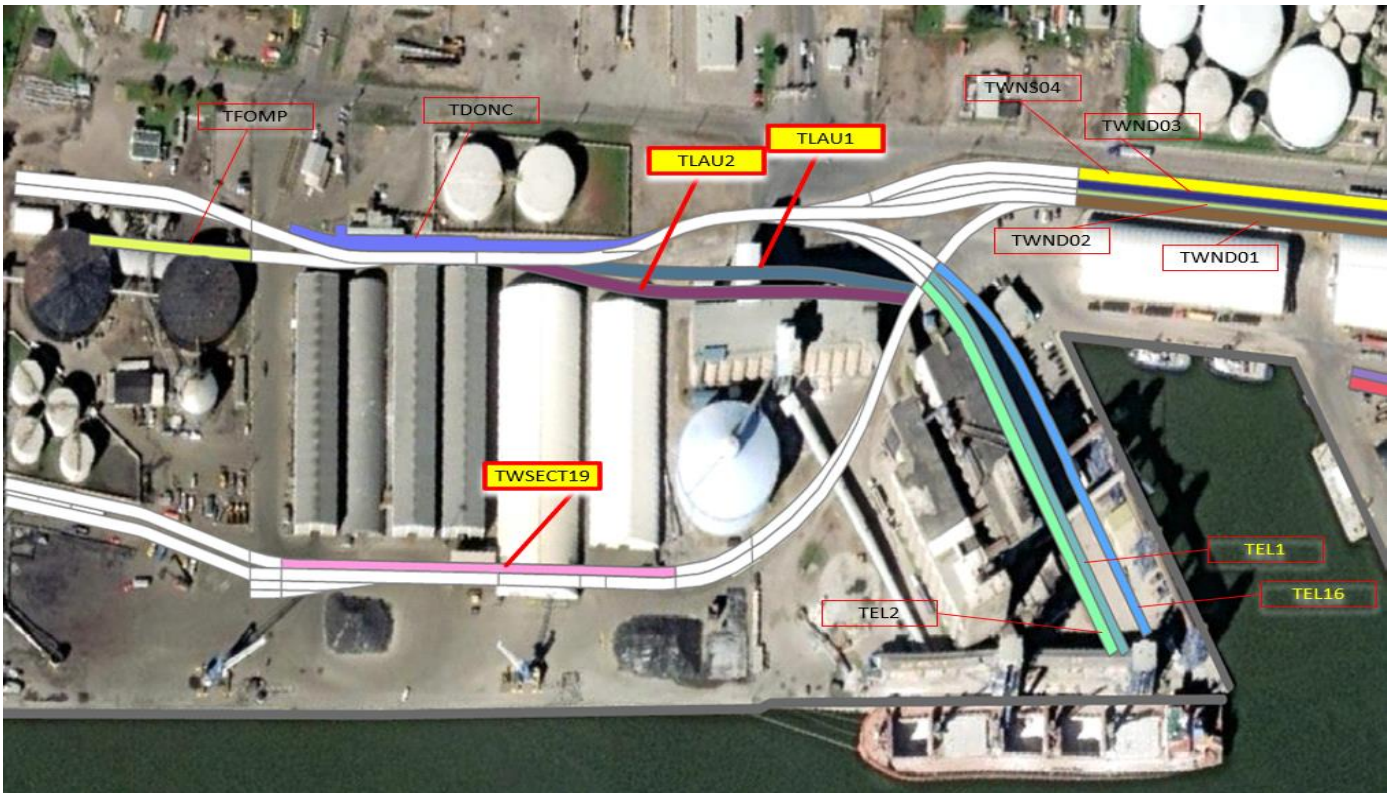

Figure 1. The rail track network in the port

This data includes the maps and layout showing the rail track network in the port.

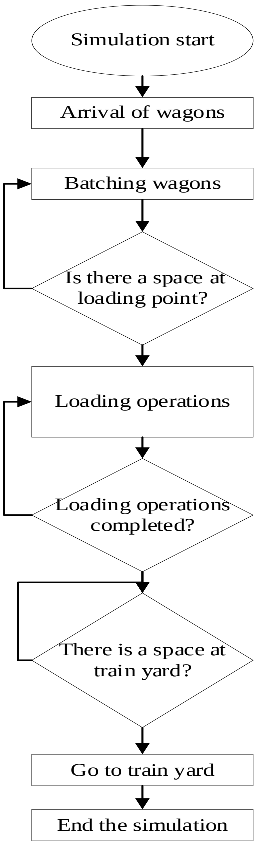

Figure 2. The flow chart of the model

Another part of the data is historical data of wagons and ships' arrival times and associated data, as well as data related to wagons such as times and dates of arrivals and departure of trains as well as amounts and types of cargo. Also, some data were taken from the previous study on the port.

We used Arena software to structure the conceptual and simulation model for the movement of wagons in the port. The objective of the model is to reflect the system's functioning and assess its performance to find out the bottlenecks in the system that negatively affects the port capacity and investigate the impact of several factors on the efficiency of the wagons network. In this context, the key system parameters were selected based on their significant impacts on the system performance, including ship arrivals, wagons arrivals, and the amount of cargo. The system performance consists of calculating the numbers of wagons, ships, and amount of cargo transported by wagons to figure out the bottlenecks in the system. Several steps are required to assess and validate the accuracy of the simulation model. They include monitoring the model operation, testing its data, displaying animations, and using debug features of the simulation software. The bottlenecks in the system can be defined based on the average number and time of wagons in the system and the amount of cargo that remains in the storage facility that must be transported out of the port.

Different simulation tests were performed to analyze and evaluate the system performance to demonstrate the congestion in the system. The model consists of the ships' movement and activities and the wagons' activities in the terminal. Each component has several operations, and each operation performs a specific task or event in the system (arrival and departure of ships, wagons arrival and departure, grouping and separating the wagons, transport, loading, and unloading cargo, etc.). The study will focus on analyzing the movement of the wagons in the terminal. The simulation model considers the port's working hours from Monday to Friday, from 8 am to 5 pm. This means the loading and unloading operations and the movement of wagons performs within these days and hours.

Because of stochastic parameters, five separate replications of the simulation model were implemented. The duration of simulation runs was set to one month, and each run takes 2.65 minutes on average for each run on a computer with a 2.00 GHz CPU. After implementing the system in Arena software, several steps are required to assess and validate the accuracy of the simulation model. These steps include monitoring the model operation, displaying animations, and using debug features of the simulation software. By simulating the rail network, the seaport can optimize the movement of wagons and improve the efficiency of the overall logistics system.

4 SIMULATION RESULTS

Since the objective of this paper is to present a part of a big project to investigate the bottlenecks in the network of rail tracks in the port of Trois Rivieres, we ran the model for one month with the consideration of working days and hours for the port. Also, the intersections in the rail network were taken into consideration. Five replications were used to reach a steady state of the model. During one month, the port received 575 wagons to be sent to rail tracks (TLAU1, TLAU2, and TWSECT19) to transport three types of cargo to their final destinations. During this month, the port received 42,200 tonnes, 15,929 tonnes, and 19,649 tonnes from (ALUMINA, CALCIND), (CU CONCENTRATES), (PETRO COKE, CALC), respectively. After running the simulation model for one month, the results of the basic model showed that the number of wagons loaded with their particular cargo was 281, 24, and 84 wagons from each type of cargo, respectively, and they were waiting at train yard to leave the port. These wagons carried 25,290 tonnes from product one, 2,160 tonnes from product two, and 7,560 tonnes from product three. The remaining cargo in the storage facilities is 38,910 tonnes from product one, 9,340 tonnes from cargo type 2, and 12,040 tonnes from cargo type 3. The remaining cargo in storage facilities points to the port's limited capacity to receive other wagons and load the existing wagons in the port because the port can receive a limited number of wagons simultaneously. The average time wagons spent in the system from the train yard at the port to load the cargo and return to the train yard was 28.031 hours. The summary of these results is shown in Table (1).

Table 1. Result of the Basic Model

Item	Number of wagons	quantity of cargo transported	quantity of cargo remaining in storage
Cargo type 1	281	25,290	38,910
Cargo type 2	24	2,160	9,340
Cargo type 3	84	7,560	12,040
Average time in the system	28.031		

In order to mitigate the bottlenecks in the system and increase the transported amount of cargo from the port, three scenarios are proposed. In the first scenario, we proposed adding another rail track to the train at the port, which means increasing the capacity of the train yard by 20 wagons because each rail track in the train yard can take 20 wagons. After running the system and considering expanding the capacity with a new rail track, the result showed an improvement compared with the basic model. The number of loaded wagons is 389, transporting 35,010 tonnes of cargo type 1, leaving 29,190 tonnes of cargo remaining in storage. For Product 2, 48 wagons transported 4,320 tonnes of cargo, leaving 7,180 units of cargo remaining in storage. For cargo type 3, 111 wagons transported 9,990 tonnes, leaving 9,610 tonnes of cargo in the storage facility. The average time of wagons in the system went to 31.657 hours. Adding another rail track to the train yard will increase the flexibility of wagon movements in the terminal. In other words, this increment in the capacity of the train yard will allow the wagons waiting in the storage facility to find an empty spot at the train yard. Once there is available space at the train yard for wagons, the system will send the wagons from the storage facility to the train yard. Consequently, the wagons waiting at the train yard will be sent to the storage facility. Table (2) shows these results.

Table 2. Result of the First Scenario

Item	Number of wagons	quantity of cargo transported	quantity of cargo remaining in storage
Cargo type 1	389	35,010	29,190
Cargo type 2	48	4,320	7,180
Cargo type 3	111	9,990	9,610
Average time in the system	31.657		

The second scenario involved adding a rail track to the train yard and a working day to the port's schedule. According to the simulation results, the average time for wagons in the system has been improved as a result of this change. The new average time is 27.98 hours, representing an enhancement over the basic model. Additionally, the number of loaded wagons for product one has increased to 404, which has resulted in an increase in the quantity of transported cargo for product one to 39,360 tonnes. These results are summarized in Table (3).

Overall, these simulation results demonstrate that adding an extra rail track and working day can positively impact the system's performance, reducing the average time that wagons spend in the system and increasing the quantity of cargo transported. These findings can be helpful for decision-makers looking to optimize rail transport systems' performance in the port.

Table 3. Result of the Second Scenario

Item	Number of wagons	quantity of cargo transported	quantity of cargo remaining in storage
Cargo type 1	404	39,360	27,840
Cargo type 2	48	4,320	7,180
Cargo type 3	111	9,990	9,610
Average time in the system	27.98		

Figure (3) shows the comparison results of three different scenarios: a basic model, a first scenario, and a second scenario. In the first scenario, there is an increase in the number of wagons for all three products compared to the basic model. Wagons for product 1 have the most significant increase, with wagons going up from 281 wagons to 389 wagons. Wagons for products 2 and 3 also increase, but these are smaller in magnitude.

In the second scenario, there is no change in the number of wagons for Products 2 and 3 compared to the first scenario. However, wagons for product 1 see a further increase, going up from 389 wagons to 404 wagons.

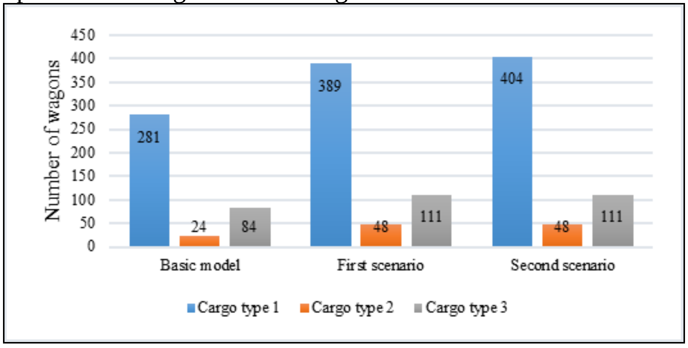

Figure 3. Number of wagons

We can observe that for the transported quantity of cargo type 1, the First Scenario and Second Scenario both outperform the Basic Model, with simulation results of 35010 and 39360, respectively, compared to the Basic Model 25290. This indicates that the First and Second scenarios have some improvements that lead to better performance for the rail network. It seems that the First and Second scenarios have improved the performance of the rail network for cargo type 1. However, it is interesting to note that both scenarios have the same simulation results for cargo types 2 and 3 due to the available number of wagons being reached. This available number of wagons came from our real data. The maximum number of wagons to carry cargo types 2 and 3 that arrived at the port are 48 and 111 wagons, and the system filled all of them, and there are no more wagons in the system to fill these types of cargo. Figure (4) illustrates the comparison of loaded wagons between the basic, first, and second scenarios for a period of one month.

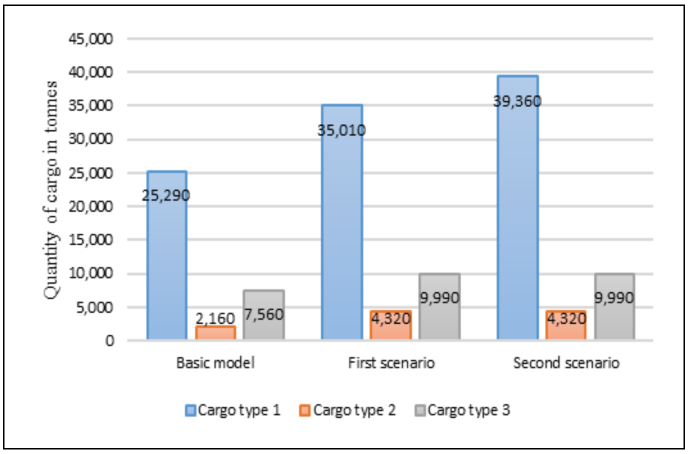

Figure 4. Quantity of cargo

Figure (5) compares the average time of wagons in the system between the scenarios.

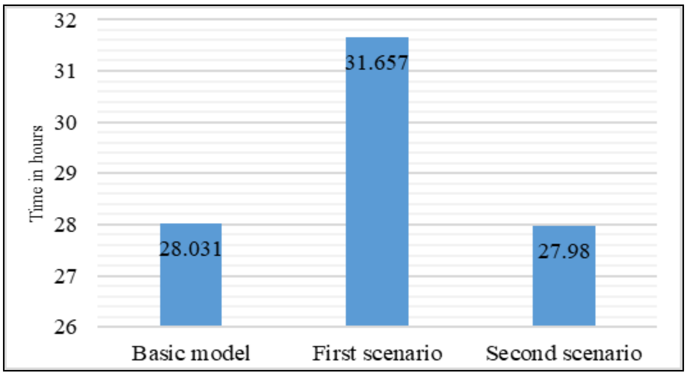

Figure 5. Average time of wagon in the rail network of the port

Since the port uses the locomotive to move the wagons between the rail tracks and uses the loaders to load the cargo into the wagons, Table (4) demonstrates the utilization of these resources. The comparison between the scenarios regarding utilizing the resources shows that the resources are not efficiently used. However, there is an opportunity to use the remaining capacity of the resources, but the port capacity from wagons limits the port to use its resources efficiently.

Table 4. The utilization rate of resources inside the port

The utilization rate of resources (%)			
	Basic scenario	First scenario	Second scenario
Locomotive	44.26	64.10	65.99
Loader Cargo type 1,3	18.11	24.67	25.45
Loader cargo type 2 and 3	1.18	2.37	2.43

5 CONCLUSION

In this paper, a discrete event-based simulation model was developed to represent the movement of wagons in the port. Based on this model, the system bottleneck has been identified to better plan the wagons' movement in the system and the timing of the wagon's departures from the port. The paper presents some preliminary results from applying this model to a real case study.

Present and future research are devoted to extending the present model to consider all the rail tracks in the port and also the import and export flow of cargo, which, of course, partially shares the resources used for port operations. Moreover, a discrete-event simulation framework is being implemented in order to model the port rail cycle in a more detailed way.

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