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ESTIMATING THE EFFECT OF PRODUCT VARIETY AT A BRAZILIAN BULK TERMINAL

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ABSTRACT

Brazil is one of the world's leading iron ore exporters, producing millions of tons annually. To transport ore, the country has specialized port terminals and logistical infrastructure designed specifically for export. The improvement of such systems remains a challenge and attracts substantial investment, generating a great synergy between companies and universities in the search for solutions. In this context, we present a case study involving a Brazilian terminal designed to handle iron ore, which must now import coal as well. The objective, therefore, is to analyze the effects of this new operation on the system's performance indicators. To evaluate and compare different scenarios, a discrete-event computational simulation model was built using the software Simul8. The results show that the new operation is viable, maintaining an 89% service level when handling three millions of tons per year of coal.

1 INTRODUCTION

According to a recent report from the Brazilian Ministry of Industry, Foreign Trade, and Services, MDIC (2019), iron ore is the third most exported product from Brazil (ranked in US$) over the past decade. This highlights the great importance of port terminal systems in the context of Brazilian international trading. For this reason, bulk terminals have been investigated from a variety of perspectives, such as productivity improvement, port capacity analysis, equipment allocation, vessel scheduling, and yard management. However, studies involving simultaneous importing and exporting bulk cargo operations at the same terminal are still uncommon in the literature.

This paper presents a case study based on the need to assess the terminal capacity. In particular, we investigate the effect of introducing coal operations (importing) on top of the current iron ore export (much more frequent in this context), which differentiates this paper from previous work. A discrete-event simulation model was built to perform this assessment. The main contribution of this study is to obtain relevant insights into the consequences of changing the operational conditions of the terminal by introducing coal importing from maritime trade. As a result of this work, the port's decision-makers will be provided with information useful for operational planning, such as equipment occupation rates, yard inventory levels, and so on. Additionally, the paper contributes to the state of the art in discrete-event models of terminal operations, presenting two simultaneous operations that have opposite flows and share equipment at the same terminal. The scope of the model built includes discharge, storage, and loading operations, with detailed equipment allocation and storage area definitions. Railway and maritime access were not considered in the model.

The document is organized as follows: The current section gives the problem statement and a brief outline of context; Section 2 provides a literature review, indicating related previous work and foundations for the present study; Section 3 discusses methodology, including a description of the terminal port and the simulation model as well as the relationship between the main subsystems and equipment on which the model is based; Section 4 gives data and results, reporting on the design of experiments, input parameters, and summary (with analysis) of the results; and finally Section 5 concludes the paper, describing important outcomes and practical contributions to improve port operations under the described conditions.

2 LITERATURE REVIEW

2.1 Discrete-Event Simulation

Miller and Pegden (2000) state that simulation is the process of elaborating a model of a real system and conducting experiments to understand its behavior and/or evaluate various operational strategies. Simulation is a tool that is used in numerous areas, such as manufacturing (de Carvalho Miranda et al. 2010; Montevechi et al. 2015), services (Baril et al. 2016), project management (Montevechi et al. 2016), education (Rocha et al. 2014), optimization (Jian et al. 2016), and healthcare (Cocke et al. 2016), among others. A number of frameworks are discussed in the literature to help simulation analysts to properly conduct a simulation project. Figure 1 depicts a method proposed by Robinson (2004).

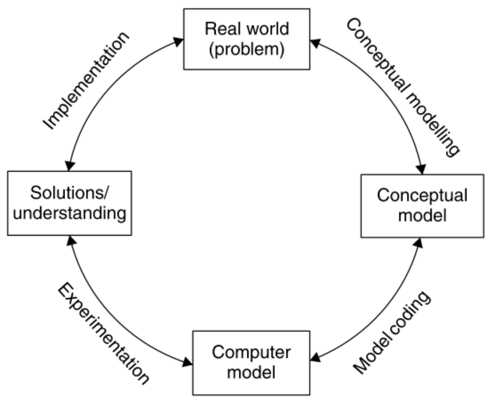

Figure 1: Key stages and processes.

A simulation begins with a real-world problem, followed by a conceptual modelling effort to create a conceptual model. The model is transferred to a computational model environment using (generally) a simulation tool such as Arena (Kelton et al. 2002), Simul8 (McGregor and Cain 2004), or AnyLogic (Borshchev 2013). The required data are prepared to feed the model. Next, after verification and validation of the model, experiments are performed. Finally, results are interpreted and solutions are proposed. It is important to emphasize the attention that must be paid to the correct processing of the available data, given the impact it can have on the results.

2.2 Material Handling in Bulk Terminals

Bulk terminal operations have been investigated under a variety of perspectives and methods. Netto et al. (2015) evaluated the capacity of a terminal associated with service level indicators using discrete-event simulation. They studied a similar system but analyzed the terminal's capacity to meet different demand levels of two iron ore products. The authors used Arena software to build the computational model. Medina et al. (2013) used a distributed simulation model approach to represent the entire supply chain of an iron ore operation in Brazil. They also used Arena to simulate several connected seaports and determine the maximum possible cargo volume supported by a shipping fleet. The authors built the model of each port based on a generic model, which was then adapted to represent the particularities of each system. van Vianen et al. (2014) studied the necessary stockyard size for operations at a bulk terminal. First, they determined analytically the parameters that affected the required stock size, and then used a simulation approach to analyze the outcomes, considering the stochastic nature of ship arrivals and service times. They successfully applied the proposed method in a case study, in which they were able to determine the necessary stockyard size.

Lastly, Tang et al. (2016) applied the Multi-Phase Particle Swarm Optimization (MPPSO) algorithm using Matlab software to solve a Non-Deterministic Polynomial (NP) problem, which aimed to minimize the total service time (waiting time and operating time) and makespan (finishing time of the last job). Different results were obtained depending on the objective function and variables considered, such as makespan, job priority, and weights for operational and queueing times.

3 METHODOLOGY

In order to investigate the effect of handling different products simultaneously (in particular ore and coal), we propose a case study as the methodological research framework for this study. Miguel and Sousa (2012) state that case studies are based on a deep analysis of one or more situations observed in real life (named cases). They note that case studies enable the development of new theories and increase the depth of understanding of events during regular operations, highlighting complex relationships between parts of the system.

The case study proposed in this research uses discrete-event simulation to build a model that represents real operations of a bulk terminal, which currently handles only iron ore. The model was validated according to a set of key performance indicators (KPIs) collected from the company's dedicated information system. Validation is an important step of the project since it ensures that the model is reliable enough to conduct analyses and draw trustworthy conclusions about the system.

The conceptual model, which will be detailed later, is the enumeration of the premises and rules that must be considered and respected when implementing the computational model. Validation is performed by comparing real data (if available) and performance indicators obtained from the model. This process can lead to a revision of the conceptual model and the implemented computational logic. Figure 1, adapted from Medina and Chwif (2007), represents this iterative process, which is executed until a validated model, capable of reliably representing the system is obtained.

All rules should be very clear and well understood among all project participants (as well as stakeholders), detailed to the maximum and, where necessary, simplified with justifications, taking into account the need to transfer the described logic to the software, which in this case was SIMUL8 (McGregor and Cain 2004).

In this study, the terminal was conceptually divided into three subsystems: discharge, storage, and loading. Each subsystem was described in enough detail so that the simulation model was as close as possible (and as necessary) to reality.

3.1 The Terminal

The iron ore terminal can be divided into three subsystems: (1) discharge, (2) storage, and (3) loading. It is important to clarify that these names are given based on the most common operation (ore) of the terminal, but in the case of coal handling, the discharge system becomes the loading system, and vice versa. Also, it is important to understand that the three subsystems do not operate completely separately. Both discharge and loading subsystems share the storage area, as illustrated in Figure 2.

The discharge subsystem consists of two car dumpers (CD) that unload wagons filled with iron ore, which is transferred to the designated storage area using a stacker-reclaimer (SR). Figure 2 shows that both CDs can unload material at any one of the storage areas. However, it is important to mention a hard constraint: there is only one railway access, which means that only one CD can operate at a time.

The second subsystem has two storage areas, divided into three partitions each (A, B, and C). There are two stacker-reclaimers for each area, as shown in Figure 2. This equipment is very important for the entire system, because they can retrieve material from car dumpers, pour it into piles in the partitions, and reclaim it from storage areas to ship loaders (SL). The same equipment performs stacking and reclaiming functions, therefore they can only be used for one function at a time; that is, if SR1 (observed in Figure 2) is currently stacking, then it cannot be reclaiming material at the same time.

Lastly, the third subsystem consists of two berths where ships can moor. Additionally, two ship loaders are responsible for transferring the reclaimed material to the ships' cargo holds. It is also possible for both SLs to operate on any berth and, unlike the CDs, they can operate simultaneously, resulting in productivity gains during operations.

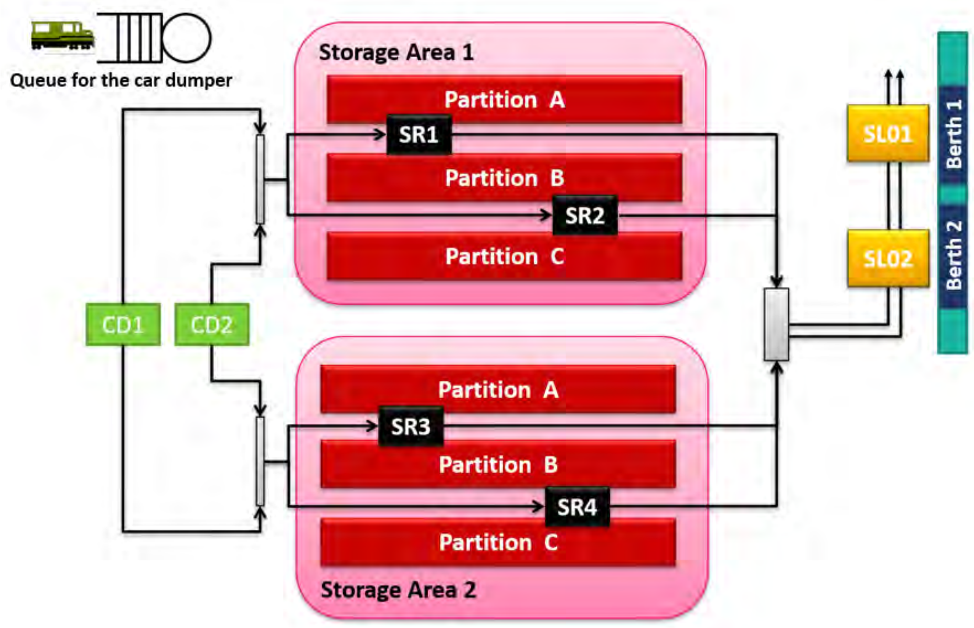

Figure 2: Overview of the terminal.

3.2 Conceptual Model

At the discharge subsystem, each train that arrives at the car dumper to unload material (ore) stays in queue for the dumper, waiting for an opportunity to unload. On arrival, there is a single line to access both CDs, and at departure, lines are connected in such a way that any CD is capable of conveying ore to any yard at the storage areas. Once a train is allocated to an available dumper, it exits the queue and does not return.

Trains must arrive at the terminal in an order that ensures that the mass balance between the load to be shipped and to be unloaded is conserved. When the CD finishes unloading a train, the model selects the next in line (respecting the FIFO rule) and checks if there is enough yard space for the product and an available stacker-reclaimer. If both conditions are met, it starts the discharge, otherwise, it selects the next train in the queue and repeats this process (in practice, the queue is already optimized by the planning department).

The capacity of the piles depends on the type of product that is allocated, due to differences in product densities. The model considers exclusive piles for each type of product.

An additional restriction is that two pieces of equipment cannot operate at the same pile simultaneously due to security regulations. Nonetheless, reclaiming on two different piles at the same time is possible, as long as there are two available SRs to perform the operations. At the arrival of a ship, berth availability is verified. If no berth is available, the ship waits in queue, otherwise, it navigates to a mooring place. A ships queue time stops accumulating when it starts moving towards a berth. When mooring is complete, a ship loader is assigned to the ship and the model checks if there is enough product in stock to meet the ships' demand and if there is a stacker-reclaimer available. Once these conditions are satisfied, the loading operation begins and the possibility of allocating a second loader to expedite the process is verified. After completely loading the ship, the SL is released and all post-operations are finished. When the unmooring maneuver is finished, the berth is considered available again.

3.3 The Simulation Model

The computational model of the bulk terminal was built using the software Simul8 (Chwif and Medina 2006) and comprises all the subsystems presented, as well as the coding necessary to ensure the interactions among them. The choice of software was based on the model builder's familiarity and license availability.

The model can be divided into three parts: The first part of the model concerns train and ship arrival and queueing; both operations are parameterized using a spreadsheet, where data such as arrival times, lot sizes, and product types can be controlled. The second part comprises the entire operation of ships, starting at the berth's entrance, continuing with the allocation of equipment (SL and SR) and storage area, followed by loading operations, and finishing at the terminal exit. The ships are transferred from the first part of the model (queue) only when a berth is available for mooring. Finally, the third part is the operation of trains, which follows the same basic steps as ships.

This division was made to simplify the explanation of the model; in reality, the entire model works as one integrated part, considering the existing relations between all subsystems.

4 DATA AND RESULTS

To obtain reliable results from a computational simulation model, it is necessary to input adequate data related to the actual system. In this study, a substantial amount of historical data was run through statistical software to perform adherence tests with known probability distributions, which were used as input for the simulation software. By doing so, the model was validated through the comparison between the data used as input and the output values obtained from the model, with a maximum error of 10% (Netto et al. 2015). Once the model is validated, the results can be used reliably in analyses to draw conclusions about the simulated system.

4.1 Input Data

In this model, we used the following data types: (1) information regarding the railway lots which supply the terminal; (2) exportation fleet composition: vessel classifications and fleet profiles; (3) operational times: navigation, mooring, pre and post-operations of the ships; (4) equipment productivity rates; and (5) yard capacities.

Tables 1-3 present details of the data types described above. Every value considered as input for the iron ore-only model is presented. For confidentiality purposes, the products and equipment are numbered rather than named (e.g., Product 1), but the operational characteristics were maintained. The term *commercial rates* stands for the real transference rates of the equipment. Commercial rates are smaller than *nominal rates*, which are the theoretical rates provided by the manufacturer.

Table 1: Details about car dumpers.

Input Parameter	Value
Number of CDs (only one railway access)	2
Maneuver and wagon positioning time (hours)	0:47:13
Commercial rate of CD 1 (tons/hour)	4,294
Commercial rate of CD 2 (tons/hour)	4,301
Wagon capacity (tons)	96
Lot size (wagons/train)	134
Lot capacity (t)	12,864
Maximum number of trains per day	6

Table 1 presents information about car dumpers. Note that (1) maneuver time is the time between the start of the maneuver, with the train stopped, and the actual moment when discharge begins; and (2) maximum number of trains per day is estimated based on the mean times of maneuver and discharge and the total hours available per day.

Table 2: Coal operation values.

	Input Parameter	Value
Ship Unloader	Number of SUs	1
	Nominal capacity (tons/hour)	970
Wagon Loader	Number of WLs	1
	Nominal capacity (tons/hour)	1,200
Demand	Coal (tons/year)	3 million
	Iron ores (tons/year)	50 million
Stacker-reclaimers (SRs)	Commercial rate of SRs – Stacking Coal (tons/hour)	11,000
	Commercial rate of SRs – Reclaiming Coal (tons/hour)	2,762
Storage Areas	Area 2 – Partition A (t) – exclusive coal storage	360,000
Fleet Profile	Types of ships considered	3
	% of Handymax of the total amount exported (40 to 60 kt)	15
	% of Panamax of the total amount exported (75 to 85 kt)	85
	% of Cape Size in the total amount exported (160 to 180 kt)	5

Table 3: Details about SRs, boarding lines, demands, berths, ship loaders, and storage areas.

System element	Input Parameter	Value
Stacker-Reclaimers (SRs)	Commercial rate of SRs – Stacking (tons/hour)	4,298
	Commercial rate of SRs – Reclaiming (tons/hour)	5,121
Boarding Lines	Number of boarding lines	2
	Nominal capacity (tons/hour)	12,000
Demand	Iron ores (tons/year) - production target	50,000,000
Mooring berths and Ship Loaders (SLs)	Number of berths	2
	Number of Ship Loaders	2
	Nominal capacity of SLs (tons/hour)	12,000
	Mean time of pre-operation (h)	0:15:00
	Mean time of post-operation (h)	5:55:00
	Mean time of mooring (h)	1:10:30
	Mean time of unmooring (h)	0:12:30
	Mean time of entering maneuver (h)	2:08:15
Storage Areas	Total capacity of Area 1 (t)	1,080,000
	Area 1 – Partitions A, B, and C (t/partition)	360,000
	Total capacity of Area 2 (t)	810,000
	Area 2 – Partitions A, B, and C (t/partition)	270,000
Fleet Profile	Types of ships considered	3
	% of Panamax of the total amount exported (75 to 85 kt)	5.5
	% of Cape Size in the total amount exported (160 to 180 kt)	89
	% of Large Cape in the total amount exported (190 to 220 kt)	5.5

It is important to point out the differences between iron ore's and coal's operation at the port. For convenience purposes, Table 2 shows only the operational data of coal that is different from that of iron ore. Values not mentioned in this table are the same as in Table 3.

4.2 Results

Two scenarios were developed in order to accomplish the objective of evaluating the capacity of the port terminal under different operational conditions while maintaining a high service level (operations efficiency). These scenarios can be described as: (1) handling different products with similar characteristics (different type of iron ore); these products use the same equipment at the same rates but cannot be mixed in storage, requiring the allocation of different stacks for each product; and (2) handling two types of coal in addition to seven other types of iron ores, in order to assess the effect of the insertion of these new products on the service level of the terminal. The coal products use different equipment and require an exclusive partition for their storage.

4.2.1 First Scenario

After configuring the model with the values presented in Tables 1 and 2, the first experiment consisted of dividing the total demand of iron ore (50 MTPY) into two different types of ore. The model was set to run for 525,600 minutes (equivalent to one year). Subsequently, the system was tested under the same conditions with 5, 6, 7, 8, 9 and 10 types of ores. The results are compiled in Table 4, followed by an analysis of the main indicators and conclusions.

Table 4: Results for 2, 5, 6, 7, 8, 9, and 10 types of products.

Number of different types of products	2	5	6	7	8	9	10
Total demand boarded at the ships (Mt)	49.84	50.11	49.31	49.18	48.29	20.37	4.31
Service level	99.7%	100%	98.6%	98.4%	96.6%	40.7%	8.6%
Mean time of ships in queue (h)	1.4	4.6	8.6	74.5	159.0	796.3	287.8
Mean time of ships in queue (days)	0.1	0.2	0.4	3.1			
Maximum time of ships in queue (h)	27.5	111.0	120.7	654.8	1,661.3	6,366.7	3,883.3
Mean occupation rate of Berths	54.3	60.7	58.6	55.9	58.9338	21.8457	4.3653
Mean occupation rate of Ship Loaders	41.4	45.1	42.4	40.9	41	17	3
Mean occupation rate of Berth 1	56.4	62.6	66.0	62.9	63	26	7
Mean occupation rate of Berth 2	51.3	59.0	51.6	48.7	54	18	2
Mean occupation rate of SL 1	50.3	51.9	50.7	47.9	49	20	4
Mean occupation rate of SL 2	48.3	51.8	44.6	42.1	43	16	2
Mean loading rate at Berth 1 (tph)	6,280	5,187	5,302	5,732	5,488	6,153	5,938
Mean loading rate at Berth 2 (tph)	4,185	4,195	4,128	4,127	3,757	4,131	3,789
Mean loading rate at SL 1 (tph)	7,040	6,251	6,904	7,533	7,141	7,978	8,970
Mean loading rate at SL 2 (tph)	4,441	4,772	4,770	4,770	4,767	4,569	4,504
Mean occupation rate of Car Dumpers	57.17	55.79	54.46	55.84	54.37	23.26	5.44
Mean occupation rate of CD 1	61.07	58.22	57.74	60.22	60.79	25.49	6.58
Mean occupation rate of CD 2	53.27	53.37	51.18	51.46	47.95	21.02	4.30

The following main indicators were used in our analysis: (1) service level, the percentage of demand that was met; (2) mean time in queue, the average amount of time that ships waited in queue prior to service; and (3) equipment occupation rate, calculated as the ratio between the total amount of time a piece of equipment was performing operations and the total available time.

The results indicate that with 2 to 8 different types of ore, the system can provide a good service level (beyond 95%), but with 9 and 10 types, the service level falls drastically (reaching below 10%). The mean time of ships in queue shows different behavior, increasing from 2 to 9 products, and rapidly decreasing with 10 products. In the case of 10 products, the low mean queueing time is explained by poor system's performance, and no vessel was capable of mooring, as shown in Figure 3.

Finally, we describe some interesting observations about the terminal's behavior, based on a combination of the results and the team's knowledge of the operations:

- As the number of different products increases, the system is capable of maintaining a high service level until 8 products. However, the results show a drastic increase in queuing time from 7 products on. The decision-maker must take this trade-off into account when considering possible operational plans. For example, is it worth having a 96.6% service level with 8 different products when the mean queue time for the ships is 159 hours? This trade-off can be observed in Figure 3, where both lines start to shift directions at 7 products. It is interesting to notice that for 10 products, the system is so overloaded that the queueing time decreases because most ships are not even allowed

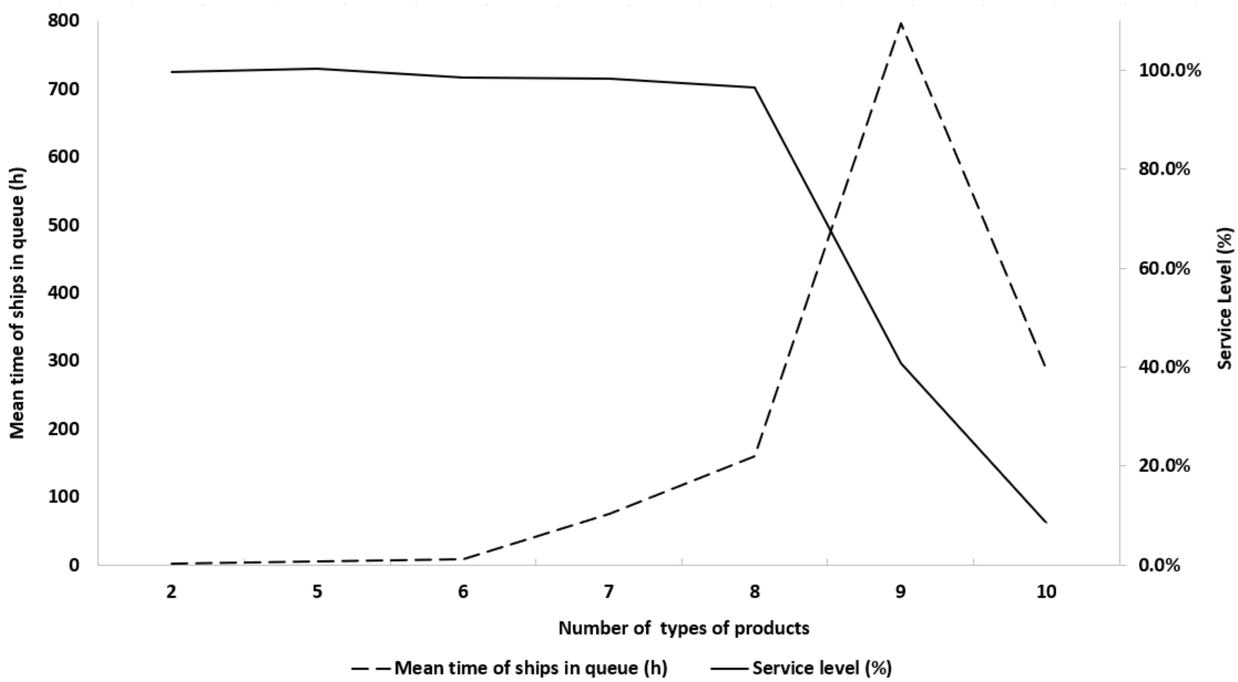

Figure 3: Mean time of ships in queue (h) and service level (%).

to moor due to lack of available storage.

- Occupation rates of the shiploaders, berths, car dumpers and stacker-reclaimers remain under 66% throughout the simulation, as shown in Figure 4, indicating that the service level decrease was not due to equipment insufficiency. Instead, it shows that the primary system limitation is storage area availability. This is an expected outcome, since different products cannot occupy the same piles in the yards, which makes the area dedicated to each product smaller for each addition to the mix.

4.2.2 Second Scenario

This scenario involved the addition of 3 MTPY of coal demand, divided into two types, to the already existent demand of 7 types of iron ores. The purpose is to observe how the system would react to the insertion of new products with opposite operational flows, using different equipment that requires exclusive storage areas. The model was run for the same amount of time as the first scenario and the results are presented in Table 5.

Figure 5 combines the results from scenario 2 with the results from scenario 1 (handling up to 7 different types of iron ores), which helps to understand the impact of adding the coal products to the previous operation.

It is evident in Figure 5 that the inclusion of the coal products in the mix decreases the service level while increasing the ships' queueing time. Also, by analyzing the equipment occupation rates, we see that adding the coal did not significantly affect the car dumpers, ship loaders, and stacker-reclaimers. This is somewhat expected since the coal products have exclusive equipment and there is still only one railway access.

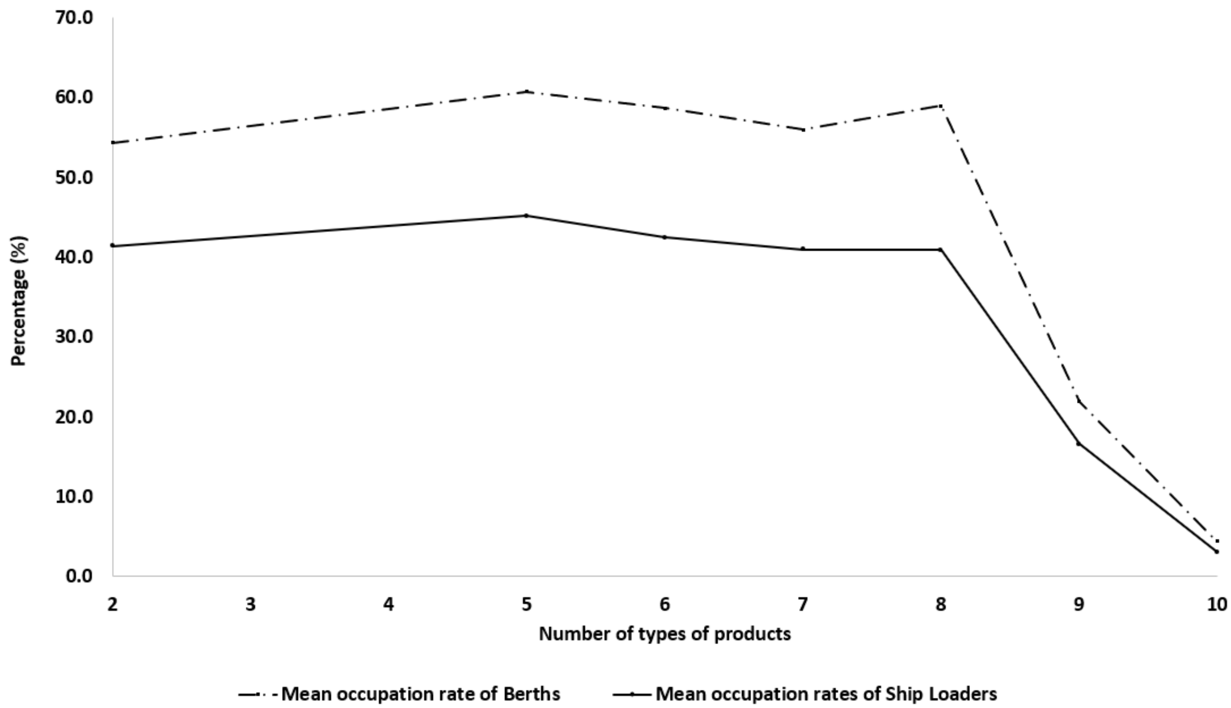

Figure 4: Mean occupation rates of berths and SLs(%) .

Table 5: Results from the second scenario.

Products	7 Iron Ores + 2 Coals
Total demand boarded at the ships (t)	47,169,562
Service level - Total	89.0%
Mean time of ships in queue (h)	489.6
Mean time of ships in queue (days)	20.4
Maximum time of ships in queue (h)	4,219.3
Number of ships in queue at the end of the simulation	36
Mean occupation rate of Berths	80
Mean occupation rate of Ship Loaders	41
Mean occupation rate of Berth 1	70
Mean occupation rate of Berth 2	90
Mean occupation rate of SL 1	56.05
Mean occupation rate of SL 2	28.37
Mean occupation rate of Ship Unloader	40.24
Mean loading rate at Berth 1 (tph)	4,845
Mean loading rate at Berth 2 (tph)	2,197
Mean loading rate at SL 1 (tph)	6,086
Mean loading rate at SL 2 (tph)	5,608
Mean loading rate at SU (tph)	950
Mean occupation rate of Car Dumpers	44.25
Mean occupation rate of CD 1	58.62
Mean occupation rate of CD 2	43.57
Mean occupation rate of Wagon Loader	30.56

Unlike CDs, SLs and SRs, there is no exclusive berth for unloading coal ships, which means that berths are shared between iron ore and coal. We see the effect of this condition on the mean occupation rate of berths in Figure 6, which shows an increase from 56% to 80%.

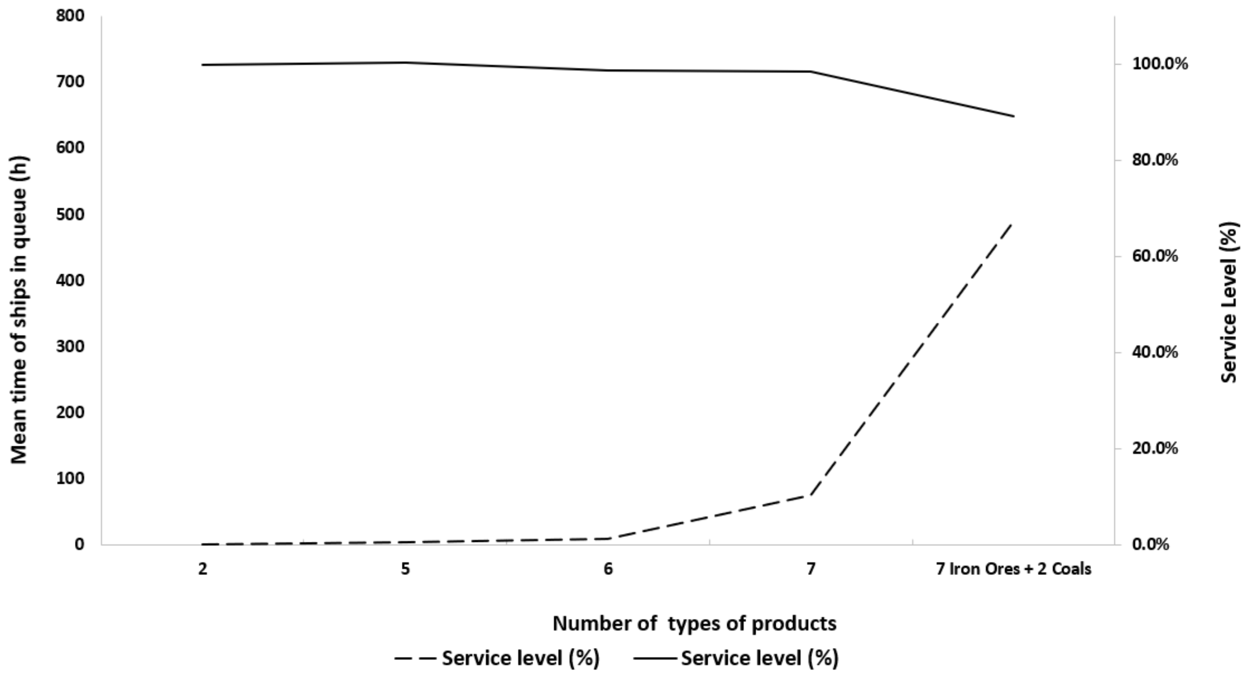

Figure 5: Mean time of ships in queue (h) and service level (%).

Table 5 shows that the mean occupation of berth 2 is considerably higher than berth 1. This happens because coal ships are only allowed to moor on berth 2. Furthermore, as in scenario 1, we can infer from the results that the decrease in service level is not only caused by yard space restriction, but also by equipment availability. Having an entire partition for coal storage guaranteed that storage capacity would not be a limiting factor. However, the result was that the iron ore had one less partition available for storage, which could partially explain the unmet demand in this scenario. Also note that berth 2 was shared by both products, thus some of the iron ore that would have been loaded in this berth had to wait for the unload operation of coal products, possibly contributing to the decreased iron ore productivity.

Lastly, note that the productivity rate of the reclaiming operation for coal products is half of the rate for iron ore, so it takes twice as long. This increases, even more, the occupation of berth 2 by coal vessels.

5 CONCLUSION

We used computational discrete-event simulation to conduct an analysis of a port terminal's capacity under distinct operational conditions, such as different product mix handling.

The main indicators considered in the analysis were service level, waiting time and occupation rates. We concluded that the import operation of coal is viable, as long as a small amount is demanded (3 MTPY). However, given that the addition of two iron ore products is considered unfeasible (service level decreases from 96.6% to 40.7%), it may be advantageous for the terminal to operate with the coal products.

Once more, it is the decision-maker's responsibility to analyze and weigh the benefits of including coal in the terminal's operation by considering not only the operational results obtained from the simulation model but also financial and economic factors that were not in the scope of this study.

The use of discrete-event simulation proved to be an effective method to assess the impact of changes in the product mix, seeing that it enables the virtual reproduction of complex processes and the intricate relations between the system's agents, which would not be possible (or easily accomplished) through simple spreadsheet analysis.

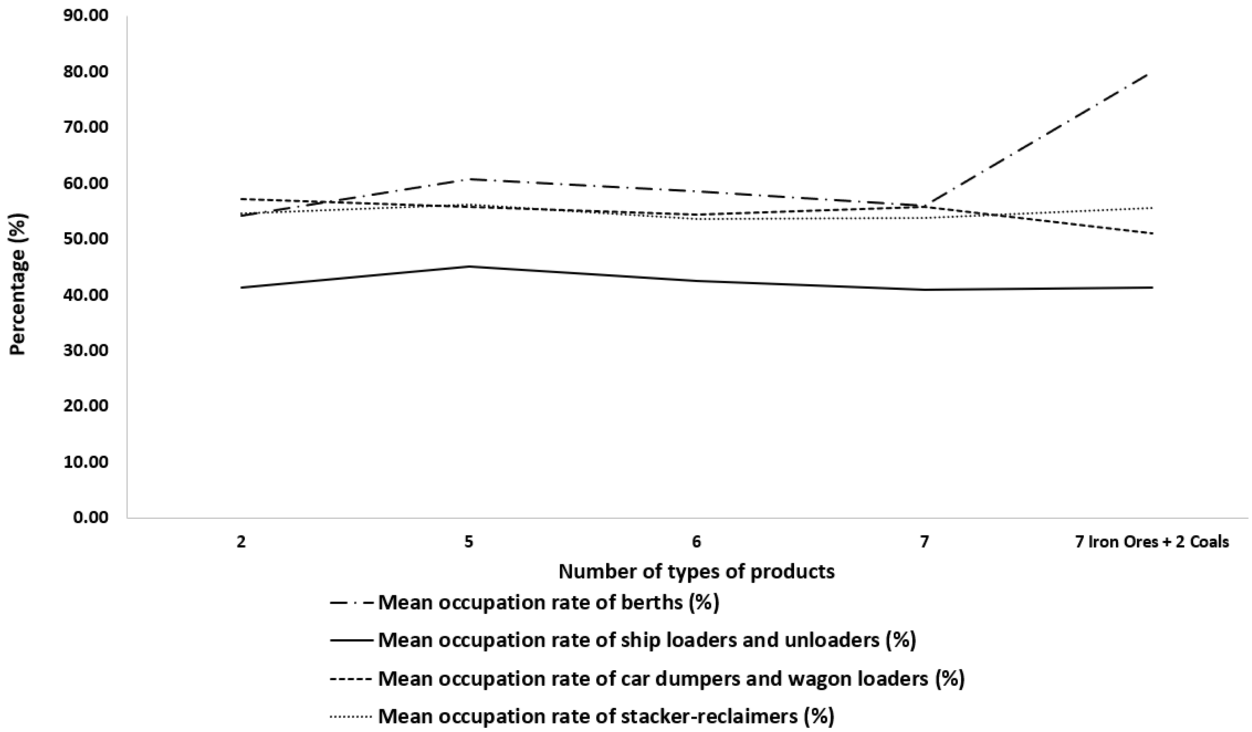

Figure 6: Mean occupation rates of equipment (%).

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