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Simulation-based evaluation of road transportation logistics in a dry port with topographic challenges

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Abstract

The extension of existing container terminals or the creation of new ones introduces new logistical challenges, including topographic issues and increased distances between the quays and storage yards located several kilometers away from the quay (dry port). These challenges are complex to evaluate analytically and directly impact the acceleration, deceleration, and average speed of a truck which in turn affect the productivity and synchronization of the overall terminal logistics. This paper proposes a transportation simulation model that incorporates detailed descriptions of the topographical and geometrical restrictions. Our simulation model evaluates various scenarios for container transportation logistics, including varying road design terminals and truck fleet size to enhance productivity. A case study from a potential container terminal on Canada's St. Lawrence River is used to demonstrate the simulation model. Several scenarios with different designs are tested and the simulation provides numerical results for supporting decision makers.

Keywords: Maritime, Simulation, Road transportation logistics, Container terminal, Topographic challenges

Introduction

Nowadays, ports are exhibiting an increasing trend of freight volume mainly because of the "gigantism" phenomenon some authors describe in container shipping (Chuah et al. 2023; Haralambides 2019; Lupi et al; 2019; Musso and Sciomachen 2020). This phenomenon is explained by the constantly growing size of ships, leading ports to face a higher volume of merchandises and posing a new set of challenges (Jeong and Kim 2024; Martin et al; 2015; Park and Suh 2019). Therefore, ports need to address these challenges and innovate considering the new container transport and handling (CT&H) technologies, the high pressure on revenues and costs, and the increased complexity in dealing with global trade flows and ensuring sustainability (UNCTAD 2023). Furthermore, current trends oblige ports to expand their storage areas (Pinder and Slack 2012). However, many existing ports find themselves in crowded or restricted surroundings and finding appropriate port expansion areas in their surroundings is extremely difficult, even impossible. These ports need to consider tracts of land that are not necessarily adjacent but could meet specific requirements. Among these requirements are the availability of sufficient area, the possibility of future extension, the availability of hinterland connections, the accessibility and distance from sea, and environmental assessments (Thoresen 2010; Perkovič et al. 2023). For some ports, the only available land areas meeting such requirements are far from the quay and/or are characterized by significant topographic challenges (see the port of Es Senia). Consequently, specific designs and logistical solutions have to be considered when the container storage yard must be located further away from the quay and at a higher altitude. The apron will resemble a transportation link between the quay and the storage yard that is located into the land. Various transportation systems, such as diesel and electric trucks, can be used on such a transportation link. This leads to logistic challenges of analyzing the required transport capacity when the container terminal (CT) needs to be developed in an area characterized by space constraints and topographic challenges. In this paper, we propose a transportation simulation model that incorporates detailed descriptions of the topographical and geometrical restrictions in order to assess potential impacts of topographic issues on transport container performance between seaports and inland ports. The rest of the paper is organized as follows: a literature section mentioned various research that have been conducted on the areas of CT operation. Then it describes the problem statement and the simulation approach, the case study and assumptions for the simulation model, the results, discussions, and finaly some concluding remarks.

Previous research

In CT operations, the storage yard plays a critical role for the terminal's overall performance because it links the seaside and landside, serving as the buffer area for storing containers (Luo et al; 2011). Storage and stacking logistics have become a topic that increasingly attracts attention in academic and practical research during the past decade (Luo et al; 2011; Carlo et al; 2014; Gharehgozli et al; 2016; Ilesaliev et al; 2019; Yu et al. 2022). As mentioned above, the link between the seaport (quayside) and the dry port (storage yard) may be more or less distant in some cases. In such cases, transport connection is required to move freight from the quayside to the dry port. This transport phase may face various issues that could impact terminal performance and thus the bottom line of the port and its competitiveness. Four categories of issues can be defined.

Operational issues

The most critical operational issue is associated with the choice of transport system used to move containers within the terminal. Once this choice is made, other operational issues may include technical characteristics such as transport methods, the type of energy to carry container, the network used, and the level of automation. Unlike rail or barge transport, road transport systems could be caught in traffic congestion. The choice of transport system and its effects on port performance has been widely analyzed in the literature. For instance, Kim and Bae (2004) studied the dispatching of automated guided vehicles (AGVs) using information about their locations and times of future delivery tasks. A mixed-integer programming model was developed for assigning delivery tasks to the AGVs. In addition, a simulation study was conducted, by these authors considering the uncertainties of various operation times and the number of future delivery tasks.

Grunow et al. (2006) presented a simulation study of AGV dispatching strategies in an automated container terminal. The dual load mode was used in the study (vehicles can transport two 20-foot containers or one 40-foot container at a time). The performance of the proposed dispatching strategies was evaluated by a scalable simulation model. More recently, Kong et al. 2024 propose a mixed-integer linear programming model o minimize the completion time of unloading operations by the tandem quay cranes considering the use of automated guided vehicles.

Storage yard layout issues

The second category pertains to storage yard design and container terminal layout optimization. Terminal layout impacts port performance because the port's current layout may lengthen the paths inside the terminal and slowdown cargohandling operations. Some authors, such as Lee et al. (2009), studied an integrated optimization problem of yard truck scheduling and storage allocation with the objective to minimize the weighted sum of total request delays and the total travel time of yard trucks. Wu et al. (2013) proposed an integrated optimization problem for storage management and vehicle scheduling at container terminals. They proposed a genetic model algorithm to illustrate how large-scale problems can be solved and illustrate the effect of different factors on optimization model performance. Xue et al. (2013) proposed a framework for optimizing yard truck dispatching, yard location assignment, and quay crane scheduling, considering the loading and discharging precedence relationships among containers in quay crane operations. Wang et al. (2015) integrated yard truck scheduling and all storage allocation problems in an effort to minimize the weighted summation of total delays and total yard truck travel time. More recently, Li et al. (2021) used agent based simulation to assess a detailed simulation research on different types of layout design in order to compare their terminal performance.

Adverse weather conditions

The impact of weather conditions on port performance should not be neglected. Athanasatos et al. (2014) highlighted that weather is one of many factors that can reduce productivity in terminals operations, as it hampers port operations such as cargohandling, creating problems along the entire supply chain of upstream and downstream industries. Through simulation-based studies, authors have highlighted weather conditions and their effects on port operations. For instance, Chhetri et al. (2016) developed a methodology to design a Container Terminal Operation Simulation, which simulates the vulnerability of port operations to adverse weather. An agent-based model was built by these authors, for a container terminal at the Port of Sydney, to simulate port operational assets such as cranes, straddle carriers, and trucks, to observe individual and collective behaviour in the case of adverse weather, using a set of key performance indicators such as crane rates, straddle productivity, truck queue length, and yard utilisation rates. By studying the Port of Shenzhen, Cao and Lam (2019) proposed a severe weather-induced container terminal loss estimation framework. Based on a container terminal operation simulation model, monthly average loss and single event-induced loss were obtained using historical hazard records and terminal operation records as model inputs. Though weather conditions such as wind, fog, and snow were not explored as much in transport operations among maritime terminals, they were proven to negatively impact transport operations because of driving conditions, consequently impacting port performance as whole. Many studies highlighted weather conditions as a risk factor for road transport, thereby increasing road accident rates (Andrey et al. 2003; Bergel-Hayat et al. 2013). Other studies have shed light on the effects of adverse weather conditions on road transport and driver adaptation (Andrey et al. 2013; Bardal 2017). Other authors combined weather conditions with road-surface conditions to stress driving speed adaptation (Varhelyi 2002; Rowland et al. 2007). More recently Léon-Mateo et al. (2021) created the Port Resilience Index (PRI) that is an indicator to measures the capacity of a port to absorb and recover from the damages of a natural disaster. Some authors also work on neural networks predictions in order to better predict disaster in port operations (Nomikou 2023).

Topographic issues

These issues have been covered in the literature as an impediment to terminal expansion (Ambrosino and Sciomachen 2014) instead of a factor related to the physical aspects of the used pathway. Among the topographic challenges that could impact transport operations are the geographic relief (e.g., mountains, forests, hills, cliffs), the road's physical state (e.g., track, gravel, asphalt), and track shape and curvature (e.g., obstacles, dangerous paths, sloped pathways). The latter may find an echo in the case of many ports because there are dry ports. Because dry ports are away from the seaside, their altitude increases. These altitude levels create sloped segments along part of the pathway or the entire pathway. For instance, the dry port of Es Senia, Algeria, is 15 kms away from the main seaport of Oran. Both ports are connected through a trucking service that crosses a pathway featuring some high slopes. The dry port in Novi L-Basaluzzo, 38 kms away from Italy's port of Genoa, connected through a dedicated rail tunnel across the Apennines, a series of hills in a straight line, and connected by high ground (Lami and Beccuti 2010). Activities at the port of Valparaíso, Chile, are constrained by a lack of space because the port is surrounded by the city and hills. Consequently, a dry port was created, 11.6 km away from the port. Like the port of Es Senia, a road connects the Valparaíso seaport with the dry port.

Simulation tools have been widely used in the port industry to evaluate various scenarios since 1961 (Steer and Page 1961). Dragovic et al. (2017) conducted a literature overview on simulation modelling in the port and container terminal industry. More than 200 papers were analysed and classified, showing how simulation can be a great tool. Discrete-event simulation remains one of the most popular techniques in port operations modelling. To our knowledge, the use of quantitative tools for assessing potential impacts of topographic issues on transport container performance between seaports and inland ports have not been covered in the literature. This paper aims to fill this gap and will pay specific heed to questions regarding (1) the number of vehicles needed to support the loading/unloading rate using quay cranes (diesel trucks are used) and (2) the impact of topographic conditions and space constraints (area available) on truck-based transportation systems and CT performance. This paper tackles the above questions with a simulation-based evaluation applied to a case study of the St. Lawrence

River that is subject to topographic issues. We point out a number of instances to analyze the impact of topographic issues on various configurations.

Material and methods

Port terminal arrangement and simulation

The transfer of containers between the quayside and the inland port is one of the most critical processes for overall productivity at a seaport terminal. A CT is described by the number of containers moved per hour and is usually expected to meet a minimum productivity threshold. Therefore, it is critical to look at the possible impacts on performance metrics when the transfer segment (from terminal to inland port) is characterized by topographic issues; in other words, when a minimum productivity threshold must be met. Figure 1 illustrates the generic representation of a seaport terminal arrangement. The top part of Fig. 1 illustrates a conventional seaport terminal setup, whereas the lower part illustrates a dry port arrangement with the consequent longer transfer of containers. When the seaport (quayside) is distanced from the dry port (storage yard), in addition to cargohandling, the transportation (transfer) of containers becomes a part of the problem to be addressed.

In our context, the SIMIO LLC software was used for simulations. Figure 2 illustrates the overall simulation model. We have adopted a simulation-based continuous improvement methodology to evaluate the impact of topographic issues on the number of containers moved per hour. The concept starts with a standard implementation (the logistics chain) and a discrete simulation event to evaluate the impact of each operational decision on performance such as the number of trucks used to carry the containers for example.

Four stages are included in the simulation:

(1) Ships berth for cargohandling operations.

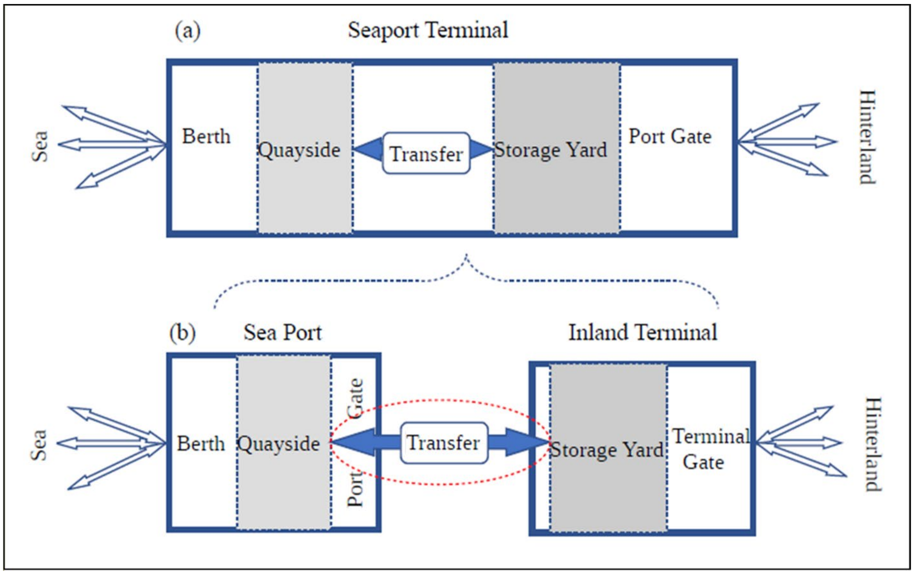

Fig. 1 Illustration of a conventional seaport terminal arrangement (**a**) and a dry port arrangement (**b**)

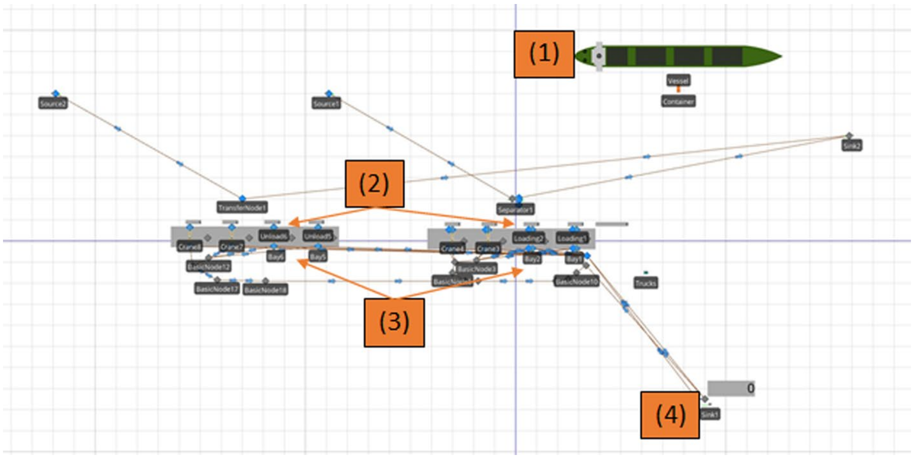

Fig. 2 Example of a simulation model using the SIMIO software

(2) A set of cranes is assigned to the ship on both quays.
(3) Trucks travel to each crane to drop or pick up containers.
(4) A container is brought to the storage yard of the dry port as soon as it is picked up. For export, the container is brought to the quay. Export containers comes from trains that arrive at the dry port. A storage yard exists at the dry port to stock all the containers.

The simulation model requires a number of specific assumptions and parameters that are specific to the case study. They are described following the presentation of the case study.

Case study

The St. Lawrence River and Great Lakes navigable system makes it possible for ocean-going vessels to travel from the Atlantic Ocean to North America's Great Lakes (Canadian Geographic 2020). This system even makes it possible for large containerships to travel all the way to Quebec City. But the bank configuration does not leave large flat areas to expand existing ports or build new terminals at this stage. From an economic and environmental perspective, the construction of a large reinforced concrete deck for the quay, including a yard for container storage on the river's shoreline, would be unacceptable. This kind of terminal infrastructure would particularly require large volumes of high-quality filler materials and large quantities of concrete, which would impact the river ecosystem. The combination of geographical, topographical, and environmental constraints would result in a terminal configuration with a storage yard away from the quay; something that would have required horizontal and vertical moves of containers. Specifically, transportation links with dry port can reach 1,000 to 2,000 m in length with a height difference up to 60 m. Figure 3 provides the case study topography. Here, the distance indicated as "0" is the location of the quay. A steep incline toward a plateau follows, where the container storage yard is located.

The general design was predetermined by the partner. We explored two route scenarios for the "cliff section". The logistics network, operational routes, and parameters used

Fig. 3 Case study topography. The altitude is measured from the quayside level

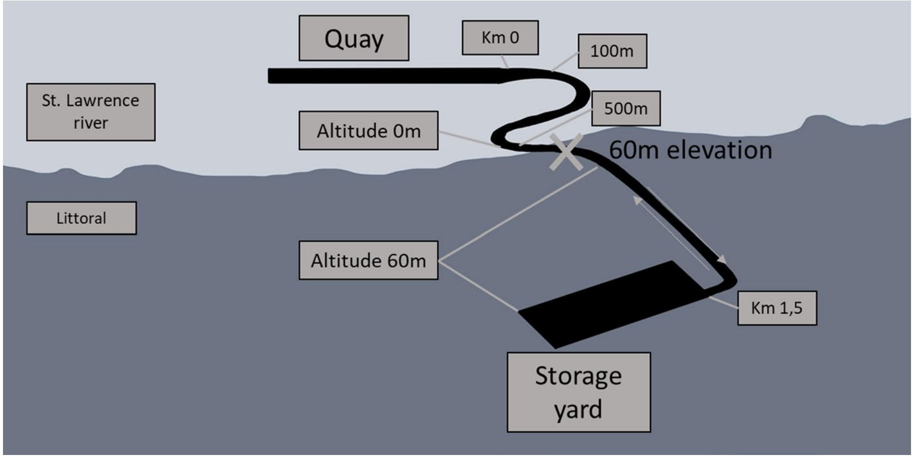

Fig. 4 Overview of the proposed St. Lawrence River design

in the simulation are based on communications with Port of Quebec experts. Figure 4 provides a design overview in which the quay is far away from the storage yard due to the topography of the area available for the latter which is higher than the quay. The distance between the quay and the dry port gate is 1,500 m. Road trucks are therefore faced with some topographic challenges. The layout allows consideration of various concepts as they pertain to how containers are transferred between the quay and the storage yard. The simulation model allows the flexibility to modify route parameters and vehicles in terms of length and slope gradient, making it possible to compare the use of different fleet sizes.

Simulation model

Containers have standard lengths of 40 feet. Each ship has a capacity of 12,000 containers. Simulation starts with two fully loaded ships arriving at the same time, one at each berth. In practice, such an exceptional situation makes it possible to simulate the highest level of operational conditions where all berthing capacity is used. Simulation stops when both ships leave the quay. Each berth has four cranes. The loading/unloading time of each crane follows a triangular law. Each crane can handle only one container at a time. The maximum speed of trucks is 15 km/h on the quay platform and 60 km/h when travelling between the quay and storage yard. The cliff section, indicated by an X

Table 1 Parameter setting for the simulation model

Control parameter	Value
Vessel arrival	2 vessels at the same time
Number of quays	2
Number of cranes at each quay	4
Crane loading and unloading time at the quay	Triangular law (2, 3,4) minutes
Truck speed at the quay	15 km/h
Truck speed on a bend	40 km/h
Truck speed on the road	60 km/h
Road distance	1500 m for the base case (flat) from the entrance to the dock to the entrance to the storage yard
Slope gradient (%)	0–5–10%
Crane loading and crane unloading time at the storage yard	Triangular law (1, 2, 3) minutes
Truck fleet size	20–150
Number of replications	15 per scenario

Table 2 Summary of the four scenarios, including additional information such as the number of bends

Scenario	Altitude	Maximal slope gradient	Road design description
S1	Flat	0%	Pathway: 1500 m 3 bends
S2	60 m	5%	Pathway: 1501.5 m 3 bends
S3	60 m	5% restricted over a short section	Pathway: 2853 m 10 bends
S4	60 m	10% restricted over a short section	Pathway: 2054 m 6 bends

in Fig. 4, is characterized by bends, slope gradients, and ascending altitudes that must be accommodated. Table 1 presents the assumptions used for the simulation, based on the case study design as well as experts and practitioners opinions.

The analysis evaluates the topographical impact on overall CT productivity, measured in number of containers moved per hour. Table 2 details and presents four scenarios: the reference scenario on flat ground (S1) and three CT scenarios of different topographical configurations with the same vertical elevation of 60 m. The latter three comprise a scenario with a constant slope from the quay to the yard (S2) and two 60-m height scenarios to be climbed on a short section (S3 and S4), where the fleet of trucks is authorized to operate in conditions with a maximum slope gradient of 5% (S3) or 10% (S4). For the sake of simplicity and comparison with the second scenario, the portion of the route after the 60-m climb is considered flat in the last two scenarios.

Scenario 1: Flat pathway

Containers are transferred by trucks from the quay to the storage yard over a flat pathway without any topographic issues. In Fig. 5, the distance from the quay to the yard is 1,500 m. Trucks can reach the maximum speed of 60 km/h.

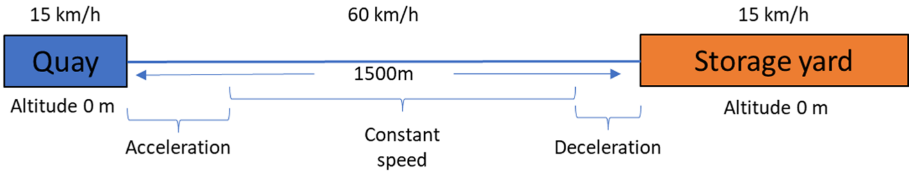

Fig. 5 Scenario 1 considering a flat pathway

Scenario 2: Constant sloped pathway of 5%

Containers are transferred by trucks from the quay to the storage yard through a sloped pathway with a 5% maximal slope capability for the climbing truck. In Fig. 6, a section is characterized by a constant slope until the right altitude is reached, followed by a flat section for comparison purposes. Owing to cost as well as the possible environmental and landscape aspects, it is not possible to have a lower constant slope throughout.

Scenarios 3 and 4: Sloped pathway (5% and 10%)

Containers are transferred by trucks from the quay to the storage yard via a sloped pathway with 5% (scenario 3) or 10% (scenario 4) maximal slope capability for the climbing truck. As illustrated in Fig. 7, ascension can be done only on a short section of the pathway, about 200 m at the sea-land interface (i.e., shore cliff).

The number of bends for trucks to climb hills in a short distance is a crucial aspect of road design. Average speeds depend on acceleration, deceleration, full or empty trucks, and downhill and uphill slopes. Figure 7 illustrates various bends to be considered when calculating an average speed. It was previously shown that the total distance

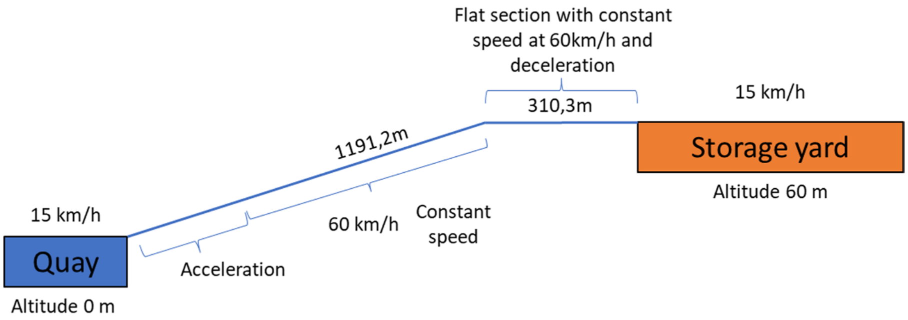

Fig. 6 Scenario 2 considering a constant slope (5%)

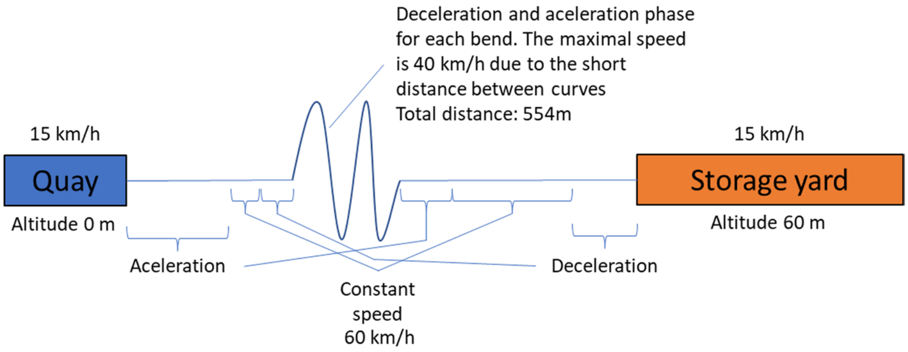

Fig. 7 Scenarios 3 and 4 considering a sloped pathway

on flat ground was 1,500 m. However, topography was considered in scenarios 3 and 4; it not only influenced the truck's average speed because it had to reduce speed in a bend but also influenced route length because the truck cannot climb a slope as easily as other vehicles. Since land topography does not make for a gentle slope from the start of the quay to the storage yard, trucks must climb along a 200-m distance. The length of the trip depends on the truck's hill climbing capability. For trucks to climb a slope while adhering to the maximum slope percentage, curves similar to those present in the mountain's road network must be used. In our case study, we adhered to climbing zones and the maximum slope percentage. Climbing a greater height introduced more switchbacks in road design, thereby extending the distance travelled and travelling time. The latter was increased by a decrease in average speed taking because many deceleration and acceleration phases needed to be considered to adhere to lower maximum speed limits in bends.

The number of bends is also dependent on the width of available area on the shore. Fewer laces could be found on a large area on the ground, which would reduce the number of deceleration and acceleration phases and the number of phases (turns) subject to lower speed limitation. Superior visual landscapes would be impacted. Acceleration and deceleration distances will be more or less important, depending if the truck was loaded or unloaded.

For the four scenarios, average distance and speed were obtained using acceleration and deceleration for a loaded or unloaded truck travelling uphill or downhill. These values are given in Table 3 and are based on literature and expert advice (Yang et al. 2016; Jain et al. 2014; Maurya and Bokare 2012).

Simulation is a good tool to adapt and evaluate various scenarios where road design can be tailored to integrate all aforementioned considerations. In the numerical testing of these scenarios, operational rules for cranes loading and unloading containers are assumed as follows. There is a first phase with single cycling of import containers transferred from the vessel to the storage yard until one-third of the vessel's shipment is unloaded. Based on various reasons, such as vessel stability and stacking logistics, this rule of thumb states that the vessel must first be about one-third unloaded so import and export containers can be loaded and unloaded on a vessel simultaneously. In other words, operations start with single cycling and unloaded operations until one-third of the vessel's shipment is unloaded. In the second phase, there is a double cycling where

Table 3 Acceleration and deceleration values for loaded and unloaded trucks for scenarios 1, 3, and 4. Scenario 2 combines scenarios 1 and 3

Scenario	**Unloaded**		**Loaded**	
	Acceleration	**Deceleration**	**Acceleration**	**Deceleration**
S1 Flat (m/s^2)	0.66	0.99	0.33	0.43
S3 Slope (5%)				
Downhill (m/s^2)	0.835	0.905	1.115	0.392
Uphill (m/s^2)	0.55	1.105	0.275	1.14
S4 Slope (10%)				
Downhill (m/s^2)	1.235	0.603	1.67	0.225
Uphill (m/s^2)	0.275	2.035	0.137	1.557

the hoist of a quay's crane unloads an import container from a vessel immediately after loading an export container. Double cycling is one of the most widely used techniques to improve quay crane efficiency by eliminating empty crane movements. The number of containers handled in a cycle is twice that of single-cycling operations; the empty moves of yard trucks are decreased accordingly. Allocation is done by each crane; each vehicle is allocated to the closest available crane. The third phase involves the single cycling of export container transfer from the storage yard to the vessel to complete vessel shipment loading.

Results

Productivity and utilization rate

Figure 8 illustrates the average productivity and utilization rates for the quay's CT cranes and trucks, which depend on truck fleet size. Scenario 1 is a baseline in the figure, for productivity is highly dependent on the number of trucks in the system. We first observe that productivity increases when fleet size increases, from 83 containers per hour for a 20-truck fleet to 123 containers per hour for a 110-truck fleet. This is a trivial increase because the truck is the main resource when transporting a container. Therefore, as the number of trucks increases, more containers are transported until a maximum threshold is reached. The maximal average productivity of 123 containers per hour is representative of the moment when the bottleneck initially located on the container transfer operations moves to the container loading/unloading operations by the quay cranes because of a small fleet size. This result could be confirmed by the two curves on the truck and crane utilization rate; the grey and orange curves specifically show the evolution of the respective truck and quay crane utilization rate in accordance with fleet size. The utilization rate of each resource is retrieved along the running simulation; the rate counts only the time when the resource is performing a useful task, namely transporting or handling a container or moving to the next allocated task to be performed. The utilization rate

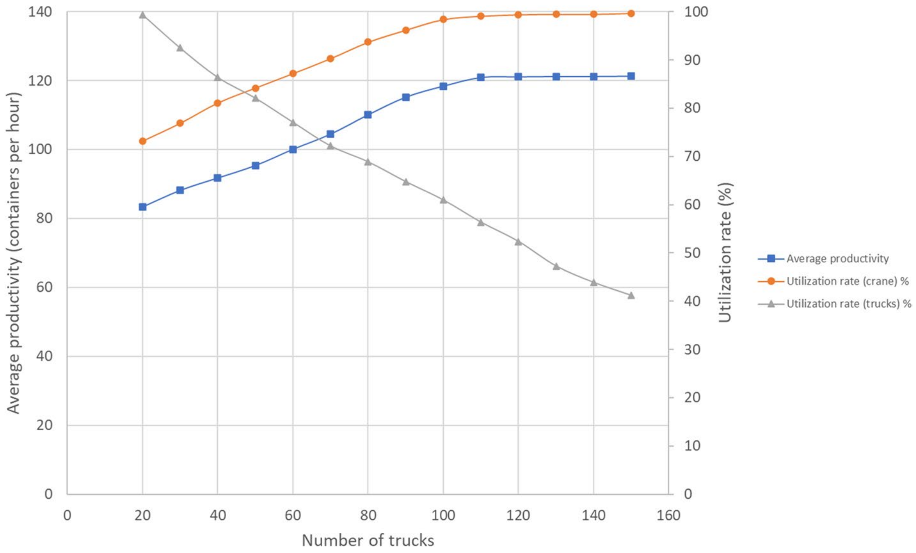

Fig. 8 Average CT productivity and utilization rate for trucks and cranes in scenario 1 (flat section) depending on the number of trucks in the system

is usually 100% for a small fleet size. As size increases, the utilization rate decreases. The beginning of an obvious plateau can be seen when approximately 110 trucks can be counted, since productivity is at its maximum and the utilization rate is only 57% for trucks, whereas the rate is around 100% for cranes. The utilization rate may seem low for the truck fleet, but it has been empirically demonstrated in the literature (Dumetz et al. 2020) that rates below 100% are expected among resources that are not bottlenecks to have a productivity rate that is satisfactorily high. In general, the vessel must remain at the quay for the shortest time possible. Keeping the quay crane utilization rate at 100% becomes a priority. Cranes were not used to having full potential before reaching the threshold of 110 trucks; consequently, this net loss of productivity will extend vessel time at the berth. Once the threshold has been reached, the system bottleneck is transferred to the cranes working at full capacity. Any increase in truck fleet increase will have no impact on overall CT productivity.

Road design and variation

Figure 9 illustrates the productivity for each of the four road design scenarios that depend on different truck fleet sizes. As a brief reminder, scenario 1 is indicated by the blue curve and presents a road design on a flat terrain from the quay to the storage yard, whereas scenario 2 indicates a constant 5% slope up to the height of yard altitude. Scenarios 3 and 4 are respectively indicated by yellow and green curves and indicate a road reaching the yard's altitude over a short section subject to a slope gradient..In scenario 3, trucks can climb a slope gradient of 5% and in scenario 4 trucks can climb a slope gradient of10%. Unlike scenarios 1 and 2, scenarios 3 and 4 have a lower level of productivity for similar fleet size. The topographical effect on the limited road section to reach the yard's altitude is felt, directly resulting in slower average speed. Consequently, more travelling time is needed to connect the quay to the yard and productivity is lower for the same number of trucks in the system. Similarly, an increase in the number of trucks in the system results in an increase in productivity until the bottleneck moves to the cranes. The topographical impact is represented by a shift in reaching this plateau. More trucks are therefore needed to reach the plateau of 123 containers per hour when the

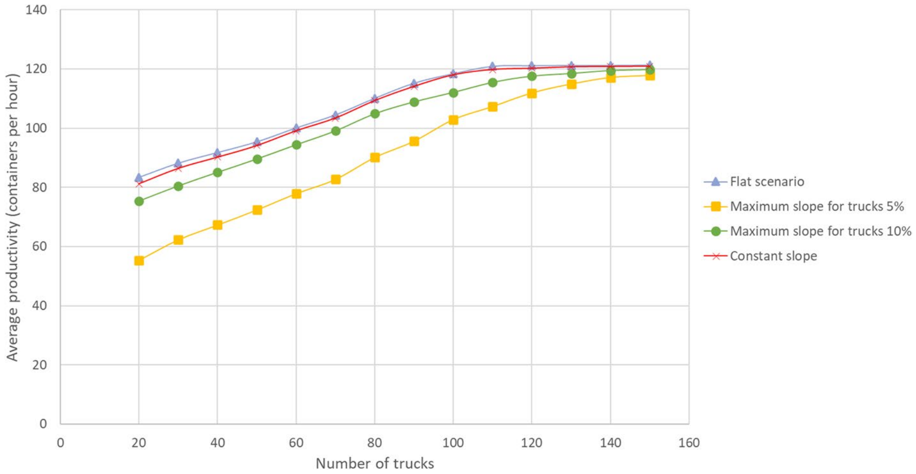

Fig. 9 Average CT productivity for four scenarios depending on the number of trucks in the system

terrain has a slope. The lower the slope percentage for a truck, the greater the number of trucks must be to reach this plateau. For trucks to reach the same altitude, they must travel shorter distances when the authorized slope percentage is high. In addition, by comparing the results between two scenarios, it is possible to evaluate the opportunity cost of building CT subject to topographic challenges (e.g., 40 additional trucks will be required to achieve an hourly rate of 123 containers for a road design with a slope in scenario 3 in contrast to a flat terrain in scenario 1). This comparison can also support the trade-off among purchasing and operating costs between trucks capable of operating on a slightly steep slope, as presented in scenario 2, or a steep slope, as presented in scenario 3.

When considering the possibility of building a CT subject to topographic challenges, the width of available area for the sloped pathway connecting the quay and the storage yard is another criterion that can significantly impact productivity. Climbing a hill with a narrow width will require many bends in road design, resulting in many acceleration and deceleration phases that will reduce average speed and decrease productivity. In contrast, climbing the same hill with a larger width will mitigate adverse situations. In Fig. 10, the diamond mark curve enhances productivity of larger width areas, thereby reducing bends to two. In so doing, the number of acceleration and deceleration phases along the road are reduced, leading to an increased average truck speed. Consequently, fewer trucks are needed to reach the overall CT productivity plateau capped at nearly 120 containers per hour.

Climatic impacts

As within any country in the northern hemisphere, Quebec is subject to various climates throughout the year. Consequently, acceleration, deceleration, and average speed are reduced during the winter due to ice and snow. It is possible to evaluate climatic impacts during the winter months with the help of the simulation model. We simulated scenario 3 based on harsh winter conditions, reducing maximum speed limit on the transfer road from 60 to 50 km/h. Figure 11 illustrates the loss of CT

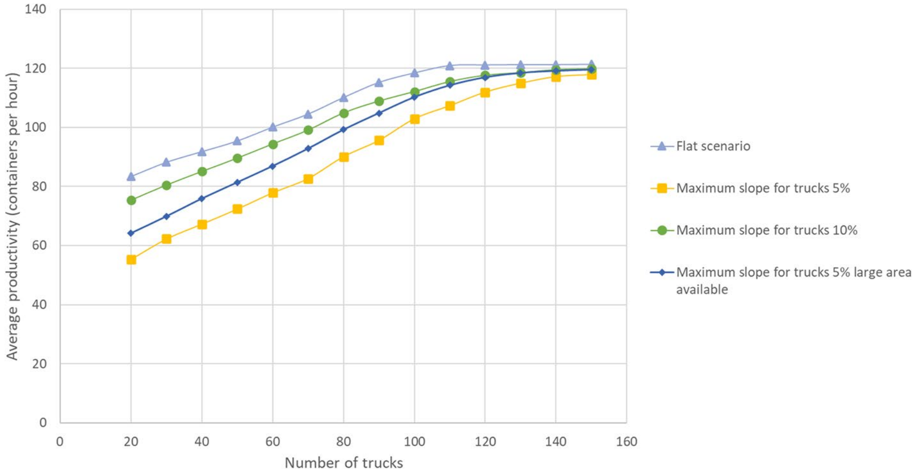

Fig. 10 Average CT productivity considering a larger area available for climbing hills

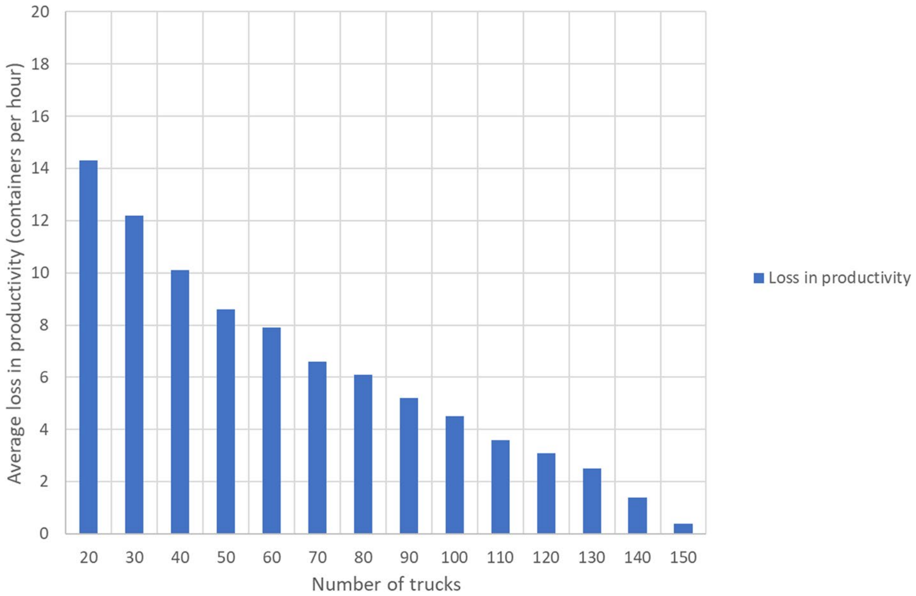

Fig. 11 CT productivity reduction subject to winter conditions

Table 4 Additional time that a truck needs to travel from the quay to the yard

Scenario for 110 trucks	Additional time(s)
Scenario 3	38.4 s
Scenario 4	28.2 s

productivity because of these conditions. The decrease is mostly linear, and a small fleet size is impacted more than a larger fleet size.

Truck travel time

It is useful to note how topographic challenges affect truck travel time. Because loading and unloading times are similar among all scenarios, the values reported in Table 4 correspond to the additional time trucks need to travel from the quay to the yard as opposed to scenario 1. Note that this is an average travel time of the entire truck fleet; trucks need to load the container at the quay and unload the container at the yard. Given the productivity target of 120 containers per hour in our baseline (flat) scenario, a fixed number of trucks in the system corresponds to our fixed productivity target of 110 trucks. We compared the topographical impact to the additional time a truck needs to travel from the quay to the yard. As we expected, higher topographic challenges led to higher additional travelling time.

The result for scenario 2 does not appear in the table because this scenario is unrealistic.

By using the simulation model and data provided by experts, we can calculate the impact of topographic constraints on various key performance indicators. We tested many scenarios with various designs; the simulation provided numerical results to support decision makers.

Concluding remarks

We have proposed and developed a generic simulation tool to support a quantitative evaluation of container transport system operational performance characterized by topographic challenges. The tool uses a detailed description of the topographic situation, distance between quay and storage yard, and design parameters such as the number of trucks and crane utilization rate. The specific output includes average productivity when a vessel is at berth.

The simulation model was tested on a case study on the St. Lawrence River, near Quebec City. The quay was 1,500 m away from the storage yard and the storage location was 60 m above sea level. One topographic particularity was climbing 60 m over a short distance, i.e., an extremely steep terrain before reaching a plateau. A low constant slope was not possible due to costs as well as the environmental and landscape aspects that would be impacted by the slope. In addition, truck operations were limited because of the types of slopes on the road.

We compared four different topographic scenarios through simulation and an increase in the number of trucks in the system. This comparison demonstrated the effects of topography on overall CT productivity. We used a scenario with a flat topographic profile and maximum productivity as a baseline. Through simulation, it was possible to determine a number of trucks from which cranes—the bottleneck in this kind of system—had a utilization rate of 100% and reached the productivity threshold. This productivity, validated by the experts in charge of developing this CT, was 120 to 125 container movements per hour per vessel at quay. It was also shown that the more topographic profile showed an accentuated relief, the greater the number of trucks were necessary to reach that threshold.

Various specific constraints, such as the number of quays, access points, topography, type of carriers, crane capacity, and the number of cranes, need to be considered when modelling and designing a CT. In our case study, we needed to consider that a vessel must remain at the dock for the minimum time and that cranes needed to operate at 100% capacity when alongside a vessel to minimize time constraint. In this case, the storage space at the quay was set to zero, meaning that a sufficient number of trucks—about 100 to 110—had to keep up with the cranes. The results will be used as an input for decision makers to construct such a terminal port.

Many assumptions used in the simulation can be evaluated and tested. It is useful to analyze the variation of average productivity during the loading and unloading phase. We used three phases, including the phase that analyzed variation until one-third of the vessel's shipment in 12,000 import containers was unloaded. Concretely, the crane needed only to unload the vessel, whereas the vessel was loaded and unloaded in the second phase until reaching 8000 import containers. Average productivity was at its best in the third and final phase because the quantity of export containers on the vessel's shipment was reduced—the final 4000 export containers were loaded—and loading was completed. It was possible for the simulation tool to answer questions that partly regarded system productivity by further combining loading and unloading and greater integration for the existing transport system.

It will be useful to conduct further research and analyze the potential of a dedicated loading zone near the crane at the quay to reach a crane utilization rate of 100% with lower fleet size. Finally, unlike in a flat landscape, executinga container transfer in the context of topographic challenges requires more energy. It will be useful to explore and evaluate the economic and environmental benefits and disadvantages of developing alternative transportation systems for diesel-based trucks.

As today vessels need to be bigger, ports need to be bigger, there is a need to evolve existing ports or create new ones. This tool can be used during decision making, in the design of a new CT, or in the expansion of an existing CT. It allows to answer "what if" questions on the adoption of technology, on the choice of a precise layout, and gives pertinent information such as the average productivity, the number of trucks needed and utilization rates of the crane and the trucks.Acknowledgements: This work has been supported by Réseau Québec maritime.

Abbreviations

CT&H	Container transport and handling
CT	Container terminal
AGV	Automated guided vehicles

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LD is the main author of this paper. He worked on the simulation model and conducted all the experiments. JFA and MR worked on this paper as supervisor and help to conduct experiments. RA worked on the literature review.

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