EnGeTec em Revista | 07
ISSN 2965-9302
v. 1 | n. 7 | e404 | Agosto 2024

Port of Paranguá: Applying the Solver Tool for Intermodal Transport Optimization of Origin and Destination Points

Porto de Paranguá: Aplicação da Ferramenta Solver para Otimização do Transporte Intermodal de Pontos de Origem e Destino

Puerto de Paranguá: Aplicación de la herramienta Solver para la optimización del transporte intermodal de puntos de origen y destino

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Keywords:
Commodities.
Simplex.
Solver.
Export.

Palavras-chave:
Commodities.
Simplex.
Solver.
Exportação.

Palabras clave:
Materias primas.
Simplex.
Solucionador.
Exportación.

Enviado em:
12 novembro, 2023

Apresentado em:
05 dezembro, 2023

Publicado em:
24 agosto, 2024

Evento:
6º EnGeTec

Local do evento:
Fatec Zona Leste

Avaliadores:
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Abstract:
The Port of Paranaguá is one of the largest exporters of agricultural commodities in Brazil. In recent years, it has consistently surpassed its export records. Despite its significant activity and importance to the economy, the port faces various bottlenecks from the origination of commodities to the loading of grains onto ships. These critical points pose challenges and impact its overall performance. This study aims to present the port, its characteristics, and complexities, along with the primary commodities exported, such as the soybean flow from the southern/southeastern interior of Brazil. Additionally, the study proposes a solution to address the costs of Road and Rail freight. The methodology employed for this article was analytical exploratory research, utilizing official data to substantiate the presented facts. However, it is observed that despite the port's considerable scale, attention from governmental authorities is still needed for road improvements and infrastructure development. This would enable the port to meet demand effectively and prevent cargo diversion to nearby ports due to efficiency concerns.

Resumo:
O Porto de Paranaguá é um dos maiores exportadores de commodities agrícolas do Brasil. Nos últimos anos, superou consistentemente seus recordes de exportação. Apesar de sua atividade significativa e importância para a economia, o porto enfrenta vários gargalos, desde a originação de commodities até o carregamento de grãos em navios. Esses pontos críticos representam desafios e afetam seu desempenho geral. Este estudo tem como objetivo apresentar o porto, suas características e complexidades, juntamente com as principais commodities exportadas, como o escoamento de soja do interior sul/sudeste do Brasil. Além disso, o estudo propõe uma solução para lidar com os custos do frete rodoviário e ferroviário. A metodologia empregada para este artigo foi a pesquisa exploratória analítica, utilizando dados oficiais para fundamentar os fatos apresentados. No entanto, observa-se que, apesar da escala considerável do porto, ainda é necessária a atenção das autoridades governamentais para melhorias nas estradas e desenvolvimento de infraestrutura. Isso permitiria que o porto atendesse à demanda de forma eficaz e evitaria o desvio de carga para portos próximos devido a preocupações com a eficiência.

Resumen:
El Puerto de Paranaguá es uno de los mayores exportadores de productos agrícolas de Brasil. En los últimos años, ha superado sistemáticamente sus récords de exportación. A pesar de su importante actividad e importancia para la economía, el puerto se enfrenta a varios cuellos de botella, desde la originación de productos básicos hasta la carga de granos en barcos. Estos puntos críticos plantean desafíos e impactan en su rendimiento general. Este estudio tiene como objetivo presentar el puerto, sus características y complejidades, junto con los principales productos exportados, como el flujo de soja desde el interior sur/sudeste de Brasil. Además, el estudio propone una solución para hacer frente a los costes del transporte de mercancías por carretera y ferrocarril. La metodología empleada para este artículo fue la investigación analítica exploratoria, utilizando datos oficiales para fundamentar los hechos presentados. Sin embargo, se observa que, a pesar de la considerable escala del puerto, todavía es necesaria la atención de las autoridades gubernamentales para mejorar las carreteras y desarrollar la infraestructura. Esto permitiría al puerto satisfacer la demanda de manera efectiva y evitar el desvío de carga a puertos cercanos debido a problemas de eficiencia.

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ISSN 2965-9302
v. 1 | n. 7 | e404 | Agosto 2024

1. Introduction

This article aims to present the Port of Paranaguá, including its geographical dimensions, infrastructure, and all logistical operations, along with its related surroundings, providing updated data at the time of the research. The objective is to demonstrate the significance of this port to Brazil's and the world's productive systems, helping the reader comprehend and acknowledge its substantial contribution in supplying commodities, finished and semi-finished products to countries reliant on Brazilian production.

Furthermore, this document will feature a simulation of agricultural product transportation operations using real numbers. It will trace the journey from various origins, through transshipment points, ultimately arriving at the Port of Paranaguá as its destination. An intermodal operation will be considered to meet this demand. To solve this proposed problem, we will employ the Solver tool with the aim of finding the most financially viable route.

As a supplementary aspect of the study, recurring problems and historically significant issues related to the operation, infrastructure, organization, oversight, maintenance, human capital, and planning of the Port of Paranaguá will be highlighted. Utilizing the analytical-exploratory research method and the Solver tool, the article will delve into less-explored points, drawing on official sources to provide a solid foundation for the discussed topics.

2. 2. Literature Review

2.1. Porto of Paranaguá

According to EMBRAPA (2020), the Port of Paranaguá is in the city of Paranaguá, in the State of Paraná, on the south bank of Paranaguá Bay, as shown in Figure 1. Maritime access is through the Galheta Channel, through two external areas, Alfa (depth (draught) of 15m and width of 200m) and Bravo-1 (depth of 13.5m and width of 150m), and an internal area called Bravo-2 (depth of 13m and width of 150m). Road access is via BR-277, connecting Paranaguá to Curitiba and connecting to BR-116 via highways PR-408, PR-411 and PR-410. "At the Port of Paranaguá and Antonina, there are well-defined restrictions and rules for each type of merchandise, and because of this, we must always be aware of any changes in the APPA Service Order to report customers in a timely manner and not jeopardize any demand." (Wilson Sons, 2018)

Also, according to Wilson Sons (2018), it stands out from other ports due to its solid infrastructure and specialized knowledge in port operations to ensure efficient service to users. Despite considerable investments in modernization and restructuring, including computer systems and improvements to the quay strip, it still faces common challenges compared to other ports, such as Santos and São Francisco do Sul. Issues such as the reduced draft and limited extension, which need to be reconsidered to accommodate larger vessels, are some of the obstacles faced.

Figure 1. Location of the Port of Paranagua and Antonina

Fonte: Gazeta do Povo (2023)

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2.2. Porto Capacities

According to APPA (2023), the Port of Paranaguá has a total area of 4,129,801.3 m², the port has an extensive structure of piers and piers, totaling 5,347 meters in length. In all, there are 24 berths available for docking ships. Of these, 16 berths are located at the Paranaguá commercial pier, intended for the loading, and unloading of various cargoes. Another 4 berths are situated on 2 specific piers for liquids, while 2 berths are available on 1 pier intended for fertilizer handling.

The static capacity of the Port of Paranaguá is impressive. For dry bulk, the port can store up to 1,775,000 tons. As for fertilizers, the static capacity reaches 3 million tons, also considering the available back-area. Regarding liquid bulk, the static capacity is 946,040 m³.

In terms of loading and unloading operations, the Port of Paranaguá has a nominal loading capacity in the Export Corridor of 9 thousand tons per hour. As for fertilizer unloading, the operational average is 6,000 tons per day per ship.

The port's infrastructure includes 6 units of Mobile Port Cranes (MHC) with capacities ranging from 64 to 104 tons. These cranes are used for the unloading of dry bulk and general cargo. In addition, the port has 10 Ship loaders, equipment used for loading ships.

The port's draught, which represents the maximum depth allowed for navigation, is 12.5 meters. This allows large ships to access the port safely.

The port's marshalling yard has an area of 330,000 m² and can accommodate up to 1,000 trucks. Considering all available yards, including those for vehicles and containers, the total area reaches 538 thousand m².

2.3. Main Exported Commodities

According to Portos do Paraná (2023), the Port of Paranaguá is one of the largest ports in Latin America and one of the main export ports in southeastern Brazil, its main exported commodities are: Soybeans, soybean meal, corn, salt, sugar, fertilizers, containers, frozen, petroleum products, ethanol, and vehicles.

Soybean shipments grew relatively in 2023 at the port of Paranaguá. According to data from ComexStat (2023), approximately 11,000,000 tons of soybeans have already been exported, as shown in Table 1. Then, soybean oil, representing the second largest volume exported, and bulk sugar, with a growth of 26% compared to last year.

According to AEN (2023a), APPA estimates that approximately 3.647 million tons of soybeans will be handled in the last quarter of 2023. This represents a significant growth of 203% compared to the same period in 2022, which saw 1.2 million tons. These figures reflect continued growth throughout the year. From January to August 2023, 10.1 million tons of soybeans were exported, an increase of 10% compared to the same period of the previous year, which recorded 8.1 million tons. Currently, the movement of soybeans corresponds to 25% of the total handled in the ports of Paraná.

2.4. Unloading Terminals and Export Corridor Rules

According to APPA (2023), the Paranaguá corridor is the only one in Brazil to use the export corridor model, interconnecting public and private terminals for grain exports. One of its differentials is the structure of warehouses, silos, and conveyors. Enabling the simultaneous embarkation of up to 3 ships with cargo from different terminals; the grains arrive in Paranaguá by train or truck, where their quality is attested and classified. Then, they go to the boarding terminals and silos of the Retroarea. There are 9 private terminals with a capacity of almost 1.5 million tons, in addition to public terminals with a vertical silo of 100,000 tons and 4 horizontal silos with a total of 60,000 tons.

The terminals in Paranaguá are: Interalli, Agtl, CentroSul, Coamo, Cargill, Cimbessul, Dreyfus, Cotriguaçu and Rocha, the latter being the one with the highest static. In addition, it is possible to carry

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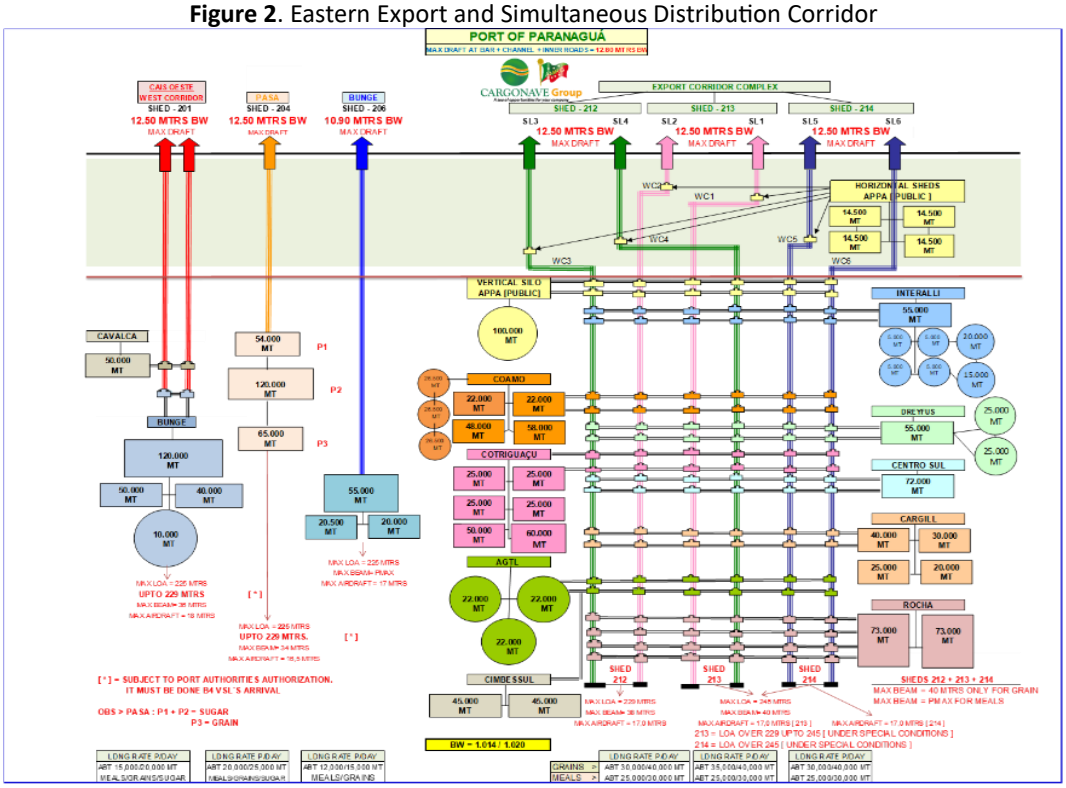
out the loading through the public Silo, popularly called "Silão". For each terminal, a static terminal is contractually agreed. That is, the maximum volume allowed to be downloaded by each company. Due to its complexity, it is necessary to manage the order and quantities to be loaded on each ship. The APPA (Administration of the Ports of Paranaguá and Antonina) is responsible for this. The meeting takes place daily where the Line-up is discussed.

The Line-up is simply the queue of boats. Berthing takes place on a first-come, first-served basis for ships at the port, and a maximum of 18 ships are allowed in sequence. The berthing does not denote the loading of the ship, since the loading depends precisely on the terminals being fit, and the terminals depend on the origination. Because of this loop, the wainting time (time between docking and loading) can take about 15 to 40 days.

For Bulk operation, there are 3 berths in the export corridor. Berth 213 has your preference for ships with only 1 type of product. Berths 212 and 214, on the other hand, give preference to bran or mixed ships. Preferences are used only when all 3 berths are in operating condition. In view of this, the alignment between terminals, players and APPA is indispensable. Figure 2 shows the distribution map of the terminals and their connections in each berth.

Figure 2. Eastern Export and Simultaneous Distribution Corridor



Fonte: Cargonave (2022)

2.5. Complexity and Obstacles

According to Stricker (2004), since 1872, when the old anchorage began to undergo its first transformation into a modern port at that time, several transformations were made until the creation of the APPA or Administration of the Ports of Paranaguá and Antonina, within the concession in force between the State of Paraná and the Federal Government. The Port of Paranaguá has a favorable location in relation to its bay but faces environmental challenges that need to be solved. The constant need for dredging for maritime access and the natural barriers of Serra do Mar for road and rail access require careful studies to ensure that they do not become insurmountable obstacles to the development of the port.

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The port of Paranaguá and Antonina has several obstacles and difficulties within its internal and external environment, according to Brasil (2018), the following problems were highlighted in its internal environment:

- Waiting for docking: As reported by APPA, the average wait for docking at COREX is 30 days, which affects the competitiveness of the Port Complex and leads to the diversion of cargo to competing ports, such as São Francisco do Sul.
- Insufficient berths: Capacity deficits indicate that the berthing structure available at the Port Complex is not sufficient to meet demand, especially for cargo such as soybeans, soybean meal and corn.
- Formation of queues at the access to Port Terminals: The analysis of port access data identified queues at nearby entrances, negatively impacting *Avenida Portuária*, an essential route for cargo vehicles in port operations.
- Presence of vehicles parked in inappropriate places: there are many trucks parked on the banks of Av. Ayrton Senna da Silva, on other streets and nearby gas stations, while drivers wait for new freight. Even though there is a sorting yard and parking available on Port Avenue, many vehicles remain on the roadsides, waiting for access to the terminals.
- Lack of maintenance of the intra-port rail network: according to information provided by the Port Terminals, some branches are deactivated, and others need renovation or reconstruction. APPA, in partnership with the concessionaire, has already identified the problems and needs, but has not yet presented investment plans with deadlines for the execution of the services.

In its external environment, the following complexities were observed:

- Location of the Complex in environmentally sensitive areas: The Port Complex of Paranaguá and Antonina is in a sensitive and biodiverse ecosystem, which encompasses conservation units, archaeological sites, indigenous lands and preservation areas. Damage caused by port activity can result in legal and administrative sanctions that affect port operations.
- Cost of road transport: According to ServComex (2023), the average cost of road freight in Paranaguá is a critical requirement for players who depend on this modality for the flow of commodities. According to Agrimídia (2023), In the state of Paraná, traveling an average distance of 150 to 300 kilometers from the center to the Port of Paranaguá, from where grains are sent for export, cost approximately R$ 400 per ton in 2021. Currently, it is below R$300, according to reports from drivers. As a result, truckers have been opting for shorter routes instead of the export corridor.

3. Research Methodology

In the article in question, the analytical-exploratory, experimental, and quantitative research method was applied. The Solver tool was used to manage numerical data, test variable hypotheses, and measure the effects of the results.

3.1. Simplex Methodology

According to Coutinho (2021), the simplex method, also called the simplex algorithm, represents a crucial technique in solving linear programming problems. George Dantzig and Koopmans developed it in 1946 during their collaboration in the U.S. Air Force, and since then, it has become one of the leading algorithms of the twentieth century. In summary, the simplex method is an approach to solving linear programming models, seeking an optimal solution to an optimization problem. It utilizes clearance variables, tables, and geometric concepts.

3.2. Complexity and Obstacles

According to Garavaglia and Sharma (2023), "dummy" means "mannequin" and is used to symbolize real people. Similarly, a dummy variable is generated to numerically express qualitative characteristics.

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These variables, also called dichotomous or binary, originate from qualitative characteristics that have two unique categories. These categories are linked to discrete values, usually 0 and 1, where 0 indicates the non-existence of the measured trait, and 1 indicates the presence (or success) of the desired trait. It is concluded that a dummy variable is one that assumes the value of "zero" or "one", indicating the absence or presence of qualities or attributes. These variables are used to classify data into mutually exclusive categories. In regression analysis, dependent variables can be influenced not only by quantitative variables, but also by qualitative variables.

3.3. Complexity and Obstacles

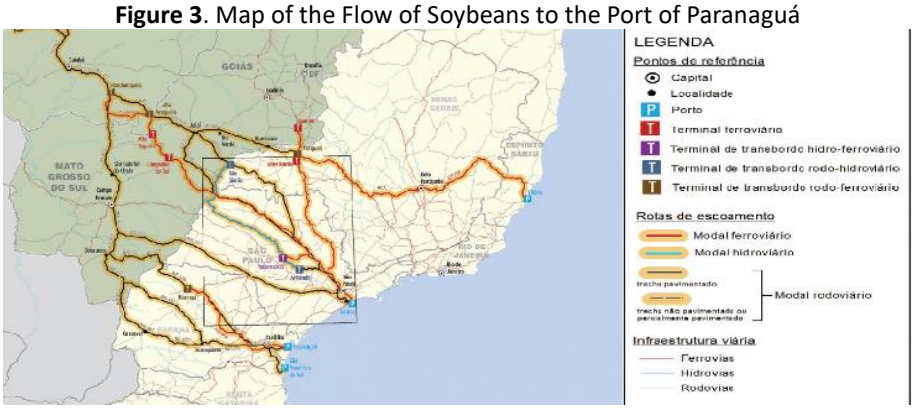
According to Rodrigues (2020), Solver is an Excel supplement that uses mathematical programming to solve linear programming problems, being useful for performing hypothesis tests and other analyses in the spreadsheet. It is a powerful and complex Excel tool that makes it possible to perform various simulations, being especially useful for sensitivity analyses with multiple variables and parameter constraints. In theory, Solver is a tool that helps to solve medium and small problems, seeking to achieve an optimized result, it can be used to determine the maximum or minimum value of a cell, considering certain parameters.

3.4. Complexity and Obstacles

According to the AEN (2023b), originally, more than half of the soybeans exported through the port of Paranaguá come from the state itself. Followed by Mato Grosso do Sul with 21.7% and São Paulo, 7.3%. During the 2023 harvest there was a record production and the states with the greatest representativeness were Paraná and Rio Grande do Sul, which are known for their modern equipment and have a very significant soybean production, in addition to soybeans, corn, sugarcane and cotton are grown. Figure 3 shows the mapping of soybean origins, noting that there are rail transshipment terminals at strategic points, where historically there is the largest volume of soybean origination.

A problem was developed to analyze the costs in cargo transportation, verifying the possible routes for four (4) origins, two (2) transshipments and four (4) destinations, comprising one (1) Dummy, with different costs for each of them, mixing two types of modes, the road, taking the cargo to the place of disembarkation. Even today, the rail modal represents only 20.2% of the operation in Porto, according to data from the latest APPA report (2022), the multi-modal option (rail and road) was used because it is more advantageous, considering the points of origin of flow, as shown in Figure 3.

Figure 3. Map of the Flow of Soybeans to the Port of Paranaguá



Fonte: CNT (2014)

Considering the total of 20,000 tons of soybeans from the origins Cambé (PR), Naviraí (MS), Arapongas (PR) and Aquidaban (PR), to be taken by truck to transshipments 1 and 2, both with a static capacity of 10,000 tons defined through contractual volume, located in the cities of Londrina (PR) and Maringá (PR) respectively. From these transshipments, the raw material leaves for the Port of Paranaguá under rails, with the logistics terminals of Interalli, Rocha and Tibagi as options for unloading.

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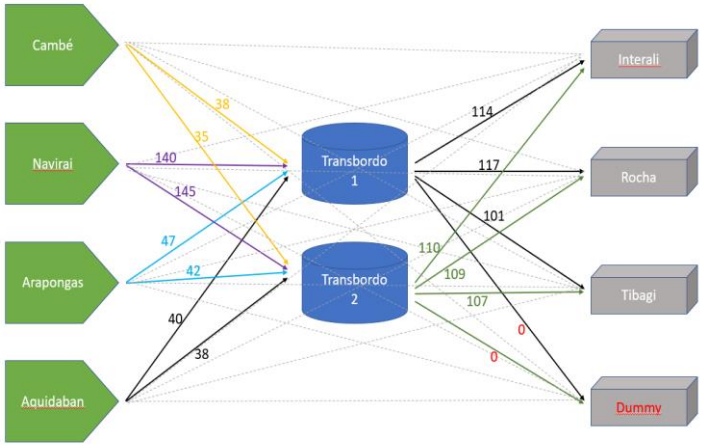
Each terminal has a static cargo capacity limit, the Interalli Logistics Terminal has a limit of 7,000 tons, the Rocha terminal has a limit of 5,000 tons and the Tibagi terminal has a limit of 3,000 tons. For the allocation in each terminal, we will have a cost per ton.

It was observed that there is an imbalance between supply (20 thousand tons) and demand (15 thousand tons) of 5 thousand tons, so it was necessary to create a destination Dummy. Dummies are revealed as a way of introducing qualitative characteristics, and are often called binary or dichotomous variables, since they assume only one of two values, 0 or 1, to indicate the presence or absence of a given characteristic (Stock; Watson, 2004).

The resolution that will be developed below will aim to achieve the lowest possible cost by transporting all the necessary demand from origin to destination. Figure 4 shows the graph of the proposed problematization, the colors of the routes identify the different origins and destinations, as well as the dotted lines show the totality of possible and non-existent routes. It is also possible to check the freight costs of each route per ton transported, noting that the Dummy destination has zero transport cost for the reason already mentioned.

Figure 4. Distribution Problem Graph



To solve the problem, the Simplex method was used, using the Excel software and its Solver complement. Solver is an add-on to the program, "Excel includes a tool called Solver that uses the simplex method to find an optimal solution" (Hillier; Lieberman, 2013). According to Microsoft (2023), the tool adjusts the values in the decision variable cells to satisfy the constraints and produce the best result for the objective function. Figure 5 shows the example layout used for programming.

Figure 5. Distribution Problem Graph

Variaveis de custo						
	Interalli	Rocha	Tibagi	Dummy	T1	T2
Cambé	999	999	999	999	38	35
Navirai	999	999	999	999	140	135
Arapongas	999	999	999	999	47	42
Aquidaban	999	999	999	999	40	38
T1	114	117	101	0	0	999
T2	110	109	107	0	999	0

Custo(Zmin)	
R$	2.722.000,00

	Quantidades (Xij)							
	Interalli	Rocha	Tibagi	Dummy	T1	T2	Disp. na origem	Enviado
Cambé	0	0	0	0	5000	0	5000	5000
Navirai	0	0	0	0	1000	2000	3000	3000
Arapongas	0	0	0	0	0	8000	8000	8000
Aquidaban	0	0	0	0	4000	0	4000	4000
T1	2000	0	3000	5000	0	0	10000	10000
T2	5000	5000	0	0	0	0	10000	10000
Capacidade do terminal	7000	5000	3000	5000	10000	10000		
Recebido	7000	5000	3000	5000	10000	10000		

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Figure 5 shows the problem resolution table using Excel Solver. You can see that the schematization of the problem has been divided into two tables, the upper table to contain the costs per ton of freight and the lower table to contain the quantities transported between each origin and destination. For destinations that are null, the value of "999" was used, representing the "big M". According to Oliveira (2006), BIG M are artificial variables that aim to cancel out the distance from the zone of valid solutions. The result of the table is given in the yellow field, after "running" the Solver.

4. Results

The Solver tool presented the optimal solution at the lowest cost based on the port constraints and capacities of each terminal. The minimum cost found was R$ 2,722,000.00 for an intermodal operation, i.e., it was necessary to use two different modes of transport from its point of origin to the destination.

The rail modal was of paramount importance for the reduction of costs, considering that although the cost per ton of the road modal is more advantageous, the transport capacity is extremely inferior to the rail network. Also considering the loading time between intermodal operation compared to road loading directly to the port is shorter, and the readiness of cargo on the port floor until the date of berthing of the ship directly affects performance. It was also noted that for the operation to be successful, it will be necessary to replace Dummy with a significant increase of 5,000 tons in one of the available terminals, so that the demand is met.

In this immense infrastructure of the Port of Paranaguá there are problems that end up generating greater competitiveness that encourage the diversion of cargo to competing ports, one of the problems is the waiting time for berthing at Corex, which is on average 30 days according to APPA, the body that manages the port due to its complexity.

Another problem is the lack of maintenance of the intraport rail network: according to data provided by the Port Terminals, since the current road structure for arrival at the Port of Paranaguá most suitable for operating in the region are the road and rail modes, considering data from producers in Mato Grosso do Sul and Paraná, today the largest quantities of commodities that pass through the Port of Paranaguá come from the South and Southeast regions.

Between imports and exports, according to the current waterway infrastructure and the operational rules currently in force, the waterway access to the Port Complex of Paranaguá and Antonina has a deficit of capacity to meet this demand.

5. Conclusion

The Port of Paranaguá plays a key role as one of the largest agricultural commodities exporting ports in Brazil. Despite its remarkable growth in recent years, it faces significant challenges that affect its performance. This study highlighted the characteristics and complexities of the port, as well as the main commodities exported, with a focus on the flow of soybeans from the south/southeast of Brazil. In addition, we suggested a solution through the mathematical software called solver to reduce the costs of road and rail transport, since an intermodal operation proved to be more advantageous compared to carrying out a direct road loading to the Port.

Through an exploratory analytical methodology and with the use of official data, it was possible to highlight the need for government attention to road improvements and increase in the port's infrastructure. These measures are essential to meet the growing demand and avoid the diversion of cargo to nearby ports for efficiency reasons. By investing in infrastructure improvements, such as more efficient roads and railways, the Port of Paranaguá will be able to optimize its operations and reduce bottlenecks that hinder the transportation of agricultural commodities. This will result in an increase in export capacity, further strengthening the port's position as a major trade hub for the country.

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In short, although Solver presented a solution for an operation at the lowest cost, it is important to highlight that it is crucial that measures are taken to improve the infrastructure and solve the logistical challenges. Only in this way will it be possible to ensure the full use of their potential and ensure that agricultural commodities are exported efficiently, benefiting both the local and national economies.

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