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Container terminal capacity utilisation modelling as a key competitive strategy; the case of Port of Santos - Brazil

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Abstract: In the dynamic global container market, the top 10 ports controlled 33% of the total of 852 million TEUs in 2022, where the Port of Santos Complex (BRSSZ) holds the 46th position, handling approximately 4.5 million TEUs, with an annual storage capacity estimated at 5.6 million TEUs. (ALPHALINER, 2023; UNCTAD, 2023). Although PIANC's terminal planning guidelines provide a general equation for estimating terminal capacity (PIANC 158, 2014), this research aims to enhance dynamic capacity modelling and analysis by incorporating the logistic breakdown of cargo mix and establishing statistical premises. The primary objective is to present a technical analysis of capacity utilisation, serving as a strategic tool for both commercial and operational intelligence economic studies. This research used the Port of Santos logistic operators' competition as a case study, introducing an analytical framework that distinguishes between static and dynamic capacities across theoretical design and operational planning approaches. Data collection involves a comprehensive survey of technical information and the processing of economic indicators using statistics from masterplan reports, ANTAQ and SPA databases mainly. The results provided a technical data sheet and economic analysis of the container terminals at the Port of Santos, grounded in infrastructure surveys and dynamic capacity utilisation. In conclusion, the study emphasises the importance of adopting a strategic port intelligence perspective, focussing on the breakdown of the logistic flow quay-yard-gate and the modelling of the storage capacity. Recognising the critical trade-off between supply and demand, the findings guide decisions on opportune moments for investing in terminal asset expansion, influenced by monitoring competitors' capacity utilisation rates.

Keywords: Container terminal, port logistics, port planning, capacity utilisation, business intelligence strategy

Introduction

The analysis of the Brazilian port system can be structured based on macroterritorial regions. Among the major 16 container ports, ten are located in the South-Southeast (S/SE) cluster, characterized by a notable concentration of industrial and economic activities. The remaining six ports are located in the North-Northeast cluster (N/NE). The Port of Santos (BRSSZ) is recognized as Brazil's largest port complex, serves as a crucial maritime hub along the East Coast of South America (ECSA). It connects with approximately 28 liner services weekly, including 20 long-distance routes and eight feeder cabotage services based on the Santos Porth Authority report (SPA, 2023).

According to statistics from the National Agency for Waterway Transportation (ANTAQ), the container throughput at BRSSZ increased from 2.7 million TEUs in 2010 to 4.5 million TEUs in 2022, representing approximately 40% of the Brazilian market share (ANTAQ, 2023). Figure 1 presents the annual throughput volume in millions (MM') of TEUs of the Brazilian container port system, along with the corresponding market share of the port of Santos. The Port of Santos is home to three of Brazil's largest container terminal, among the 20 that have handled more than 100,000 TEUs in the last few years. The terminals in focus for this study were Brasil Terminal Portuário (BTP), DP World Santos (DPW) and Tecon Santos Brasil (TSB). Figure 2 presents an aerial view of the Santos Estuary, Brazil, illustrating the key container logistics infrastructure, including the BTP, DPW, TSB, and Ecoporto (ECO) container terminals. The picture also outlines the access channel and retro-port area within the port's adjacent logistic zone.

The Port of Santos holds a key leadership position along the ECSA coastline, emphasising the importance of monitoring capacity utilisation as a vital economic strategy. Furthermore, the logistic zones of Brazilian container ports generally offer additional capacity in retro-port bonded areas, mainly serving container storage and warehousing services.

From the port literature, the existing formulations and fundamental for estimating container storage capacity, such as PIANC's terminal planning considerations, presented a generic and simple outlook (PIANC 158, 2014; PIANC 185, 2019; KOX, 2017). However, to conduct a detailed analysis of the competitiveness of ports and terminals, with a focus on dynamic breakdown analysis of yard capacity utilisation, it became essential to refine existing formulations. This involved creating a comprehensive data survey and mathematical modelling process, grounded in a deep understanding of statistical data sources, with analytical premises stablished to address the complex logistical interactions among import, export, and transshipment flows.

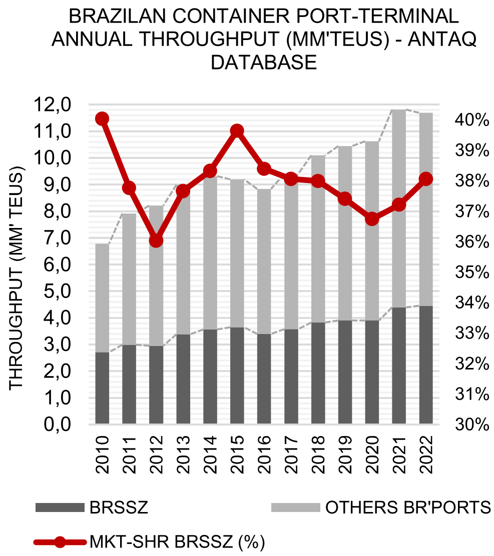


Figure 1: Annual throughput volume of the Brazilian container port system (in million TEUs) over historical years from the ANTAQ statistics database (ANTAQ, 2023); Highlighting the evolving market share (MKT-SHR) of the Port of Santos (BRSSZ).

Figure 2: Aerial view of the Estuary of the Port of Santos, highlighting the access channel and major logistics infrastructure of the container terminals, such as Brasil Terminal Portuário (BTP), DP World Santos (DPW), Tecon Santos Brasil (TSB), and Ecoporto (ECO). Source: Google Earth (July 2022).

This research presents a structured study procedure that aim to improve the understanding of the trade-off analysis between capacity offerings and volume demands, with focus on the competitive environment between container logistics operators at the Port of Santos as a case study. The primary objective is to position this approach as a practical analytical tool for commercial intelligence analysis.

The process involved four key steps: (i) employ effective data collection and survey techniques; (ii) conducting comprehensive logistic data processing and analysis; (iii) perform capacity mathematical modelling; and (iv) conducting a correlation analysis of capacity utilisation. The study also establishes clear capacity definitions to refine the analysis between the design and operational planning approaches.

Methods and Techniques

The methodological approach involves presenting an analytical procedure based on data surveys and statistical breakdown analysis within the operational area of a container terminal, including quay-yard-gate flows. Subsequently, the presentation covers the calculation of terminal capacity utilisation, specifically focussing on yard storage capacity modelling. Before exploring these aspects, it is crucial to establish clear definitions for capacity-related terminologies among static and dynamic perspectives, across theoretical, technical, operational, and productive viewpoints.

On the one hand, the theoretical and technical capacity modelling in a container terminal can be comprehended through a static analysis perspective, aligning with the design planning approach. The theoretical static capacity establishes the maximum capacity based on layout design, while the technical static capacity is determined by the nominal productivity of the handling system. On the other hand, for the operational and productive capacity modelling, a dynamic analysis perspective was used, utilising a production and performance efficiency approach based on handling throughputs. From a managerial point of view, the dynamic operational and productive capacities mirror the overall equipment efficiency. (BICHOU, 2018; PIANC 158, 2014; PIANC 185, 2019; KOX, 2017; PINTO; GOLDBERG; CARDOSO, 2016).

The data survey involved consulting official databases, statistical report, and utilising online mapping software. To collect pertinent data on infrastructure and superstructure metrics, a mapping measurement technique was used. This technique included surveys of terminal operators' areas and equipment counting, based on port authority masterplan reports and technical details. Additionally, relevant statistical data from were collected using the ANTAQ, (2023), SPA, (2023) and ABTRA, (2023) databases. These data facilitated cargo-mix breakdown analysis and the formulation of key performance indicators (KPIs), enriching the analysis of productivity indexes.

Statistical data collection and processing begins from berth and quay throughput, focussing on vessel handling productivity, where the corresponding vessel timestamps at berth were the data basis for quay performance KPIS assessment. The quay throughput ($N_{C_{quay}}$) can be estimated as the sum of container units and volume (Nc) handled by the departed vessels ($N_{C_{vessel}}$) measured in both box (N_{BOX}) and TEU (N_{TEU}). This calculation includes loaded (Nc_{load}) and discharged boxes (Nc_{dsch}), along with equivalent moves (N_{eq}) for hatch covers, lashing bins, and double lifts. See equations 1, 2, 3 and 4.

$$N_{C_{quay}} = \Sigma N_{C_{berths}} = \Sigma\ N_{C_{vessel}} \quad (1)$$

$$N_{C_{vessel}} = N_{c_{dsch}} + N_{c_{load}} + N_{eq} \quad (2)$$

$$Nc_{dsch} = Nc_{impo} + Nc_{T/S} + Nc_{rstw} \quad (3)$$

$$Nc_{load} = Nc_{expo} + Nc_{T/S} + Nc_{rstw} \quad (4)$$

The loaded and discharged waterside flows are further disaggregated into landside logistic flows (quay-yard-gate), based on the yard storage operational approach. This involves segregating storage volumes between import (Nc_{impo}), export (Nc_{expo}), transhipment ($Nc_{T/S}$) and restow (Nc_{rstw}), with each transshipment and restow unit accounting for two visits at the quay. See equations 5, 6 and 7. A subsegregation analysis could also be possible considering the nature of the cargo, such as dividing between full and empty volumes, electrified reefers, hazardous cargoes and special sizes, as given the availability of data.

$$Nc_{quay} = \Sigma Nc_{impo} + \Sigma Nc_{expo} + 2 * \Sigma Nc_{T/S} + 2 * \Sigma Nc_{rstw} \quad (5)$$

$$Nc_{yard} = \Sigma Nc_{impo} + \Sigma Nc_{expo} + \Sigma Nc_{T/S} + \Sigma Nc_{rstw} \quad (6)$$

$$Nc_{gate} = \Sigma Nc_{impo} + \Sigma Nc_{expo} \quad (7)$$

To advance to terminal capacity modelling, it is crucial to comprehend both design planning and operational management perspectives, both were based on the same terminal planning formulation by PIANC guildeine report 158, (2014). From the design planning perspective, this formulation provides the relative theoretical capacity, considering technical yard density and estimated overall storage cycles. On the contrary, from an operational planning perspective, it yields the effective capacity, accounting for cargo volume breakdown and demand fluctuations. Therefore, the simplified formulation for the dynamic storage capacity of a container terminal (CAP_{Dyn_yard}) ca be presented at equation 8.

$$CAP_{Dyn\_yard} = \Sigma YB_{TGS} * \left(\frac{Occ_{\text{yard }\%}}{f_p}\right) * \left(\frac{t_{cal}}{t_d}\right) \quad (8)$$

Where, YB_{TGS} **=** the terminal ground slot represents the static storage capacity of the container yard in volume, determined by ($\Sigma A_{Yard} * \rho_{Yard}$); container storage area multiplied by average gross storage yard density (TEU/m²;); O_{yard}= estimated technical storage occupancy index in (%), usually recommended 75%; f_p = the yard peaking factor was determined by the ratio and frequency between maximum and average of the yard related index (I_{max}/I_{avg}); t_d = average overall container dwell time in days; t_{cal} = calendar time in days;

The container's dwell time can be established by its exit-to-entry timestamps during each unit visit. In this context, achieving a comprehensive breakdown of the storage cycle based on a logistic approach involves segregating average dwell times for specific landside flows. As a result, the overall dwell time ($t_{d_{overall}}$) can be estimated using a weighted average formulation, as outlined by equation 9.

$$t_{d_{overall}} = \frac{\sum_i^n (t_{d_i} * I_{NC-i})}{\sum_i^n I_{NC-i}} \quad (9)$$

Where: t_{d_i}= landside cargo-mix (i) average dwell-time; I_{NC-i}= respective cargo-mix index of volume.

Finally, from the landside perspective, the yard occupancy index ($Occ_{\text{yard}\%}$) reflected utilisation level of yard storage facilities, as defined by equation 10.

$$Occ_{\text{yard}\%} = \frac{N_{c_{Yard}}}{CAP_{Yard}} \quad (10)$$

In addition, from the waterside perspective, the berth occupancy index ($Occ_{berth\%}$) can be estimated by summing the berth times of vessels alongside the quay, as defined by equation 11

$$Occ_{berth\%} = \frac{\Sigma t_{berth}}{\Sigma t_{cal}} \quad (11)$$

Where, t_{berth}: The berth time reflects the moored period between the actual time of berth arrival (ATB) and departure (ATD) of the vessel measured by the mooring lines attachment and release timestamps.

Results and Discussion

The presented results tailed the proposed analytical procedure, encompassing the following steps:

I. Technical and statistical data collection and survey;
II. Logistical data processing and capacity math modelling;
III. Data correlation and analysis of results.

The initial set of results consolidated the data survey and processing concerning the design planning approach. This highlighted the theoretical and technical capacities of the existing container terminals in the Port of Santos. Utilising the area mapping technique, the infrastructural aspects were surveyed and detailed for DPW, BTP, and TSB, as illustrated in figures 3, 4, and 5, respectively.

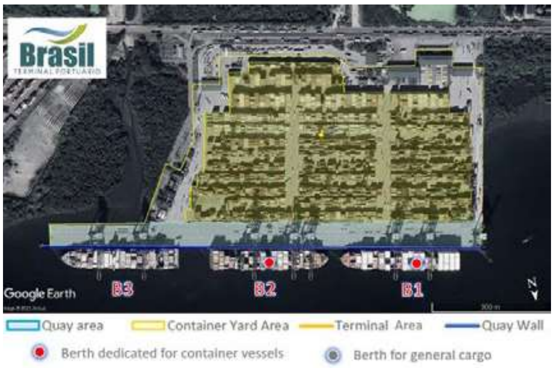
Certain empirical premises required clarification before data processing to leverage comparative analysis between container terminals. This involved assuming technical equivalence based on similarities in handling systems and layout designs, considering the following criteria.

- Since all terminals employ the Rubber Tyred Gantry Crane (RTG) as the main yard handling system, the yard area density was assumed to be equivalent to 0,16 TEU/m².
- Due to restricted container dwell-time data, the assumption was made that overall cargo storage times were similar among the Port of Santos terminal operators. According to ABTRA, (2023) statistical reports and. SPA masterplan reports that the overall dwell-time was estimated to be 6.5 days. (PLANO MESTRE, 2019).
- Technical yard occupancy related to peak factor were also defined following rules of thumb for design planning $\left(Occ_{\text{yard}\,\%}/f_p\right) = 0.75$.

The subsequent data sheets consolidate the main technical details surveyed, presenting estimated static and design capacities, along with additional comments on the recent substantial evolution of the terminal infrastructure.

The BTP terminal is located on the right bank of the Santos Estuary within the SPA leasing area and commenced operations in 2013. It is operated jointly by APM Terminals and TIL, with a declared terminal capacity of 1.5MM TEUs/year, close to the estimated 1.65MM TEUs/year (BTP, 2023). No significant infrastructure expansion were observed. More details are illustrated in Figure 3.

Figure 3: Technical data sheet of the Brasil Terminal Portuario (BTP) container terminal, derived from a 2022 data survey covering infrastructural and superstructural aspects. The Google Earth image is based on a capture from May, 2023.



Terminal Name	Brasil Terminal Portuario (BTP)
Terminal Operator:	APM Terminals / TIL
INFRASTRUCTURE	
Quay / Berths Length (m):	1100
Number of Berths:	3
Berth Depth (-m):	-14.5
Terminal Area (m²)	436,000
Quay Area (m²)	67,000
Container Yard Area (m²):	241,000
Yard Static Capacity (TGS)	38,500
Dynamic Capacity (TEUs/year)	1,650,000
SUPERSTRUCTURE	
No. of STS:	8
Yard Handling System:	RTG & RS
No. of YC:	30
No. of RS & ECH:	9
No. of TT:	66
No. of Gate Kiosks:	8 in + 8 out

The DPW terminal is the only private terminal (TUP) in the Port of Santos, situated in the left bank, an started its operations in 2013. Quay operations are shared with general cargo, primarily pulp. In 1H-2020, the continuous quay length expanded by 400m, adding two berths.

Despite reported four continuous berths, only two are dedicated to container handling. In 2H-2020, there was observed terminal area expansion of 215,000 m², including a landfill and 25,000 m² for container yard storage. The declared terminal capacity was 1.2MM TEUs/year, close to the estimated 1.35MM TEUs/year. More details are illustrated in Figure 4.

Figure 4 Technical data sheet of the DP World Santos (DPW) container terminal, derived from a 2022 data survey covering infrastructural and superstructural aspects. The Google Earth image is based on a capture from May, 2023.

Terminal Name	DP World Santos (DPW)
Terminal Operator:	DP World
INFRASTRUCTURE	
Quay / Berths Length (m):	660 — 1100
Number of Berths:	2 — 4
Berth Depth (-m):	-14.5
Terminal Area (m²)	660,000
Quay Area (m²)	40,000 - 57,000
Container Yard Area (m²):	205,000
Yard Static Capacity (TGS)	32,800
Dynamic Capacity (TEUs/year)	1,350,000
SUPERSTRUCTURE	
No. of STS:	6
Yard Handling System:	RTG & RS
No. of YC:	22
No. of RS & ECH:	5
No. of TT:	42
No. of Gate Kiosks:	6 in / 5 out

The TSB was one of the first terminals at the port, has been in operation since 1998, situated at the left bank of the Santos Estuary. In 2H-2022, the continuous quay length expanded by 220m, adding one more berth. Quay operations are shared with RoRo from the Terminal of Vehicles (TEV).

Despite having five berths, only three are considered dedicated to container handling. In 1H-2020, four STS quay cranes were replaced by two new largest Super Post Panamax cranes. The declared terminal capacity was 2.2MM TEUs/year, close to the estimated 2.3MM TEUs/year. More details are illustrated in Figure 5.

Figure 5: Technical data sheet of the Tecon Santos Brasil (TSB) container terminal, derived from a 2022 data survey covering infrastructural and superstructural aspects. The Google Earth image is based on a capture from May, 2023.

Terminal Name	TECON Santos Brasil (TSB)
Terminal Operator:	Santos Brasil Participações
INFRASTRUCTURE	
Quay / Berths Length (m):	980 — 1500
Number of Berths:	3 — 5
Berth Depth (-m):	-14.5
Terminal Area (m²)	570,000
Quay Area (m²)	65,000 - 35,000
Container Yard Area (m²):	341,000
Yard Static Capacity (TGS)	54,500
Dynamic Capacity (TEUs/year)	2,300,000
SUPERSTRUCTURE	
No. of STS:	13
Yard Handling System:	RTG & RS
No. of YC:	39
No. of RS & ECH:	12
No. of TT:	118
No. of Gate Kiosks:	10 in + 7 out

The second and third steps involved presenting a breakdown analysis of statistical data collection, processing, and capacity modelling correlation, focussing on seaside-landside logistics flows divided into quay-yard-gate operations. Using ANTAQ and SPA databases mainly, the monthly 2022 volume breakdown was obtained for import (IMPO), export (EXPO), transshipment (T/S), and restow (RSTW). Monthly yard dynamic capacity modelling was also conducted to highlight the operational level of storage occupancy.

Figure 6 illustrated the 2022 monthly cargo-mix volume for BTP in thousand TEUs (kTEUs), peaking at 189k TEUs in September, driven by an increase in export volume, with an estimated yard over-occupancy of 116% from a statistical perspective. Figures 7 and 8 illustrated the 2022 monthly cargo-mix volumes for DPW and TSB. Both terminals achieved their maximum quay volume throughput in September, with 104kTEUs and 189kTEUs, respectively, driven by an increase in import volumes. The corresponding yard occupancies stood at 73% and 84% from a statistical perspective.

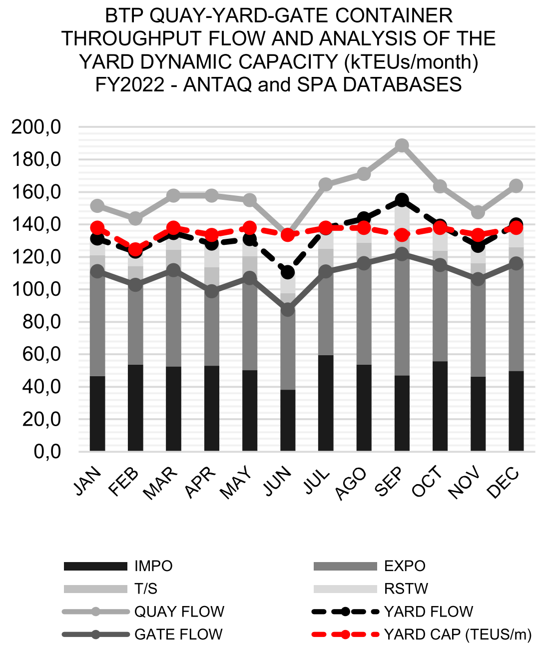


Figure 6 Monthly-2022 waterside-landside cargo-mix flows and throughput volumes (IMPO, EXPO, T/S, and RSTW) for the BTP terminal, together with the corresponding dynamic yard capacity follow-up estimation (YARD CAP) in kTEU. Data sourced from ANTAQ and SPA statistics reports.

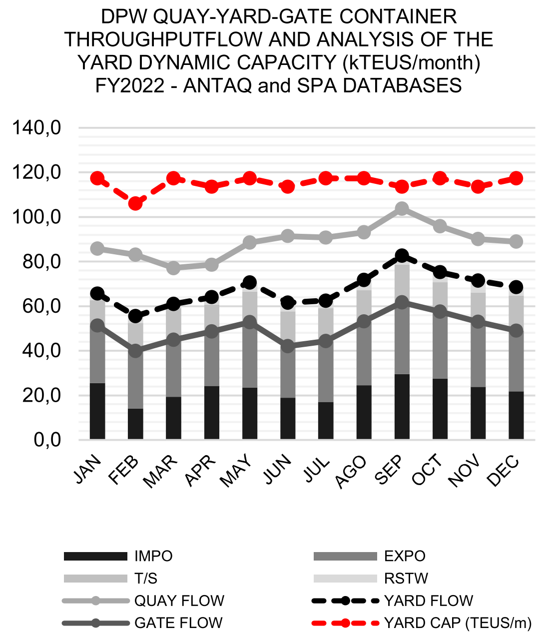


Figure 7: Monthly-2022 waterside-landside cargo-mix flows and throughput volumes (IMPO, EXPO, T/S, and RSTW) for the DPW terminal, together with the corresponding dynamic yard capacity follow-up estimation (YARD CAP) in kTEU. Data sourced from ANTAQ and SPA statistics reports.

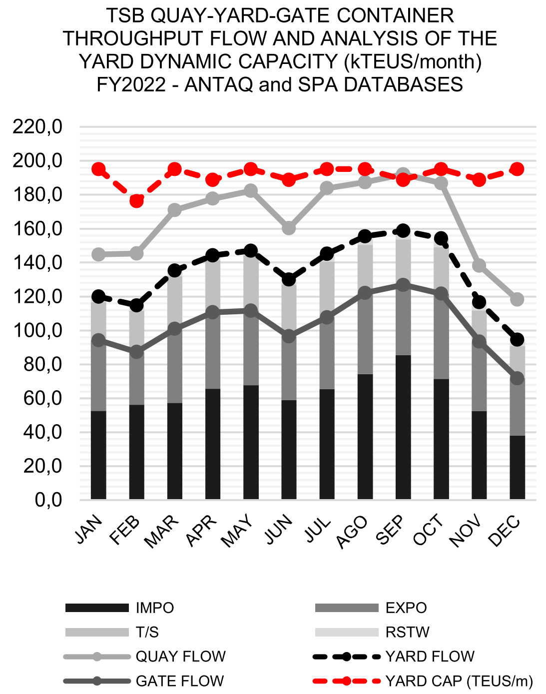


Figure 8: Monthly-2022 waterside-landside cargo-mix flows and throughput volumes (IMPO, EXPO, T/S, and RSTW) for the TSB terminal, together with the corresponding dynamic yard capacity follow-up estimation (YARD CAP) in kTEU. Data sourced from ANTAQ and SPA statistics reports.

The breakdown analysis highlights the total importation of full volumes in kTEUs from each terminal, correlating with the overall Port of Santos storage capacity equivalent to the import-full market share. In particular, the months of August, September, and October 2022 observed the highest volume demand, reaching 135k, 150k, and 136k TEUs, respectively, while December recorded the lowest at 82k TEUs.

The import-full interest is influenced by cargo perceived as the most profitable, influenced by Brazilian port tariff policies guided by the government's tax strategy on import duties (TRADE, 2023). Figure 9 illustrates the monthly demand for full import volumes for the year 2022 in kTEUS, along with the estimated overall yard capacity (kTEUs/month) offered by the container terminals of Port of Santos, sourced from the ANTAQ database.

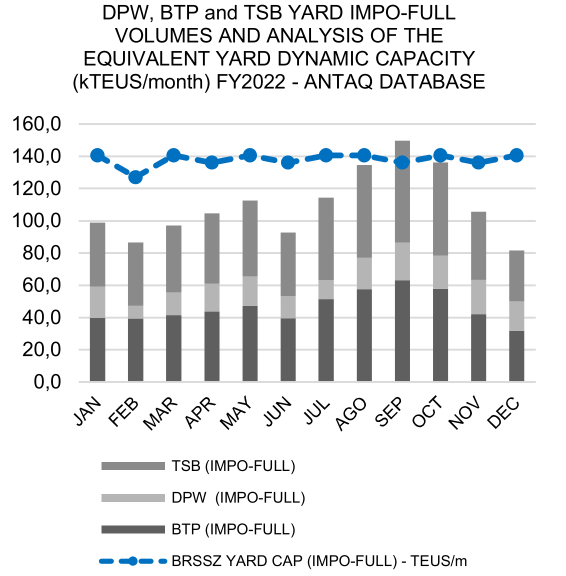


Figure 9: Monthly-2022 cumulative import full volumes from BTP, DPW, and TSB terminals, with the equivalent dynamic yard capacity of the corresponding BRSSZ, in kTEUs. Data sourced from ANTAQ.

In summary, monthly yard storage follow-up provides insights into each terminal's occupancy index and peak seasons, crucial for understanding capacity utilisation levels and indicating the need for storage expansion. When the yard storage index exceeds 100%, it reveals the terminal's contingency plan to provide additional capacity. Figure 10 illustrates the monthly follow-up of the yard storage utilisation ratio for the Port of Santos and the terminal operators. In September 2022, the port reached the highest overall occupancy index at 91%, while December recorded the lowest at 69%, averaging at 77%. This results in a statistical peak factor close to 1.2.

To improve the comprehension of annual throughput and overall capacity utilisation, Figure 11 presented a clear distribution based on quay-yard-gate volume flows. The annual yard utilisation index was highlighted using estimated storage capacity, revealing critical levels with BTP container terminal at 99% storage occupancy, while DPW and TSB were at 59% and 70%, respectively.

To measure berth and gate capacity utilisation rates, it is necessary to obtain productive and performance times of each transportation element - vessels and trucks - during terminal visits, also influenced by queuing waiting times and lengths. In an effort to improve the evaluation of critical capacity bottlenecks between the logistic operational infrastructure of the studied terminal operators, ANTAQ vessel timestamp data were also collected and processed to provide total berth time analytics, considering only the berths dedicated for container handling. However, the trucking turnaround time data were not included in this study.

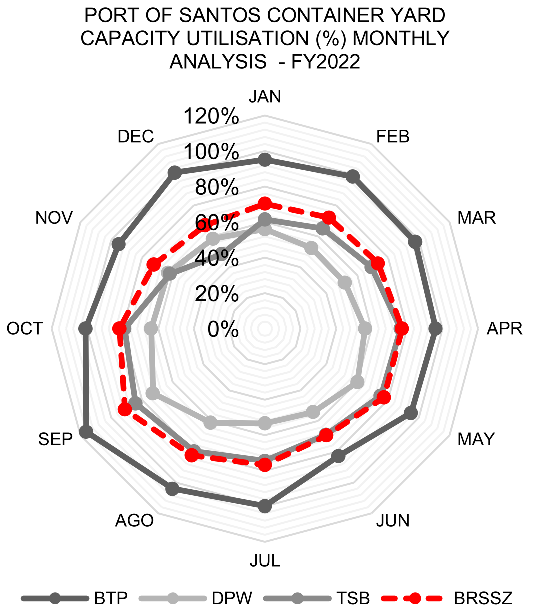


Figure 10: 2022 Monthly Yard Storage Capacity Utilization Ratio (%) Summary for Terminal Operators (BTP, DPW, TSB) and the Port of Santos (BRSSZ).

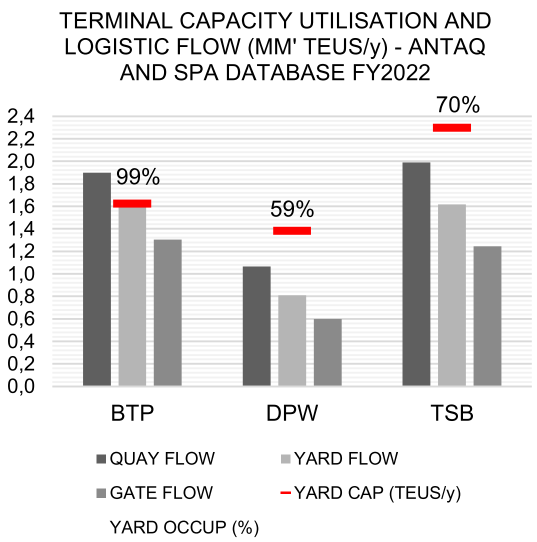


Figure 11 "Consolidated 2022 Annual throughput and overall yard capacity utilization (%), derived from quay-yard-gate volume flows in MM'TEU, for Terminal Operators (BTP, DPW, TSB).

Figure 12 illustrates quay occupancy levels estimated from the sum of container vessel times at the berth, along with the yard storage occupancy levels. On average, the Port of Santos container terminal demonstrates 70% berth utilisation and 76% yard storage utilisation This analysis emphasises that understanding a container terminal's dynamics depends on the observed elements. In addition, the acceptable level of berth occupancy is conditional on the acceptable duration of vessel waiting time for berthing.

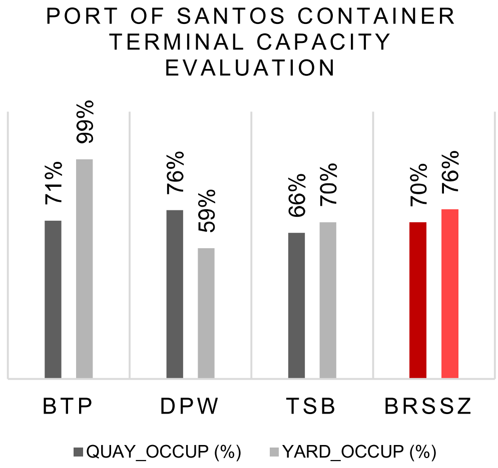


Figure 12 Consolidated comparative evaluation of the quay and the yard estimated occupancy levels, based on the overall vessel times at berth and yard storage utilization, for Terminal Operators (BTP, DPW, TSB) and the Port of Santos (BRSSZ)

Conclusion

In conclusion, the presented modelling framework serves as a practical tool for analysing the trade-off between container terminal capacity utilisation and volume demands, guiding strategic decisions on port infrastructure expansion and commercial strategy within the competitive landscape of logistic operators. Utilising the Port of Santos as a case study, the framework addressed technical details in infrastructure and superstructure, clarifying the similarities and differences between BTP, DPW, and TSB terminals. This achievement enhances the understanding of the correlation among quay-yard-gate flows and the analysis of the utilisation of terminal capacity, emphasising the occupancy ratio of yard storage.

It is crucial to highlight the challenge of data processing, specifically addressing the divergence between official databases to provide a reasonable breakdown analysis for landside cargo-mix flows among import, export, and transshipment. Although data on restow volume were only available in the SPA database, it was complemented with ANTAQ data to provide the total quay throughputs approach. The mathematical modelling of the applied capacity formulation from PIANC terminals planning was carefully reviewed and explained, demonstrated with this practical application of research, from both design and operational planning perspectives. Important premises were considered to overcome data unavailability and simplify the technical capacity approach, such as assuming uniform yard density due to layout similarities and overall storage dwell times.

Therefore, future work could focus on refining these technical details to improve the dynamic capacity analysis, regarding a sensible breakdown data survey of storage static capacity and container storage times by logistic flow category. The Port of Santos logistic operators and the port authority can leverage this analytical tool to improve discussions on continuous investments in infrastructure capacity expansion aligned with increasing demand, preceding the consideration of a new container terminal. Recent discussions by the Port Authority considered business development in the STS10 area for a new container terminal with an estimated annual capacity of 2.4MM TEUS (PPI, 2023). However, it was necessary to clarify demand forecasting to avoid overcapacity. Therefore, monitoring the level of utilisation of terminal infrastructure is a key analytical tool to drive strategic decisions in terms of capacity investments and improve terminal master planning development.

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