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Operational Performance of Container Terminals in the North Adriatic Ports

Maja Stojaković*, Elen Twrdy, Bojan Beškovnik, Gašper Fatur

University of Ljubljana, Faculty of Maritime studies and Transport, Pot pomorščakov 4, 6320 Portorož, Slovenia, e-mail: maja.stojakovic@fpp.uni-lj.si; elen.twrdy@fpp.uni-lj.si; bojan.beskovnik@fpp.uni-lj.si; gasper.fatur@gmail.com

* (Corresponding author)

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ABSTRACT

The significant increase in the number of calls by larger container ships also has an impact on productivity and therefore on the performance of container ports in the northern Adriatic. The productivity of a container terminal depends heavily on the processes at the berth, yard and in the gate area. In our analysis, we have therefore analysed the current capacity and operational performance of each terminal subsystem using KPIs (Key Performance Indicator) and outlined the investment plans required to enable the ports of Koper, Trieste and Rijeka to accommodate larger container vessels. These container ports handle less than 2.4 million TEU per year (2024), which is below what they could achieve given the backhaul market. Analyses have shown that improving the productivity of loading and unloading in the berth area is an effective measure to increase container traffic in the ports of the North Adriatic and improve their market share. Investments in the procurement of new quay cranes, increasing the draught at the berths and expanding the berths play a key role in this. Only with timely measures will the ports of the northern Adriatic be able to compete with their northern European rivals.

1 Introduction

In the last twenty years, container traffic has increased significantly worldwide. In 2024, growth of 3.5 was higher than that of total maritime trade that was 2 percent in the same year. The total weight of goods transported by container ships thus exceeded 1.65 billion tonnes [31, 32]. According to UNCTAD [32], total maritime trade is expected to grow by an average of 2.4 per year in the period 2025-2029, with container trade growing by 2.7. This will have a particular impact on the ports, which will have to handle enormous volumes of freight that will probably exceed last year's 900 million TEU. Even though the majority of container throughput is usually handled by large ports (approx. 80%), the remainder is handled by smaller ports (approx. 20% or around 180 million TEU). As a result, smaller ports are becoming increasingly important in maritime transport. However, they are under enormous pressure from shipowners, who are constantly increasing the size of ships for reasons of economies of scale. According to Rodrigue and Notteboom [19] the maximum capacity of the largest container vessels has grown from approximately 5,500 TEU in 1995 to over 24,000 TEU by 2024, and this trend is expected to continue. Although these largest ships do not call at smaller ports, they still need to be prepared to receive ships with the capacity bigger than 15,000 TEU. Smaller ports are therefore forced to optimise their terminal capacity and increase operational productivity if they want to maintain existing services or provide new services. In the meantime, shipping companies are increasingly demanding faster cargo handling and reduced port costs. For this reason, port authorities need to ensure that forecasts are methodologically sound, clearly communicated and support long-term investment decisions [17]. In this context, substantial financial investment becomes crucial not only for the development of port infrastructure, but also

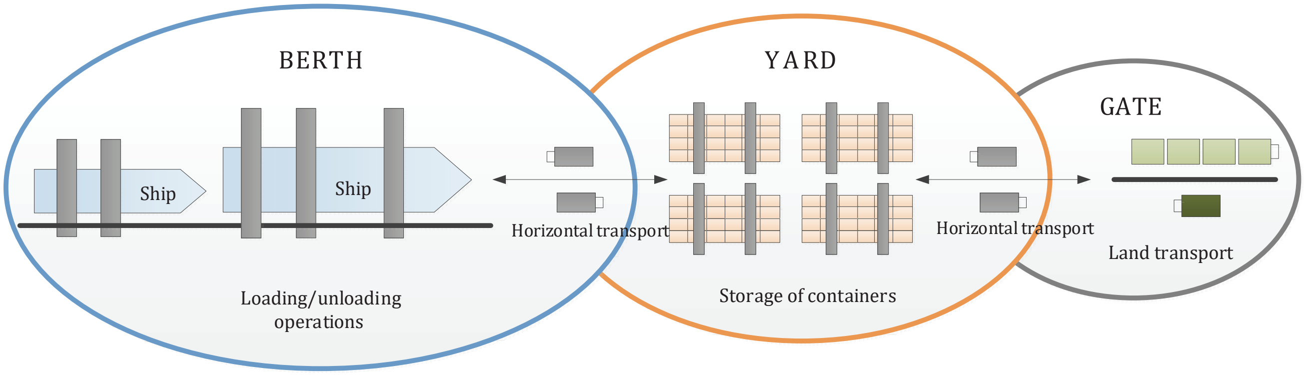

Figure 1 Container terminal subsystems

for the promotion of broader regional economic growth. Without targeted investment, particularly in terminal modernisation and hinterland connectivity, smaller ports risk being marginalised in the evolving maritime transport network [2, 34].

The three North Adriatic ports of Koper, Trieste and Rijeka, whose container terminals will be forced to accommodate ships of up to 20,000 TEU or two large ships at a time in the coming years and provide them with efficient handling in order to maintain their market share, have been dealing with this issue for a long time. These terminals are crucial for the Adriatic region as they are located in the trans-European corridors and offer the fastest access to Central and Eastern Europe, giving them a time advantage over Northern European ports [30]. As things stand, it is expected that the rerouting of container flows via the Adriatic terminals will reduce fuel consumption by 20% compared to the North European terminals, which will bring economic and environmental benefits to the region. This depends mainly on the situation in the Red Sea and the passage of ships through the Suez Canal. The three selected terminals work together within the North Adriatic Port Association (NAPA), but also compete with each other as they are competing for the same cargo. This paper therefore analyses the operational performance of the three selected terminals (Koper, Trieste Marine Terminal-TMT and Adriatic Gate Container Terminal-AGCT) to handle larger post-Panamax vessels and their current productivity in all three subsystems – berth, yard and gate – in comparison to each other.

To address these new challenges, this study introduces a Key Performance Indicator (KPI)-based subsystem analysis aimed at assessing the operational capacity and development readiness of smaller ports. By dividing port operations into critical subsystems — berth, yard and gate — we create a structured framework for benchmarking performance and identifying priority areas for investment. The novelty of this approach lies in its ability to quantitatively assess the resilience and adaptability of port infrastructure in response to global shipping trends, using metrics that consider both technical capacity and service quality. This multi-criteria assessment provides a deeper understanding of how smaller ports can strategically position themselves in the increasingly competitive maritime logistics network.

The structure of the paper is as follows. Section 2 gives an overview of the theoretical foundations and presents the key elements of a CT operating system and preliminary field studies. Section 3 presents the characteristics of the selected CTs in the Northern Adriatic, while Section 4 presents the methodology and results. Section 5 contains the interpretation of the results and a discussion. The conclusion is presented in section 6.

2 Container terminal operations background

Container terminals (CTs) serve as a transshipment point for containerised goods between seagoing vessels and land transporters [20]. Nowadays, they represent an important part of port infrastructure. Their development and operation have a direct impact on global logistics, the competitiveness of ports and economic flows in general. Seaport container terminals vary considerably in size, function and geometric layout, but they all represent a complex system consisting in principle of the same subsystems [11]. These are the berth, yard and gate subsystems [10]. The berth subsystem is intended for the loading and unloading of ships, the yard subsystem for the temporary storage of import and export containers, and the gate subsystem enables the arrival and departure of containers to/from the landside terminal (Fig.1). According to Stojaković and Twrdy [25], each of these subsystems represents a technical and organisational whole without which the port container terminal could not function.

Although each of the subsystems as a whole has its own operational purpose, they must be well connected and their operation must be coordinated if the terminal is to achieve good throughput and high productivity. The best known papers dealing with container terminal operating systems and forming the basis for further research were published in the early 2000s by Vis and De Koster [33], Steenken,Voß and Stahlbock [23], Günther and Kim [7], Murty,Liu,Wan and Linn [15], Stahlbock and Voß [22]. Later, Böse [5] published a handbook on terminal planning, which provides an overview of the most important elements of container terminals and their development. The berth represents the most important subsystem, as it determines the number and size of ships the terminal can accommodate, while the yard subsystem indirectly influences the reception of ships with its operations [11, 24]. As ships are getting bigger, they require more capacity in the individual subsystems of the terminal. This affects the infrastructure elements as well as the handling equipment and efficiency. In the berth subsystem, the most important elements that affect the ability to accommodate ships are the draught, the length of the quay and berths and the number and capacity of quay cranes (QCs). The most important thing for shipowners is that the ship leaves the port as quickly as possible, which means that high efficiency is required from CT. This is usually measured in terms of operational productivity, e.g. ship turnaround time or yard utilisation. Ship handling depends not only on the operation of QCs, but above all on the operation of horizontal mechanisation (e.g. yard trucks – YTs, straddle carriers – SCs, automated guided vehicles – AGVs), the main purpose of which is to serve the QCs on the one hand and the yard cranes (YCs) on the other (e.g. rail-mounted gantry cranes, rubber-tyred gantry cranes – RTG, SCs, container manipulators and forklifts) [9]. It is therefore crucial to achieve good coordination between the loading and unloading operations of the ships, horizontal transport and storage of the containers in the yard [3]. According to Zeng and Yang [35], ship productivity, quay productivity and quay crane productivity are the most important metrics to consider when measuring terminal productivity. These can have a significant influence on the turnaround time of the ship in a container terminal. The turnaround time comprises the processes of berthing, unloading, loading and departure [35]. In this context, Mazibuko Mazibuko,Mutombo and Kuroshi [14] conducted a study using regression and multiple regression to identify KPIs that influence CT productivity. The research results showed that the identified KPIs contribute to ship turnaround time at the port. Therefore, to increase the productivity of CT, the focus should be mainly on ship working hours and gross crane hours to improve the dwell time of ships in the port. Sislioglua,Celik and Ozkaynak [21] developed a model that aims to minimise the average ship turnaround time at the port while maximising the container throughput generated by the terminal. The model helps to decide on optimal investment alternatives to improve CT productivity and focuses on the number of quay cranes, the total length of a quay, yard trucks and the yard cranes. The productivity measures of container terminals were also discussed by Beškovnik and Twrdy [3], who proposed a productivity simulation model based on four productivity indicators, enabling terminal operators to find suitable optimisation opportunities. The study was conducted by analysing more than forty terminals. Later, Beškovnik,Twrdy and Bauk [4] analysed the changes that several global container terminals, including four terminals in the eastern Adriatic, have made to the productivity of the berth subsystem over the last ten years. This article is an improvement of the two previous papers as it focuses on the current productivity of all three terminal subsystems at the three selected terminals in the northern Adriatic Sea, taking into account the KPIs and presenting the results.

3 Basic characteristics of container terminals in ports of Koper, Trieste and Rijeka

The capacities of the selected terminals themselves vary greatly, but all three terminals can currently accommodate large post-Panamax vessels of up to 15,000 TEU. A common problem is that they are not able to handle two such ships simultaneously, which would be essential given the number of services and shipowners' requirements. For this reason, optimisation is required, and has already been initiated. The current capacity of the individual terminal subsystems is described in detail below. This is followed by an analysis of the annual throughput and market share of the terminals from 1990 to 2024.

3.1 Koper CT

The container terminal in Koper is located at Pier I and covers an area of 27.6 hectares, of which 2.8 hectares are dedicated to the berth, while 22 hectares are used for the storage of full containers. Empty containers are normally stored within the terminal (Fig. 2). The characteristics of the terminal are as follows [12]:

BERTH: Berth length-694.5 m; draught-14.5 m; 11 QCs (3 Panamax QCs, 4 Post-Panamax QCs and 4 Super-Post-Panamax QCs).

YARD: Total storage capacity-20,700 TEU; Empty storage capacity-15,000 TEU; Reefer storage capacity-1,200 containers; 15 E-RTGs; 12 RTGs; 12 reach stackers; 8 forklifts.

GATE: Railway trucks-5 x 700 m, 2 x 270 m and 2 x 300 m; 4 RMGs; 61 terminal tractors; 61 trailers.

3.2 Trieste TMT

In Trieste, the total area managed by TMT is 40 hectares, of which about 4.5 hectares is dedicated to the berth and 21 hectares to the storage of full containers (Fig. 3). The total area of the main parts of the container terminal, excluding other surfaces, is comparable to that of Koper and is approximately 27 hectares. The characteristics of the terminal are as follows [29]:

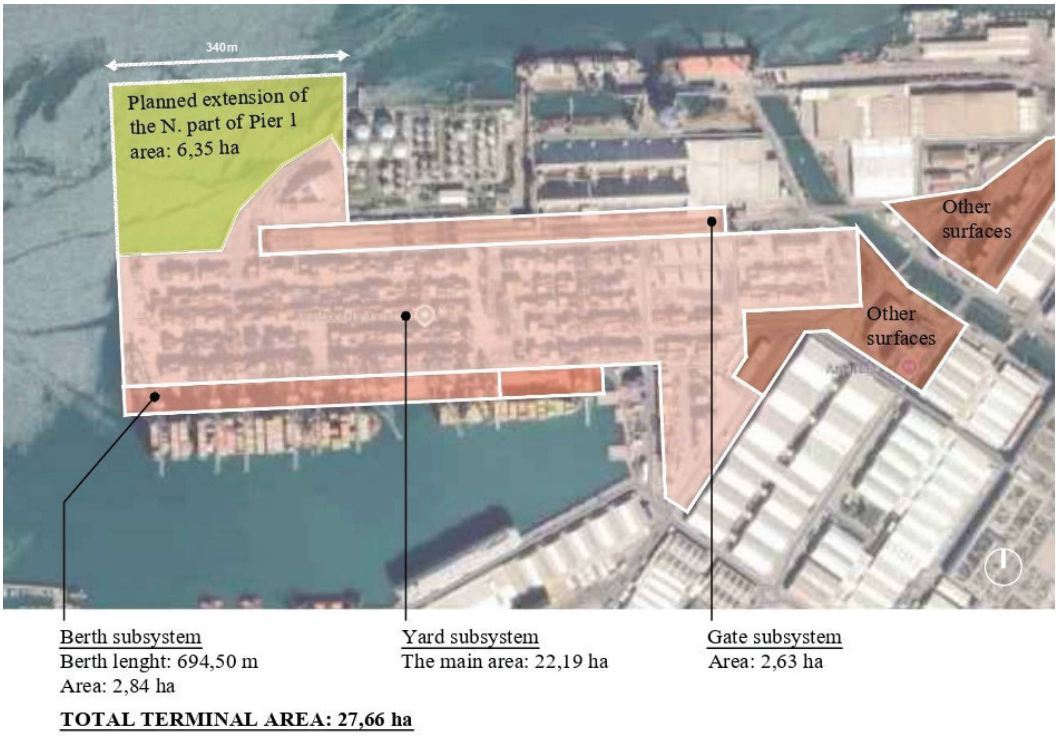

Figure 2 Koper CT

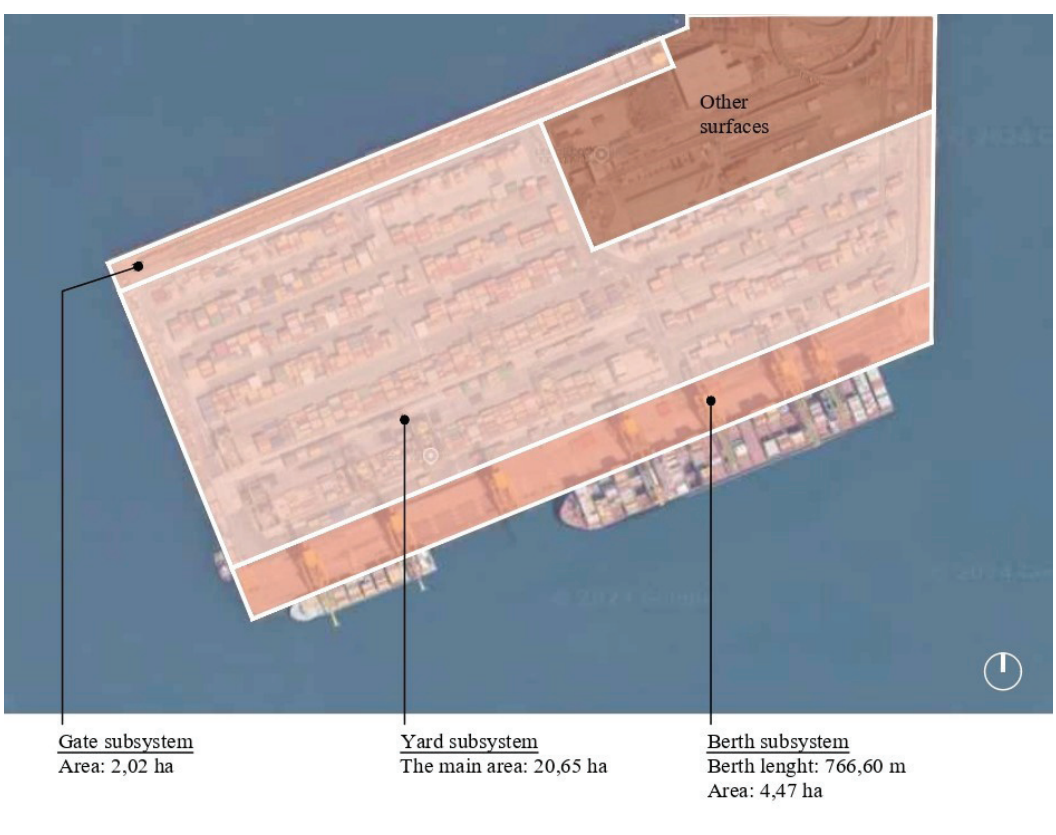

Figure 3 Trieste TMT

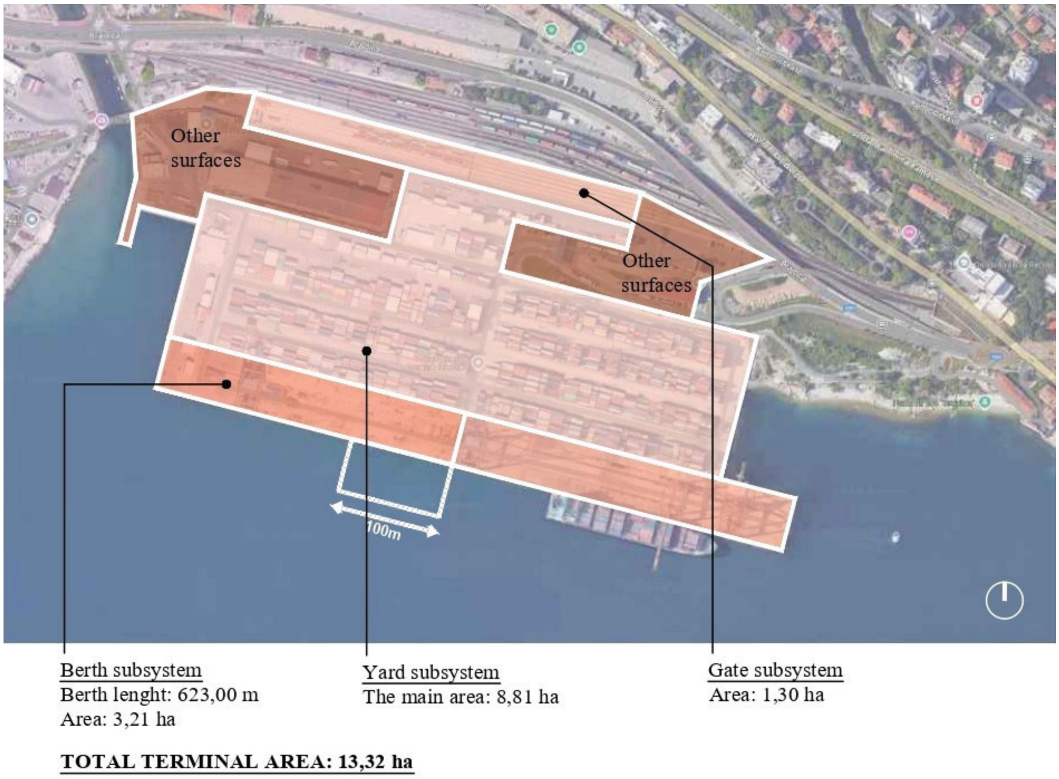

Figure 4 Rijeka AGCT

BERTH: Berth length-770 m; draught-18 m; 7 post-Panamax QCs.

YARD: Storage block capacity-20,650 TEU; 425 reefer slots; 7 RMGs; 18 reach stackers.

GATE: Railway trucks-5 x 600 m; 3 RMGs; 33 terminal tractors and 47 trailers.

3.3 Rijeka AGCT

AGCT is the smallest of the three terminals compared. Its total area is approx. 17 hectares, while the total area excluding other surfaces is approx. 13 hectares. Of this, 3.2 hectares are used for berth operations, while the storage area covers around 9 hectares (Fig. 4). Two external depots, Škrljevo and DepoLink, are available for the storage of empty containers. The detailed characteristics of the terminal are as follows [28]:

BERTH: Berth length-628 m (first part-300 m with a draught of 11.2 m and equipped with 2 Panamax QCs and second part-328 m with a draught of 14.88 m and equipped with 2 Post-Panamax QCs).

YARD: Storage of regular containers; reefer storage capacity-1.5 ha; 6 RTGs; 5 reach stackers; 4 forklifts.

GATE: Railway trucks-4 x 420 m; 2 RMGs; 23 terminal tractors; 27 trailers.

3.4 Terminal performance

According to the Container Port Performance Index (CPPI) [1], which assesses the performance of terminals based on the dwell time of ships in the ports, the three ports in question perform relatively poorly in 2023. Of the 405 ports assessed, Koper ranks 362nd, Trieste 394th and Rijeka 400th. The index is roughly divided into five classes by ship size (Table 1), within which ter-

Table 1 Port ranking after CPPI index

Port	Container ship categories				
	Less than 1.500	1.500-5.000	5.000-8.500	8500-13.500	More than 13.500
Koper	218	291	116	140	102
Trieste	192	233	128	183	109
Rijeka	268	287	216	165	115
Ports considered by category	327	374	227	186	117

minals are categorised according to the number of manipulations required for each ship.

It was found that the dwell time of a vessel is influenced more by the number of QCs assigned to the vessel than by their productivity. Ships in the 8,501 TEU to 13,500 TEU size class are handled the fastest. A key factor for efficiency is the volume of handling required – a higher number of handling operations can lead to higher turnaround times. Dwell times are therefore influenced more by the number of handling operations than by the size of the ship itself [1]. Table 1 shows that CT in Koper performs best among the three selected terminals when it comes to receiving ships with a capacity of more than 5,000 TEU (ranks 116; 140 and 102), while TMT performs best when it comes to receiving ships with a capacity of up to 5,000 TEU. In 2023, 462 ships called at Koper CT, 380 ships at TMT and 214 ships at AGCT.

3.5 Traffic analysis

The traffic analysis shows that TMT had the highest traffic volume until 2006, after which Koper took the lead. The market share of the ports has also changed over the same period. In 1997, TMT had a market share of over 70%, which then gradually declined as the port focussed more on other goods and did not invest much in CT. Koper, on the other hand, has focussed mainly on investments in CT over the last 15 years, resulting in a gradual increase in market share, which reached its highest level of 55% in 2016. AGCT had the lowest market share during the period under review, but was the only that managed to increase its share during the pandemic, which is consistent with the completion of infrastructure projects – the extension of the berth and the modernisation of the yard, which confirms the justification of the investments made. Compared to 2014, container throughput in AGCT was 113.24% higher in 2024, while traffic in Koper increased by 68.14% in the same period. After a relatively constant growth in traffic volume in TMT, which increased by 68.41% from 2014 to 2023 and thus almost reached the terminal's maximum capacity of 900,000 TEU, traffic volume surprisingly fell by 16.67% in 2024. Traffic volumes in Koper and Rijeka increased last year.

Looking at the current annual capacities of the three comparable container terminals – Koper 1,300,000 TEU, TMT 900,000 TEU and AGCT 600,000 TEU – AGCT could achieve a share of 21.43% with a simple split. TMT's share would then be 32.14%, while Koper's share would remain almost the same as in 2023 at 46.23%. However, AGCT's actual share in 2024 was slightly lower at 18.1%, TMT's at 32.13% and Koper's at 49.86% (Fig. 6). Thus, Koper has the highest terminal utilisation (almost 87%), which shows the need for investment in terminal expansion and increasing capacity.

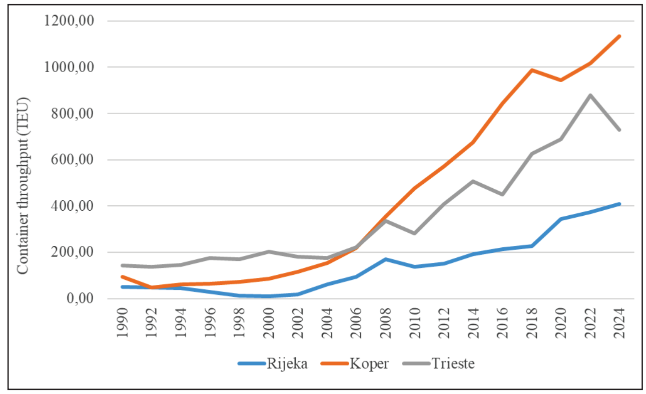

Figure 5 Container throughput in three NA ports

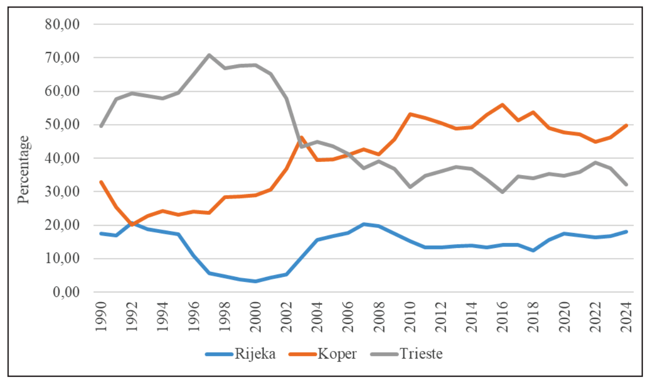

Figure 6 Market shares of the selected NA ports

According to the World Bank report [1] the share of these three ports in EU throughput rose from 1.53% in 2014 to 2.26% in 2022 and would reach 3.35% by 2032 if the growth trend continues, which corresponds to almost 4,000,000 TEU. Given the potential of the hinterland markets, it could even reach 5% of EU throughput or 5,800,000 TEU. For this reason, optimising terminal capacities and increasing current productivity in all three terminals will be crucial in order to meet the requirements of the market and shipowners.

4 Methodology and results

The main objective of the study is to determine and compare the current capacities and productivity levels of the selected terminals in the three subsystems – berth, yard and gate.

To assess the operational efficiency of container terminals, we have developed a set of Key Performance Indicators (KPIs) focussing on the berth, yard and gate subsystems. These indicators were selected because they reflect infrastructure utilisation and the degree of mechanisation and allow meaningful comparisons between terminals of different sizes and configurations. The analysis is based on the data received from the se-

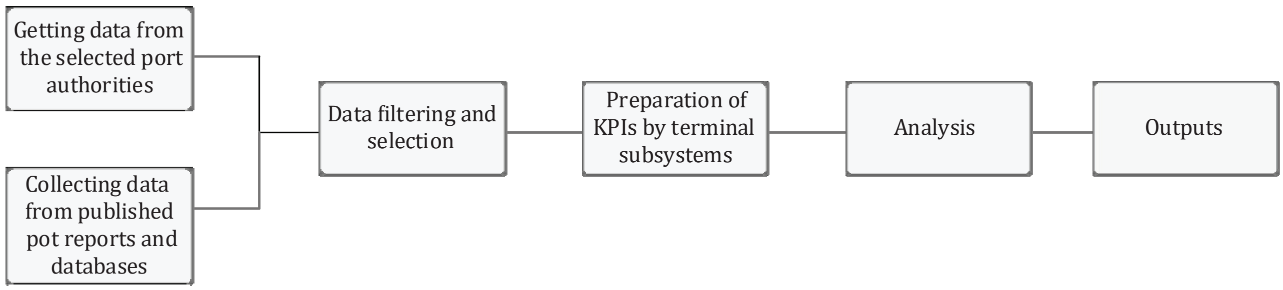

Figure 7 Data analysis process

lected ports and assumes uninterrupted operation of each terminal in 2023 (362 days × 24 hours = 8,688 operating hours), which ensures the consistency of the time-based productivity calculations.

To this end, we have focussed on four indicators developed by Beškovnik and Twrdy [3] to compare the productivity of the berth subsystem and the utilisation of the yard. The parameters are:

- number of TEU per berth length;
- number of TEU per QC;
- number of TEUs per hour for each QC;
- number of TEUs per hectare of yard area;

Building on this, we have developed indicators that also allow us to analyse the productivity of the yard, focusing on the mechanisation and of the gate subsystems. The following indicators were used for this purpose:

- number of TEU per yard crane; this metric measures the average workload handled by each rubber-tyred gantry crane (RTG), rail-mounted gantry crane (RMG) or straddle carrier. It reflects the coordination between the container flow and the use of the equipment.
- number of TEU per hour for each yard crane; this time-based performance indicator evaluates the effectiveness of the yard equipment in handling containers during operating hours. It can reveal bottlenecks in equipment utilisation or highlight the benefits of automation.
- number of TEUs per hour at the road gate; this indicator quantifies the volume of containers handled per hour at the truck gate. It reflects the capacity of the gate, the automation (e.g. OCR, RFID) and the efficiency of the planning.
- number of TEU at the gate for rail vehicles. This key figure records the total container handled by rail at the terminal gate. It is particularly important for evaluating intermodal connectivity and the modal split between road and rail.

The data was compiled from a mixture of primary and secondary sources, including real data from the selected ports, reports from port authorities, infrastructure databases, European transport statistics (e.g., Eurostat, EMSA), and information from terminal operators. Figure 7 shows the flowchart of the data analysis process (from data collection to KPI calculation).

4.1 Comparison of productivity at the berth subsystem

According to the data received from the ports, 85% of the total throughput is handled by larger Post Panamax (PP) and Super Port Panamax (SPP) QCs, while the remaining part is handled by small Panamax QCs. As this analysis relates to the ability of the terminals to accommodate larger vessels, the total throughput for the traffic handled by small QCs has been reduced in order to obtain a more accurate calculation of the productivity of the berth subsystem in relation to larger vessels. For this purpose, the berth length was also adjusted to the length used by larger QCs.

The results show (Table 2) that when analysing the throughput achieved with PP and SPP QCs and the number of QCs used at each terminal, these are quite proportional and that Koper CT has the lowest throughput

Table 2 Berth productivity at the selected CTs

Container terminal	Throughput in 2023 (TEU)	Total no. of QC	85% of 2023 throughput (TEU)	No. PP and SPP QC	Berth length (m)	TEU/berth length	TEU/QC	TEU/hour/QC
Koper	1.066.093	11	906.179,1	8	544,5	1.664,24	113.272,38	13,04
Trieste	852.193	7	852.193,0	7	770	1.106,74	121.741,86	14,01
Rijeka	385.794	4	327.924,9	2	430	762,61	163.962,45	18,87

Table 3 Yard productivity at the selected CTs

Container terminal	75% of 2023 throughput (TEU)	No. of RTG/RMG	TEU/(RTG/RMG)	TEU/hour/ RTG/RMG
Koper	799.569,8	20	79.956,98	9,20
Trieste	639.144,8	7	182.612,8	21,01
Rijeka	289.345,5	6	96.448,5	11,10

Table 4 Yard utilisation at the selected CTs

Container terminal	Throughput in 2023	Total terminal area (ha)	Yard area (ha)	TEU/terminal area	TEU/Yard area
Koper	1.066.093	27,66	22,19	38.542,77	48.043,85
Trieste	852.193	27,14	20,65	31.399,89	41.268,43
Rijeka	385.794	13,32	8,81	28.963,51	43.790,47

per QC. The problem is the large number of handled containers and insufficient storage space. This means that operations cannot be carried out quickly enough and the results are low. The productivity of the QCs is therefore 44.7% lower in Koper and 42.6% lower in TMT than in AGCT. AGCT has the highest crane productivity, which could be due to lower throughput in the analysed period. The productivity of QCs per hour is roughly proportional in Koper and Trieste, as it is only 7.47% higher in TMT. Comparing the terminals in terms of throughput and berth length shows that Koper has the best throughput, with 50.37% more TEUs per metre of berth than TMT and 118.22% more than AGCT. TMT also has a 45.12% higher throughput than AGCT. This shows that while Koper has the highest throughput, the productivity of the QCs there is the lowest, suggesting that they are underutilised and that there is an opportunity to accept much more cargo than is currently being handled. TMT also has a lot of room for manoeuvre in this respect, while AGCT urgently needs to increase the number of QCs.

4.2 Comparison of productivity at the yard subsystem

In the main yard area only full containers are handled with RTG/RMG, which is why empty containers were not included in the analysis. They account for around 25% of total throughput in 2023 at the three selected terminals. Due to the similarity of the terminals, 75% of the annual throughput was therefore used in the calculations, assuming two RTG/RMG movements.

In Koper CT, the functioning of 20 RTGs was analysed, of which there are 4 on each of the 5 blocks. The rest are in service positions and are rotated as required.

Table 3 shows that Koper has the largest crane park and the lowest productivity both overall and per hour. TMT is the most efficient here. TMT achieves 128% more than Koper and 89.33% more than AGCT. The highest RTG productivity per hour is at TMT and the lowest at Koper, showing that Koper is almost three times more mechanised but only achieves 44% of TMT's productivity. AGCT has slightly less mechanisation but better productivity (TEU/RTG) than Koper, but only 53% of TMT's productivity.

As far as the utilisation of storage space is concerned, Table 4 shows that the operating areas of the terminal in Koper and Trieste are almost the same size, but the utilisation of the terminal area in Koper is much higher, namely 22.74% compared to Trieste and 33.07% compared to Rijeka. The difference between the utilisation rates in Trieste and Rijeka is 8.41% in favour of Trieste. The terminal in Koper also makes the best use of its storage space. In this respect, it is 16.41% better utilised than TMT and 9.71% better than AGCT. AGCT also outperforms TMT by 6.11%. The storage capacity of Koper and Trieste is significantly higher than that of Rijeka, namely by 152% in Koper and 134% in Trieste.

4.3 Comparison of productivity at the gate subsystem

When analysing the gate subsystem, only the proportion of throughput that passes through or leaves the terminal via this subsystem was taken into account. The total throughput was therefore reduced by the number of containers handled from ship to ship. For the terminals in Koper and Trieste, a ratio of 55% to 45% was assumed in favour of rail for containers arriving or departing on the land side. In Rijeka, the ratio is lower at 30% to 70% in favour of road transport. All three terminals use RMG cranes for the handling of train compositions, whereby the number of containers on each RMG crane and the number of TEUs per operating hour were analysed.

The results show that Koper has 25% more railway traffic than TMT and four times more than AGCT (Table 5). TMT has the highest number of TEUs per hour with 3 RMG and AGCT the lowest. It can therefore be

Table 5 Gate productivity at the selected CTs – rail transport

Container terminal	No. of TEU – gate subsystem	No. of RMG	TEU/RMG	TEU/hour/ RMG
Koper	746.265,1	4	102.611,50	11,81
Trieste	596.535,1	3	109.364,77	12,59
Rijeka	270.055,8	2	40.508,37	4,66

Table 6 Gate productivity at the selected CTs – road transport

Container terminal	Number of TEU/ year	Trucks annually Mon-Fri.	Trucks per day/ peak hours	Trucks/hour – pick hours	Average No. of trucks/day
Koper	335.819,3	136.006,8	368,19	46,02	17,39
Trieste	268.440,8	108.718,5	294,32	36,79	13,90
Rijeka	189.039,1	76.560,82	207,26	25,90	9,79

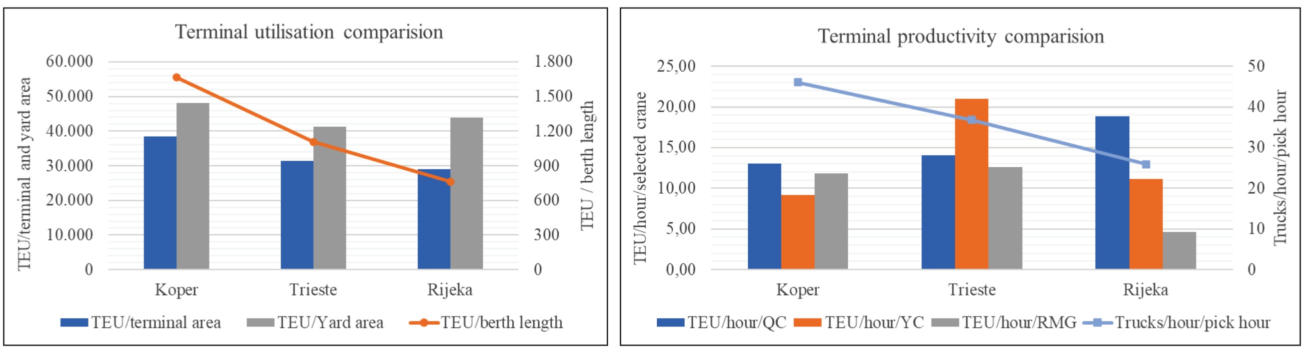

Figure 8 Comparison of KPI factors by port

seen that RMG utilisation is poor at all terminals, but worst at AGCT, where a single RMG handles only 40,508 TEUs. Compared to AGCT, Koper has a 153% higher utilisation per RMG and Trieste a 170% higher utilisation per RMG.

When calculating the number of road freight vehicles required for the arrival and dispatch of containers through the terminal's cargo entrance, we took into account the ratio between 40- and 20-foot containers, which at North Adriatic is 4:1 in favour of the larger containers. For all three terminals, we have assumed that empty containers account for around 25% of total traffic and have therefore reduced the number of trucks in the storage area accordingly. According to road traffic regulations, around 90% of trucks are on the roads from Monday to Friday between 6am and 6pm, with the peak period being between 8am and 4pm. We estimate that 70% of these 90% of trucks are active during this time.

To make it easier to compare the results, we have summarised the data in the two diagrams below (Fig. 8). The first diagram (left) summarises the usage results of the three terminals under consideration, while the second diagram (right) compares the productivity results of the terminals.

It is obvious that Koper has the highest occupancy rate, both in terms of the total area of the terminal and in terms of the storage and berth itself, which means that it is more prone to congestion and therefore needs to optimise its infrastructure capacity in the short term. Productivity at the berth is currently highest at the AGCT terminal, while productivity in the storage area is best in Trieste. However, the majority of trucks are handled via Koper, which indicates a need for optimisation.

5 Discussion

The indicators presented in Chapter 3 enable a detailed performance analysis at the level of the subsystems in the quay, yard and gate areas. By quantifying both the spatial (e.g. TEU per berth length or hectare) and temporal (e.g. TEU per crane hour) dimensions of productivity, the framework facilitates a comprehensive assessment of terminal operations. In particular, this approach supports benchmarking between terminals of different sizes, configurations and operating models. Gonzalez and Quesada [6] compare variables — including berth and gate utilisation — in three geographically diverse ports using standardised benchmarking methods. These indicators also allow the identification of performance gaps, such as underutilised infrastructure or overloaded equipment. Policy makers are usually concerned with the overall functioning of ports, which includes economic performance, land-use planning and environmental sustainability [16]. Through strategic investment planning, including prioritising equipment upgrades or improving terminal layout, ports can achieve better performance. Lin,Sun,Wang,Shang and Xu [13] found that infrastructure investment not only improves the competitiveness of ports but also promotes national economic development by facilitating trade and optimising the efficiency of the shipping system. Assess the impact of mechanisation and digitalisation, highlighting the role of technology in improving throughput performance. Smart port technologies offer significant benefits to the operational efficiency and competitiveness of global trade, making them key components for future supply chains and sustainability [27].

Taken together, these KPIs provide a solid foundation for evidence-based benchmarking. Furthermore, they can be systematically integrated into a composite assessment system or decision-support tool to guide terminal optimisation, infrastructure modernisation and long-term strategic planning in line with evolving operational requirements and sustainability goals.

To find out why the container terminals analysed performed so poorly in the Container Port Performance Index, we determined (based on the data presented in Chapter 3) that the biggest problems at all three analysed terminals lie in the berth subsystem that the biggest problems in all three analysed terminals lie in the berth subsystem. In Koper and Rijeka, the current depth along the operating quay does not allow ships with a capacity of 18,000 TEU, which require a draught of 16 to 17 metres, while Trieste has a head start in this area, as the natural sea depth allows this. All three terminals cannot accommodate two large mother ships of 350 metres or more at the same time, as the current quay length is too short. The options are therefore to accommodate one mother ship and one smaller ship. Koper has most large QCs, which is also reflected in the productivity results, as it handles the fewest TEU/hour and could have better capacity utilisation. TMT shows similar results in 2023, although the number of TEUs handled per hour has almost doubled from the original 7.43 to 14.01. The results show that Koper has the highest berth utilisation, while the QCs at the AGCT terminal handle the most with 18.87 TEU. This is due to the lower annual throughput and the high congestion of the berth subsystem, which can no longer increase traffic without buying additional QCs, although the storage capacity allows for a throughput of 650,000 TEU/year. However, these are gross calculations that do not take into account all the circumstances of terminal operations that have a significant impact on QC productivity, such as the efficiency of horizontal transport, the efficiency of the yard cranes and the strategy chosen to carry out handling operations. Taking these factors into account, net QC productivity in all three terminals is between 20 and 25 movements/hour. Based on a ratio of 20 to 40-foot containers in 2023, this would mean 35 TEU/h or more per QC in Koper.

The yard cranes in Trieste are the most heavily utilised, which has a negative impact on the operations and indicates the need for additional investment in equipment. On the other hand, Koper and Rijeka still have a lot of room for manoeuvre. In Koper, less than 80,000 TEU per year fall on one RTG, which means that the utilisation rate is quite low and therefore allows the terminal to increase traffic without purchasing new cranes. The utilisation of the cranes in Rijeka is also quite low, which is also due to the lower annual traffic volume. On the other hand, capacity in the full container yard subsystem is most heavily utilised at the container terminal in Koper, while Trieste and Rijeka still have reserves in this area. In Trieste in particular, one would expect the main storage area to be more heavily utilised. Although the analysis shows high figures for TEU handling per RMG, these are not entirely realistic, as the RMGs are not distributed over the entire area and handling is mainly carried out by reach stackers. The purchase of additional RMGs would significantly improve productivity. In Rijeka, a further increase in container handling by rail to the Škrljevo terminal is expected. According to information, the procurement of an additional RMG crane for the rail vehicle transfer area is already underway. This would significantly reduce the dwell time of containers at the terminal and increase the annual handling capacity. The rail transport services at the gate subsystem are comparable in Trieste and Koper, while Rijeka still has reserves. In order to increase container handling and the proportion of containers transported by rail, the rail network must be modernised, which is also crucial for the sustainable development of the port. The new terminal will further increase the pressure.

According to Hess,Hess,Novaselić and Grbić [8], the port of Koper is reaching its capacity limits, but maintains realistic growth ambitions by optimising space and maintaining services. In contrast, the Port of Trieste is experiencing significant expansion, driven by MSC's strategic investments in hinterland connectivity and intermodal logistics, making it a major transhipment centre for cargo from the Far East. Meanwhile, the Port of Rijeka will strengthen its role with the upcoming commissioning of the Zagreb Deep Sea Container Terminal, which will increase its competitiveness in the region.

The greatest potential for improving the yard subsystem lies in optimising the supply of external trucks. The analysis revealed considerable congestion at peak times. This leads to problems in all subsystems and makes the redistribution of labour more difficult. As soon as the ports have completed their investments and the modernisation of the container terminals, we can assume that they will rank higher in the Container Port Performance Index.

6 Conclusion

Today, more and more large ships with a capacity of over 24,000 TEU are setting sail, leading to changes in global maritime transport. As a result, the largest ships, which previously only called at the world's largest ports, are now also calling at smaller international ports. To remain competitive, these ports must be able to accommodate such ships, which will require massive investment and infrastructure adjustments. Our analysis analysed the current operational capacity of each terminal subsystem and outlined the advantages and disadvantages of CTs in Koper, Rijeka and Trieste in terms of their ability to accommodate large ships.

The ports analysed have the advantage of their geographical location, which puts them in a good position compared to northern European ports when it comes to bringing cargo from the Middle or Far East to Europe, but they will not be able to accommodate ever larger ships without additional investment.

In Koper, the aim is to reach 2 million TEU per year by 2030. This will only be possible by optimising current capacities and improving operational productivity. As Pier 1 can no longer be extended to the south (towards the open sea) due to a marina, the plan is to extend it to the north. This will create an additional 340 metres of operational quay, which is intended for smaller ships. Large ships will berth in the southern part. Here, the berth will have to be dredged to 16 or 17 metres. The current number of QCs is sufficient to meet demand. However, it would make more sense to examine the possibility of extending the first part of Pier 1 into the land part of the terminal or at least converting the first 150 metres to ensure the unimpeded movement of post-Panamax QCs along the entire length. On the northern part of Pier 1, it would make sense to replace the Panamax QCs with new Post-Panamax QCs, thus maintaining the total number of QCs while increasing their productivity. The construction of the northern part of Pier 1 will therefore provide the port with new storage space and an additional operational quay with berths. To ensure fast and smooth movement of containers out of the system, the capacities of the gate subsystem must also be optimised. To this end, the construction of a second track is already underway, as is the construction of the access road to Sermin, which will connect the port of Koper directly to the motorway network. The current capacity of the existing track is 94 trains per day with an annual capacity of 12.7 million tonnes of freight. After the construction of the second track, the total capacity of both tracks will be 212 trains per day or 36.9 million tonnes of freight per year.

In Trieste, there are plans to extend Pier 7 by 200 metres in order to gain more quay length and new storage space. The extension will give the south quay a net length of approx. 870 metres, of which approx. 810 metres will be accounted for by the operating quays, which will allow two mother ships to dock at the same time, including one with a capacity of 19,000 TEU. As the port does not currently have QCs that can unload container ships with this capacity, the new part of the terminal will be equipped with two super post-Panamax QCs with a range of up to 24 containers. This expansion will increase the terminal by more than 8 hectares, with the operating water area increasing by 1.2 hectares and the storage area by 6 hectares. Seven new RMGs will be purchased for the storage area. The most ambitious plan, however, is the construction of Pier 8 on the opposite site. This is being built in cooperation between the state and the operator HHLA. The first phase of construction is due to be completed by 2027 and will include a 450 metre long berth with a capacity of 500,000 TEU. In the final phase, the terminal will comprise 900 metres of berths with an annual handling capacity of 1.9 million TEU. This will significantly increase the port's capacity compared to its direct competitors.

The most important project in Rijeka is the construction of the Rijeka Gateway. The first phase of this project was completed in May 2019 with the construction of 400 metres of functional quays. The CT is called Zagreb Deep Sea and is directly connected to the Croatian motorway network. The concession for the operation of the CT was awarded to the company Rijeka Gateway, d.o.o., in which APM Terminal holds a 51% stake, while the remaining 49% is owned by the Croatian company ENNA Logic. It is planned to extend the operating quay to 680 metres. The terminal will be equipped with an electrical power supply for the berths and an automatic control system for the QCS. With a natural depth of 20 metres, this will make it possible to accommodate the largest ships. The planned capacity of the container terminal in the first phase is 650,000 TEU per year. The main storage area will cover just over 4 ha in the first phase, while the total area of the terminal will reach approximately 17 ha after completion of the second phase, comparable to the AGCT. According to internal sources, there are plans to purchase an additional QC at AGCT. Given the improvement in the CPPI index, it would also make sense to run post-Panamax cranes along the entire quay length of the AGCT and gradually replace the Panamax cranes. At least one of the QCs should reach over 24 container types. The deepening and increased capacity of the AGCT currently allows it to accommodate larger ships with a capacity of 18,000 TEU, increasing the terminal's throughput and operational efficiency. The second mother ship is to be accommodated in the new terminal, which is scheduled to open in 2025. This year, the port of Rijeka will therefore be able to handle containers from two large mother ships of up to 400

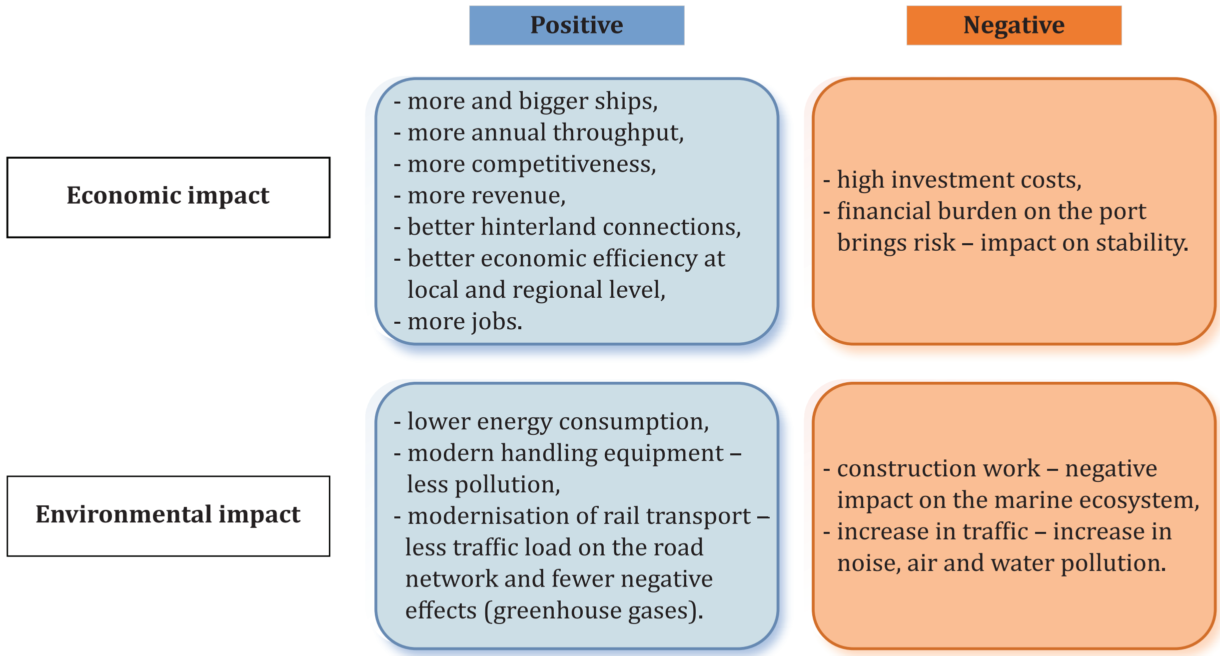

Figure 9 Economic and ecological effects of the optimisation measures in the three ports

metres in length at the same time, giving it an advantage over competing ports in the northern Adriatic.

Today, sustainable development plays an important role in the optimisation of container terminals; however, every investment has a good and a bad side, which is reflected in economic, social and, above all, environmental terms. Figure 9 shows the summary of economic and environmental impact of the optimisation measures implemented in the three ports. The environmental aspect is of crucial importance today and the ports are focusing their optimisation efforts primarily on this, as they want to reduce the environmental impact of maritime transport. Ports are increasingly committed to the decarbonisation of maritime transport, a trend that will continue in the future. As part of these initiatives, ports are pursuing sustainable strategies that balance environmental responsibility with safe and efficient operations [18]. They combine new technologies and sustainable practises to improve operational efficiency, safety and environmental protection. Today, ports are not only competing with each other in terms of annual traffic volume, infrastructure capacity and equipment, but also increasingly in terms of environmentally friendly development. For this reason, one of the first tasks in a terminal is to prepare technical, operational and financial measures that promote the development of environmentally friendly activities. This starts with the acquisition of handling equipment and a better distribution of modes of transport when it comes to transporting goods from the port to the hinterland.

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