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Visibility Performance Assessment: Simulation of a Digital Shadow in a Port

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Abstract: The growth of goods transported by ship affects the entire maritime industry, which is central to the global supply chain. Faced with an increased pressure from the industry, ports need greater visibility on the flow of goods and logistics operations. To tackle this challenge, improvement opportunities as well as weaknesses must be identified in order to define an efficient data acquisition strategy that will allow port authorities to enhance their current visibility within their port ecosystem. This article presents the simulation of a digital shadow based on a Canadian port case study. The study uses the simulation of a digital shadow to diagnose a Canadian port authority's current visibility, with an accent on data accuracy, in order to identify improvement opportunities aimed at overcoming weaknesses identified in a current practice scenario and then compare the performance of the current system with said improvements in a second scenario. To our knowledge, this is the first simulation study on visibility performance assessment in a port's digital shadow.

Keywords: industry 4.0; maritime and port logistics; systems simulation; digital shadow; data acquisition

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1. Introduction

In today's globalized world where most goods are delivered and consumed worldwide, the supply chain and the transportation industry are under considerable and increasing pressure to meet demand. The pressure is particularly strong for the maritime shipping industry, which is involved in more than 90% of the transport of goods (Fruth and Teuteberg, 2017) [1]. In 2022, the transport of goods by the maritime industry reached 11 billion tons, which corresponds to a growth of 3.2% compared to 2020, (United Nations Conference on Trade and Development, 2022) [2]. Among the multiple actors along a maritime supply chain, the port is a key actor who allows national and international trade which ensures the connection between the different transport modes and connects the different producers and consumers to the markets (Douaioui et al., 2018) [3].

As ports are a central node in the supply chain, they are faced with the need to optimize their performance at economic, environmental, energetic, and above all, operational levels in order to meet the growing needs of maritime transport (Molavi et al., 2019) [4]. To meet current and future challenges, ports have recently turned to new technologies from Industry 4.0. Industry 4.0, which is the basis of the fourth industrial revolution initiated by Germany in 2011, has captured the interest of the industrial field for several years already. The interest in ports for Industry 4.0 is recent, but growing. Indeed, it has been noted that this industrial revolution brought about by the emergence of new technologies such as the Internet of Things (IoT) and big data present development opportunities not only for the industrial sector, but also for other fields and applications such as supply chain management and logistics (Douaioui et al., 2018). However, as stated in Heilig and Voß. (2017) [5], ports are seen lagging behind in regard to the development of information technology and information systems. This statement is furthered by Jović et al. (2022) [6], who noticed through their literature review that there is a lack of a comprehensive overview of digitalization in maritime transport with an emphasis on the implementation of information and communications technologies.

While information technologies are used for collecting, measuring, and transmitting data, information systems manage, analyze, store, and disseminate information and knowledge to support decision processes of various port actors (Heilig and Voß., 2017).

Ports striving toward the integration of information technology and information systems are also faced with a large array of options that need to be carefully considered, since many of the implemented technologies will be consolidated within the port and merged with each other in integrated systems. Thus, ports must know what data they wish to collect and the desired accuracy in order to devise a long-term plan for the integration of information technologies and systems. Heilig and Voß. (2017) demonstrate this when explaining that a port might use optical character recognition (OCR) technology to read the license plates of trucks entering a terminal. In some cases, OCR might be enough to identify the trucks entering certain areas, but in other cases, this technology could be combined with other technologies and systems, such as a driver card or the use of the drivers' mobile devices to further confirm each driver entering the terminal. For example, bad weather such as a snowstorm or heavy rain could impair the OCR, and using a complimentary system or technology would enable the information system to function nonetheless. Most technologies have their strengths and limitations, as well as their prices, and the port authority must weight their benefit with the desired data accuracy it seeks.

The Canadian port authority involved in this study is one such organization that seeks to evolve and face its challenges using, among other things, innovative technological solutions. In particular, the port authority has expressed interest in digital twin technology. In the maritime field, Erikstad (2017) [7] defines the digital twin as "a virtual model that renders the state and behaviour of a physical asset in near real time, based on sensor observations, in its operational environment". As certain authors point out in the literature, the digital twin is a technology complementary to other 4.0 technologies, such as the IoT and big data (Erikstad, 2019) [8] since it leverages real-time data acquisition to provide vision and experience to port actors through simulation and data analysis (Taylor et al., 2019) [9].

The digital twin is a tool that relies heavily on accurate data. In order to guide the port authority towards their digital twin goal, issues and improvement opportunities touching data acquisition, data quality, and connectivity must first be addressed. To do so, this paper presents the simulation of a digital shadow to diagnose the port authority's current visibility and improvement opportunities.

The digital shadow is similar to the digital twin on a subpar level. Indeed, the digital shadow is defined as a digital representation of an existing or planned physical object where there exists an automated data flow between a physical object and a digital object and in which a change in state of the physical object leads to a change of state in the digital object, but not vice versa (Kritzinger et al., 2018) [10]. A digital twin is similar to a digital shadow, which in addition includes an automatic data flow between the physical and digital objects in both directions. Thus, the physical and digital objects are fully integrated and can induce changes of state in each other. There are many levels to a digital twin. Julien and Martin (2021) [11] specify that the models and data collected will initially be used for analysis and simulation, which at the first level of this technology, mostly contributes to the visibility and traceability of products and processes.

Before reaching the state of a fully integrated system such as a digital twin, the port authority's initial strategic plan is to aim towards the development of a digital shadow. In this paper, the simulation of a digital shadow is used, with the Simio simulation software (Simio Version 11.197), to diagnose the current performance of the port authority's visibility on the flow of one type of merchandise passing through the port (i.e., alumina) and compare the performance of the current system with different improvement scenarios relying on new technologies from Industry 4.0. The goal of this paper is to present the simulation of a digital shadow to assess the port authority's current visibility as well as to identify improvement opportunities aimed at overcoming weaknesses identified in the current system. This study aims to provide the port authority with an accurate assessment of the system's current visibility in order to drive future projects and enable collaboration opportunities with stakeholders such as the railway transport company and port actors.

In Kim et al. (2008) [12], simulation is used to compare the performance of a current practice scenario versus new practice scenarios in order to analyze the value of additional data provided by an RFID location-tracking device. This approach is also used in Cimino et al. (2017) [13], in which the authors realized a what-if analysis to measure how certain changes in a set of parameters would impact on the process performance of a harbor. The what-if analysis was conducted by comparing an "as-is" system, which is used as a baseline for measuring progress, with a "to-be" system, which includes scenarios of optimized versions of the current business model. Because it is often impossible or expensive to observe the actual "to-be" system, simulation is a fundamental tool used in this type of study. With the use of simulation, it is possible to observe a large number of "to-be" scenarios.

Similarly, this paper analyzes a current practice scenario with a second "to-be" scenario, which evaluates the effect of different improvements on the port authority's visibility. The improvements considered for the second scenario are information technologies from industry 4.0 enabling to collect data. Technologies such as radio-frequency identification (RFID) can be used in real-time location systems and to exchange information on cargo (Heilig and Voß, 2017). Another example is optical character recognition (OCR) systems. OCR technology already has several applications in modern ports, allowing asset identification and the automation of checking procedures (Rodrigo González et al., 2020) [14].

The method used in this paper is comparable to the approach proposed by Marquardt et al. (2021) [15], where an ideal model experiment is showcased to illustrate the potential consequences of indolence for the case in which a digital shadow lags behind changes in a real-world system. The authors use discrete event simulation to pinpoint ways in which a digital shadow can deviate from the real-world system due to shocks in parameter values, structure, and diverging assumptions. The model simulates the real world (RW) and the digital shadow (DS) in the same simulation model and studies the impacts of different changes within the RW on the performance of the DS by tracking the mean and individual output of items being processed in a manufacturing line. The authors conclude that in the case of shocks in parameter values or structure, the change in the RW should be immediately mirrored by the DS to avoid any data gap. In the case where there is a delay before the DS updates to the changes in the RW, the systems will align after a burn-in period if the changes are undone or the DS is updated. In the case of diverging assumptions, the experiments show that comparing the RW and DS indicators superficially and in a steady state is not enough to identify deviations resulting from diverging assumptions.

While Marquardt et al. (2021) apply their concept to a theoretical system to prove their concept and draw conclusions on the deviations between a digital shadow and a real-world system, this paper presents a case study of a non-containerized port with a focus on visibility performance, data gaps, and the impact of data loss and update rates of a system on its digital shadow through the use of discrete event simulation.

1.1. Project Context

The port of this study is a public-owned medium-sized urban port specializing in the storage and multimodal transport of a large variety of non-containerized goods. Goods pass through the port by sea, rail, and road, and the underlying logistics operations such as handling, warehousing, and transport are carried out by port actors that operate independently from the port authority. In other words, the port authority is responsible for the well-being and development of its port area, but does not intervene in various port actors' operations within the port.

1.2. Problem Definition

Currently, the port authority has limited visibility on the flow of goods and port logistics operations while it must ensure sound governance of the port. This situation raises performance issues affecting everyday operations, such as bottlenecks, underuse of port infrastructure, security, and environmental impacts (e.g., greenhouse gas emissions, dust, noise).

The port authority's limited visibility can be explained by the incomplete data acquired regarding the flow of goods and logistics operations from the entrance to the exit of the port. Absence of data acquisition technologies, delays in data update times, data privacy as well as the uncertain quality of the data further contribute to reducing the port authority's visibility.

This paper presents the simulation of a digital shadow to diagnose the port authority's current visibility and improvement opportunities. The simulation model, designed with the concept of the digital shadow in mind, is used to identify the main visibility issues in the current system as well as highlight the areas in which improvements will yield the best results. The conclusions of this study aim to assist the port authority and its associated stakeholders to identify future actions and projects to improve their visibility, as well as provide a first step to opening discussions on the subject of data sharing and collaboration between port stakeholders.

To our knowledge, this is the first simulation study on visibility performance assessment for a port's digital shadow. Considering the lack of literature on non-containerized ports, this paper addresses a novel concept in a field with many research opportunities.

Discrete event simulation was used for this study because of its potential for exploring multiple scenarios and comparing multiple systems (physical and virtual) simultaneously.

1.3. Simulation Model Boundary

The model developed is limited to the flow of goods and port logistics operations involving a single good, which is alumina. Alumina transiting through the port is normally transported by ship (inbound) and by train (outbound). In addition, the infrastructure included in the model is the silo for the storage of alumina and the scales for weighing railcars. The simulation of the digital shadow encompasses all the operations between the arrival and departure of the alumina ships and railcars. Currently, the port authority has low visibility for many logistics operations within the port. Indeed, the storage of alumina in the silo, the weighing of the railcars and the loading of the railcars embed key data to which the port authority does not have access since the equipment used in these processes belong to a private port actor.

Although the model described in this study is used only for the study of alumina, it is generalizable and can be applied to other single or multiple goods within a port system using road, rail and maritime transport to achieve the same type of analysis presented in this paper. It is important to emphasize that the simulation model in this study is not an operational management tool to be used by the port authority for managing operations. The proposed model isn't a detailed reproduction of the port's activities, and solely focuses on simulating the main logistics operations and the flow of alumina, which provide enough to diagnose the port authority's current visibility.

The paper is organized as follows. Section 2 addresses the materials and methods used for the research. Section 3 presents and discusses the results. Finally, Section 4 covers the conclusion.

2. Materials and Methods

2.1. Input Data

Most of the data used in the simulation model comes from various data sources compiled by the port authority for administrative purposes. Therefore, a significant work of data analysis had to be performed in order to flesh out usable and satisfactory data, since errors and missing data were not uncommon. After careful consideration, the simulation model uses rail and maritime data from 2018 to create the ships and railcars arrivals over a one-year period. For the maritime transport of alumina, the arrival and departure dates and hours as well as the quantity of alumina transported were the data used in the model. More specifically, the model uses the exact date and hour of historic arrival of the ship to reproduce the arrival of ship entities in the simulation model. The transported quantity of alumina is generated by a distribution in the model. The ship's unloading time is estimated by a distribution using the delay between the ship's arrival and departure in the port authority's data.

For the rail transport of alumina, similarly to the ship arrivals, the historic arrival dates and hours generate the railcar arrivals in the model. The quantity of alumina transported by railcars is generated by a distribution in the model. It was not possible to estimate the railcar's weighing and loading time since there are many operations and inactive periods between the arrival and departure of the railcars. The lack of data regarding the railway transport led to the use of certain assumptions. Every assumption used in the model were implemented following discussions with the port authority for their validation and revision.

Regarding the capacity of the alumina silo, the maximal capacity of the silo was never reached during the simulation.

2.2. Assumptions

In order to be able to complete and execute the simulation of the digital shadow, a few assumptions had to be made. Assumptions were made out of necessity, due to lack of information, and are based on information obtained from consultations with the port authority's employees. The assumptions affect the duration of the port's logistics operations, but do not alter the quality of the results presented in Section 3, since both the physical and virtual layers of the simulated digital shadow are subject to the same assumptions, thus leading to stable results dealing with the data gap concerning the flow of alumina in the physical and virtual layers.

The first group of assumptions is that the operating time of weighing railcars (empty and loaded) as well as the loading time of railcars were approximated after discussions with the port authority.

The second assumption used is that 25,000 tons of alumina is stored in the silo at the start of the simulation. Since the precise quantity of alumina in the silo at the beginning of the year 2018 is unknown, the quantity of 25,000 tons was chosen after a few validation tests with the model as well as validation from the port authority.

The third assumption is that the maritime data update is carried out every 24 h at 3 p.m. precisely. The port authority's harbor master acquires and updates the maritime data manually, which can cause a delay in integrating the data into the port authority's database. With this assumption, the maximal delay between the unloading of a ship and the updating of the quantity of alumina being unloaded is therefore 24 h.

The fourth assumption is that the percentage of errors in railway data results in data loss. The port authority's employees explained that, following an internal analysis, the railway database has about 3% of missing data. The percentage of error has been incorporated into the model by assuming that 3% of the railway data is lost during the simulation. This means that 3% of alumina transport by railcar is not recorded in the data flow of the model.

2.3. Conceptual Design

The simulation model is made up of two layers. The first layer, referred to as the physical system, represents the "real" flow of alumina within the port as well as the associated logistics operations in real time and with exactitude. The second layer, referred to as the virtual system, represents the captured data by the port authority using a given system. The virtual and physical system are similar except that the virtual system is subject to various delays and inaccuracies and only shows the data that has been successfully captured in the physical system.

Certain events occurring in the physical system trigger a process in the background. Background processes have the function of releasing information into the two aforementioned layers. The first layer (physical system) illustrates the information (quantity of alumina in inventory, alumina flow) in real time and represents the real flow of alumina. The second layer (virtual system) illustrates the information (quantity of alumina in inventory, flow of alumina) captured in the first layer by the port authority with a given system. The data captured by the port authority, represented in this second layer, is subject to update times and errors, causing certain gaps between the physical alumina flow and the virtual alumina flow. The purpose of the simulation is to measure this difference caused by the different independent variables, which is the data gap.

2.4. Scenarios

In this subsection are presented the scenarios used for the experiments in this study.

2.4.1. Scenario 1

Scenario 1 consists of the simulation of the current system without collaboration between the port authority and the port actors. The absence of collaboration is emphasized, because the port authority has no access to the port actors' equipment or information relating to weighting or the loading and unloading of alumina in the silo. In addition, in scenario 1, it is assumed that there is no new data acquisition technology and that all the data is captured by the current means of the port authority. Scenario 1 is mainly used to illustrate the performance of the current system.

2.4.2. Scenario 2

Scenario 2 consists of the simulation of an improved system, assuming collaboration between the port authority and the port actors. In order to be able to implement data acquisition technologies or to have access to external data, it is necessary to assume a form of collaboration between the port authority and the port actors. In addition, in scenario 2, we assume the integration of new data acquisition technologies. The impacts of technological solutions from Industry 4.0 are studied in scenario 2 of this study. The scenario is used to illustrate the potential performance of a new system for the port authority's visibility and is compared to scenario 1.

2.5. Model Variables

2.5.1. Dependent Variable

One dependent variable is measured, namely the deviation percentage between the real average quantity (layer 1) and the virtual average quantity (layer 2) of alumina. The dependent variable is a value calculated at the end of the simulation with the following expression:

$$\left(\frac{(Physical_{Silo}.AvgInStock - Virtual_{Silo}.AvgInStock)}{Virtual_{Silo}.AvgInStock}\right) * 100 \tag{1}$$

The virtual alumina stock represents the data acquired by the port authority while the actual alumina stock is represented in the physical system.

2.5.2. Independent Variables

The independent variables used in the simulation model were determined following discussions with the port authority. The first two independent variables used in the model deal with the work schedule of the employees loading the alumina in the railcars and the schedule of the railway company entering/leaving the port with the unloaded/loaded railcars.

The third independent variable is the delay in receiving railway data by email. Currently, there is a three-day delay between the railway activities taking place at the port and the reception of the data by email.

The fourth independent variable is the delay in railway data update in the port authority's database. Currently, the railway data update by email is carried out automatically every two hours. There can therefore be a maximum delay of two hours between the reception of the data by email and the data update in the port authority's database.

The fifth independent variable is based on the third assumption mentioned in Section 2.2. This variable is the maritime data update delay in the port authority's database. In scenario 1, the maritime data is manually updated by the harbor master at 3 p.m., as previously stated by the third assumption of the model.

The sixth independent variable is based on the fourth assumption mentioned in Section 2.2. This variable addresses the 3% missing data in railway data.

The seventh and last independent variable is the delay between physical inventories. Physical inventories are executed in the model as an explored solution to reduce the port authority's data gap. By doing a physical inventory every month, the port authority updates its database with the quantity of alumina evaluated during the physical inventory.

2.5.3. Control Variables

Control variables are independent variables that are modified in the project's experiments in order to simulate different scenarios in Simio. The third, fourth, fifth, and sixth independent variables presented in Section 2.5.2 are the variables that are modified in the different experiments in order to analyze their impact on the performance of the port authority's visibility.

2.6. Simulation Model

The simulation of the digital shadow was carried out using Simio. During the simulation, the events (e.g., ship unloading, railcar loading) occur through the use of background processes in the physical and virtual layers of the model. The physical layer simulates the flow of alumina through the supplier, the port's silo, and the client by using inventories to store alumina and respect flow balance during the simulation. The same logic is applied to the virtual layer, where the alumina flow perceived by the port authority is represented. Both layers are illustrated in Figure 1.

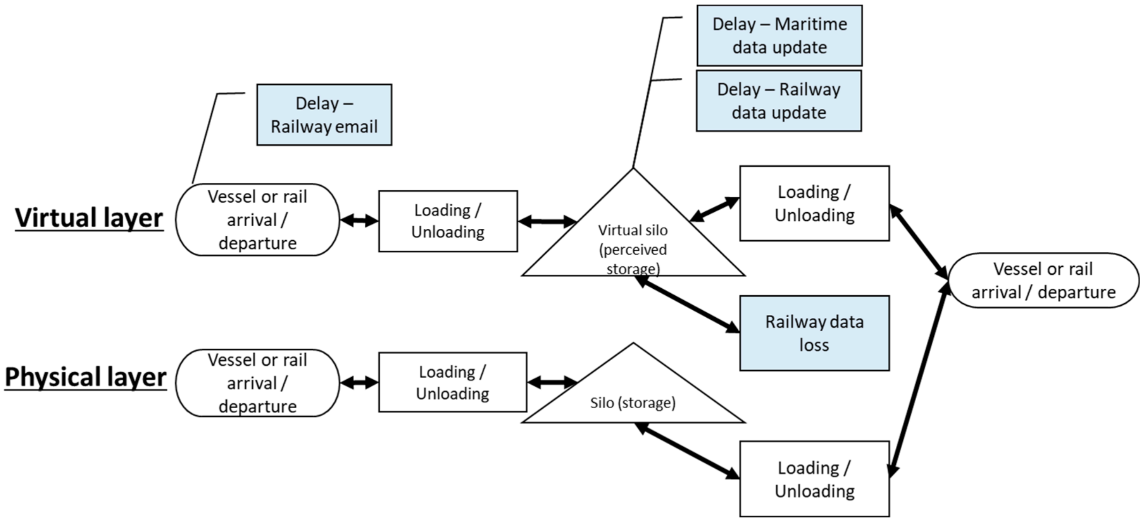

Figure 1. Physical and virtual layers of the simulated digital shadow.

3. Results and Discussion

In this section, the results obtained by executing the experiments in the simulation model are presented and discussed.

A total of five experiments with twenty replications each were conducted for scenario 1. The first experiment includes the results for all control variables in scenario 1. As shown is Table 1, the port authority's current performance (experiment 1), using the assumptions specified in Section 2.2, shows there is a 20.4% average deviation between the physical and virtual layer. This deviation illustrates a significant lack of visibility by the port authority over the flow of alumina.

Table 1. Scenario 1 results.

Scenario 1	**Control Variables**				**Deviation (%)**	**Standard Deviation**
Experiment	**Delay Email Railway (Days)**	**Delay Railway Update (Hours)**	**Delay Maritime Update (Days)**	**Railway Data Loss (%)**		
1	3	2	1	3	−20.43	0.887
2	3	0	0	0	−7.95	0.2364
3	0	2	0	0	−0.13	0.00437
4	0	0	1	0	1.66	0.2756
5	0	0	0	3	−15.83	0.976

The next four experiments (2 to 5) present the impact of each control variables separately in order to identify the most important sources of deviation. The results presented in Table 1 show that the three days of delay in railway data as well as the railway data loss of 3% highly influence the deviation (7.95% and 15.83%, respectively), while the delay in railway and ship database update has a minor impact (0.13% and 1.66%, respectively).

In order to further illustrate the impacts of the control variables on the alumina data gap, the real quantity of alumina and the virtual quantity of alumina in the system during a full year was plotted for the current practice scenario as shown in Figure 2.

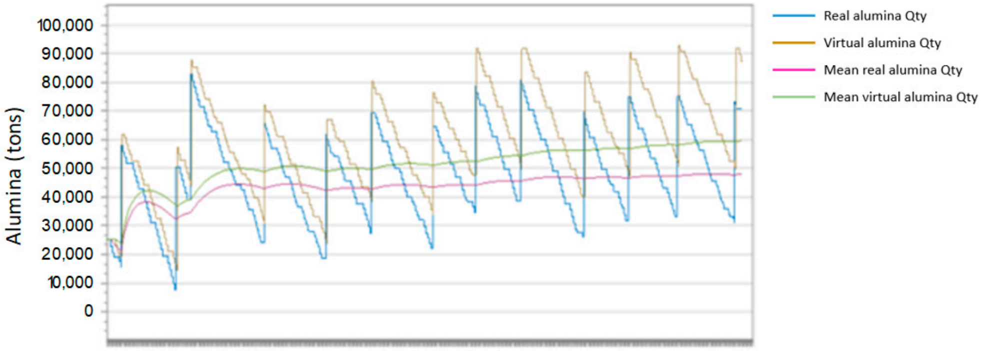

Figure 2. Real quantity vs. virtual quantity of alumina of the current practice scenario.

By paying attention to the real alumina quantity (blue line) and the virtual alumina quantity (brown line), we notice that the virtual quantity is always higher than the real quantity of alumina in the port. The superior quantity of virtual alumina seen in the system is explained by the three days of delay of the railway data. Alumina is transported out of the port by railway and the delay in obtaining important railway data impacts the quantity of alumina seen by the port's data acquisition systems, showing a greater amount of alumina (virtual alumina) than what is really in stock (real alumina). Since the delay for maritime update is smaller and less impactful than the railway delay, the extra virtual alumina stock is added to the new shipments of alumina throughout the simulation, raising the data gap higher as time passes.

The railway data loss is also an important factor responsible for the continuous rise of the alumina data gap. Because certain outgoing railway transports are not recorded, tons of virtual alumina remain in the port's database, increasing the data gap between the virtual and the real quantity of alumina within the port.

Scenario 2 was carried out to determine the system's performance following different improvements aiming to achieve higher visibility of the alumina flow and logistics operations within the port. Table 2 presents the simulation results of scenario 2. Experiment 9 represents an ideal scenario where there is no delay and no data loss in the railway and maritime data. Because of these ideal conditions, the deviation of the last experiment is almost zero. It is important to emphasize that the ideal scenario, in this point in time, is idealistic and illusory because many elements required to attain this scenario depend on the collaboration of external organizations that are presently unwilling to share private data. Excluding the ideal scenario previously mentioned, experiment 6 and experiment 7 offer the best visibility with a deviation of only 1.53% and 1.66%, respectively. These results are explained by the fact that both the delay in receiving the railway data by email and the loss of railway data have been reduced to zero.

Table 2. Scenario 2 results.

	Control Variables				Deviation (%)	Standard Deviation
Experiment	**Delay Email Railway (Days)**	**Delay Railway Update (Hours)**	**Delay Maritime Update (Days)**	**Railway Data Loss (%)**		
1	0	2	1	3	−14.75	0.985
2	3	0	1	3	−20.35	0.888
3	3	2	0	3	−21.45	0.881
4	3	2	1	0	−6.66	0.3105
5	0	0	1	3	−14.66	0.987
6	0	2	1	0	1.53	0.2741
7	0	0	1	0	1.66	0.2756
8	0	0	0	3	−15.83	0.976
9	0	0	0	0	0.000006	0

Indeed, as explained previously for scenario 1, the delay in railway data as well as the loss of railway data has an important impact on the deviation between the quantity of alumina in the silo of the physical and virtual layers. We also see that the difference between the two best experiments is negligible, even though the delay in railway data update was reduced to 0 in experiment 7. This confirms the negligible impact of the delay in data update for the railway. It is important to point out that although experiment 9 is the ideal scenario, experiments 1 to 8 of scenario 2 are more or less idealistic. Indeed, each of these experiments requires the full resolution of at least one to three of the control variables. To immediately attain a full resolution of the data loss or railway and maritime data delays is unlikely for the port authority, and many solutions and efforts will need to be put forward to attain these goals. The interest in simulating the impact of idealistic scenarios is to present the port authority with the best possible outcome upon acting on the identified problems. In the same order of ideas, the port authority might want to focus on changes in practices and not only on the identified problems to attain a higher overall visibility.

An example of practice change explored in this research is the use of physical inventories in order to mitigate the growing data gap in the port authority's database. This approach would not act on the identified variables, but would instead reduce their impact on the port authority's visibility. Table 3 presents the deviation (%) for experiments of both scenario 1 and scenario 2 where there is not the practice of physical inventory as is proposed in scenario 3.

Table 3. Scenario 3 results comparison with previous results without physical inventory.

Experiments	Scenario 1		Scenario 3		Scenario 2		Scenario 3	
	Without Physical Inventories		Physical Inventories (Every 4 Weeks)		Without Physical Inventories		Physical Inventories (Every 4 Weeks)	
	Deviation (%)	Standard Deviation	Deviation (%)	Standard Deviation	Deviation (%)	Standard Deviation	Deviation (%)	Standard Deviation
1	−20.43	0.887	−4.62	0.2654	−14.75	0.985	−0.03	0.2914
2	−7.95	0.2364	−4.71	0.1449	−20.35	0.888	−4.5	0.2647
3	−0.13	0.00437	−0.14	0.00437	−21.45	0.881	−5.91	0.1859
4	1.66	0.2756	1.46	0.2756	−6.66	0.3105	−3.52	0.2686
5	−15.83	0.976	−1.31	0.1529	−14.66	0.987	0.11	0.2931
6	-	-	-	-	1.53	0.2741	1.32	0.2741
7	-	-	-	-	1.66	0.2756	1.46	0.2756
8	-	-	-	-	−15.83	0.976	−1.31	0.1529
9	-	-	-	-	0.000006	0	0.000006	0

Table 3 illustrates the deviation between the virtual and real alumina stocks when physical inventories are realized every four weeks to update the port's database (virtual alumina is this case) with the real amount of alumina in stock. This parameter is analyzed separately from the other control variables since, unlike the other variables, it is not identified as a weakness or problem in the current port. The execution of physical inventories is a change in the port authority's practice and would require collaboration with different port actors to have access or to install technologies on private infrastructure. The results presented in Table 3 show that for the current port (scenario 1), doing a physical inventory of alumina every 4 weeks has a major impact on the deviation and is effective to counter the delay in railway emails (experiment 2) and the lack of railway data precision (experiment 5). The impact on the current practice experiment (experiment 1) also shows a significant reduction in data deviation. Figure 3 illustrates the impact of physical inventories on the measured deviation for the current practice of scenario 1 (experiment 1).

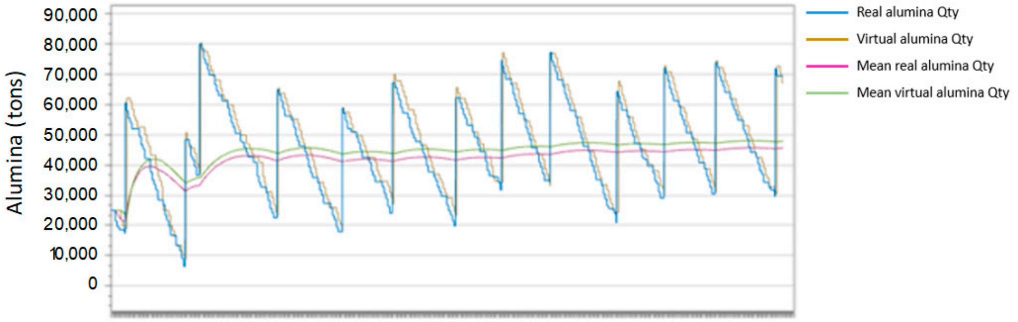

Figure 3. Real quantity vs. virtual quantity of alumina of the current practice scenario (physical inventories every 4 weeks).

By observing Figure 3, we notice that the gap between the real quantity of alumina (blue line) and the virtual quantity of alumina (brown line) is smaller and does not grow as large as the gap in Figure 2 over time. This is shown more clearly by observing the mean quantity of real (pink line) and virtual (green line) alumina throughout the simulation. The gap between the mean values grows larger in Figure 2 while it remains stable in Figure 3. From these observations can be concluded that while physical inventories do not eliminate the data gap, they effectively keep said gap under control by stopping its growth caused by the loss of railway data and delay in railway emails.

By taking into account the execution of physical inventories every four weeks, we notice an important deviation decrease in many experiments for both the first and second scenario. The most important deviation decreases are seen in experiments in which railway data loss is present, confirming the important positive effect of the physical inventories in reducing the data gap cause by the data loss. The four-week period between each physical inventory was used in this research, but in the advent the port authority wishes to implement this feature, it will need to decide its desired level of accuracy for its stored goods in order to implement an appropriate delay between physical inventories.

These observations and results demonstrate that the port authority must above all concentrate its efforts on the completeness of its data as well as on the reduction of delays in the acquisition of railway data. Regular physical inventories are also shown to be an effective solution to reduce the data gap caused by the railway data loss and the delay in railway emails. It should be noted that the "to-be" experiments explored in scenario 2 are not actual solutions being proposed to the port authority, but instead are improvement areas that are to be targeted in order to optimize their current visibility performance. As for the physical inventories of scenario 3, this new practice would be an adequate way to maintain the port authority's visibility under control and stop possible deviations in the data from increasing continuously as seen in Figure 2.

4. Conclusions

This paper studied the development of a digital shadow to assess a port authority's current visibility as well as to identify improvement opportunities aimed at overcoming weaknesses identified in the current scenario. The simulation model developed illustrates the alumina flow and logistics operations in a physical layer and a virtual layer. The deviation between the quantity of alumina in the physical silo and virtual silo was the variable used to assess the performance of the port authority's visibility. With a deviation between the physical and virtual layer, the simulation analysis shows that the current visibility of the port authority is problematic. Scenario 2 demonstrated that reducing the delay in the reception of railway data as well as reducing the railway data loss result in significative improvements for the port authority's visibility. In addition, the execution of monthly physical inventories presented in scenario 3 showed positive results in reducing the data gap caused by the railway data loss and the delay in railway emails. If the port authority is unable to reduce the data loss or delays in receiving railway emails, the use of physical inventories would be an effective solution to keep the data gap under control. Moving forward, the port authority can refer to the study's results to enact concrete actions aimed at improving their visibility. The results also provide the port authority with a basis to open discussions with stakeholders on the subject of data sharing and collaboration.

It is worth mentioning that the simulation model was validated by performing the simulation of the alumina flow using the port authority's data without the control variables to verify that the model tends toward the studied system's real behavior. Considering the internal validation of the model as well as the external validation by the port authority, we are confident in the adequacy of the conclusions given in this paper.

Another improvement opportunity pertains to information sharing within the port system. As stated by Yau et al. (2020) [16], shared information is important to cater for the increasingly complex port operations in order to ensure the supply chain and port operations run smoothly. This solution was not explicitly explored in this study, but would certainly act upon the observed control variables.

Potential future work connected to this study would address the digital twin technology and elements such as bottlenecks within the system and the effect of data uncertainty and deviations, as seen in this study, on the performance of this technology. Such a study would also analyze a larger and more diverse array of goods within a model.

To our knowledge, this is the first simulation study on visibility performance assessment for a port's digital shadow. The use of a physical and virtual layer to show performance of the visibility achieved by the simulated digital shadow demonstrate the current limitations of the port authority and the areas in which improvements must be made in order to achieve a higher visibility of the flow of merchandise and logistics operations.

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