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THE IMPACT OF CONTAINER FLOWS IN BALTIC PORTS ON SUSTAINABLE PORT DEVELOPMENT

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Abstract. The article examines container flow dynamics in the Baltic ports of Klaipėda, Riga, and Tallinn, emphasizing their impact on sustainable port development. Using statistical data from 2005–2024, the study applies the Compound Annual Growth Rate (CAGR) model and Pearson Correlation analysis to forecast container handling volumes up to 2030. The methodology incorporates three scenarios—baseline, optimistic, and pessimistic—to assess the potential effects of geopolitical, economic, and environmental factors on port performance. The findings reveal Klaipėda as the regional leader in growth rate, followed by Riga and Tallinn, with all ports demonstrating strong positive correlations in container throughput trends. These results indicate systemic interdependence among Baltic ports, suggesting that coordinated regional strategies could enhance resilience and sustainability. The study highlights that integrating traditional statistical tools with sustainability perspectives supports informed infrastructure planning, energy efficiency improvements, and the development of green logistics systems.

Keywords: Container flows; Compound Annual Growth Rate (CAGR); Pearson correlation; Baltic ports; sustainable development; forecasting

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1. Introduction

Containers are one of the most important elements of import and export in modern society, ensuring not only fast transportation but also protecting cargo from damage and facilitating its storage (Tang et al., 2019). However, global economic and geopolitical challenges have a significant impact on container flows. The pandemic had a negative impact on transshipment volumes due to reduced consumption and quarantines, but activity has recovered over time (Bartosiewicz & Jadczyk, 2023).

Since 2022, container volumes have risen rapidly, exceeding 1 million TEU. Global container transport capacity has grown significantly in recent decades, with growth driven by the end of the pandemic and changing consumer habits (Kerbiriou, 2024). European Union sanctions against Russia have led to a redistribution of flows and higher cargo volumes in Lithuania (Kerbiriou, 2024).

The growth in cargo volumes is also linked to sustainability: the expansion of wind farms and solar batteries is increasing the need for efficient logistics solutions (Bartosiewicz & Jadczyk, 2023). Optimizing maritime terminal operations reduces CO₂ emissions and is in line with sustainable development goals. Reducing ship

turnaround times using artificial intelligence improves terminal efficiency (Tran & Lam, 2024; Benghalia et al., 2025).

With container traffic on the rise, ports need to ensure growth and profitability while reducing their environmental impact. This is particularly relevant in limited space conditions, where it is necessary to optimise traffic flows and use available resources efficiently (Weerasinghe, Perera & Bai, 2024). If ports or terminals do not invest sufficiently in infrastructure—quay deepening, automation, digitization, renewable energy solutions—this limits their ability to accommodate larger ships and serve them efficiently and sustainably. In such cases, downtime, transshipment, or delays not only reduce operational efficiency but also increase the ecological footprint (Kamara et al. 2025; Mohite & Mathew, 2025). Therefore, container flow analysis and forecasting are becoming essential not only for effective logistics process management but also for sustainable development: they enable infrastructure capacity planning, reduce resource waste, ensure smooth intermodal transport, and contribute to green logistics goals (Zhuang, Li, & Xu, 2022).

The study integrates container-flow forecasting with sustainability aspects and investment considerations. In conducting such research, forecasts are typically prepared for a single, specific port in isolation, but comparisons with competitors or neighboring ports are not performed. The novelty of this study lies not only in providing forecasts for three Baltic ports but also in conducting a correlation analysis that reveals the interdependence of Baltic ports; therefore, decisions on sustainability and resilience should be coordinated at the corridor level rather than only at individual ports.

This study aims to assess the growth potential and interdependence trends of container flows in the Baltic ports, taking into account sustainable development pathways driven by investments in innovation, technology, and sustainable growth.

2. Theoretical background

Maritime transport is a crucial sector supporting the global economy, and ports are considered strategic elements of the logistics chain as they play a key role in integrating different goods handling systems (Cocuzza et al., 2025). The interaction between the port and its surrounding environment is particularly significant, as port activities have a direct economic, social, and environmental impact on the city, creating opportunities for development but also challenges related to sustainability and land management. Maritime transport and port activities have both direct and indirect impacts on the environment and local communities (Cocuzza et al., 2025).

Digitalization is becoming a valuable tool for green port transformation, and new routes, such as the Arctic Northern Sea Route, offer strategic opportunities for global supply chains. In addition, new methods such as futures analysis, which helps to manage industry planning, are playing a significant role in container transport forecasting (Su et al., 2024). At the same time, increasing volumes pose challenges in terms of higher CO₂ emissions, but as Hasan, Zhang, and Shi (2023) point out, although total emissions are increasing, emissions per container or ton may be decreasing.

Container terminals usually consist of two main parts – a quay and a storage yard, where loading, unloading, and container storage take place. Quay cranes (STS) start operating as soon as the ship docks, and internal terminal transport vehicles ensure the transfer of containers between the ship and the yard (Vis, de Koster & Savelsbergh, 2005). In order to optimize these processes, modeling and optimization methods are widely used at all decision-making levels (strategic, tactical, operational) (Kim, Lee & Hwang, 2003; Benghalia et al., 2025).

Storage is an integral part of the container transshipment chain, ensuring smooth transport flow management. Upon arrival, containers are registered in the terminal operating system (TOS), where they are assigned an identification code. The TOS system integrates processes, allows monitoring of the location and status of containers, and ensures data transfer (Hervás-Peralta et al., 2019). The port area is usually divided into two zones: temporary storage, where containers are stored for a short period of time, and the main zone, intended for longer storage (Ilesaliev et al., 2019). Information technologies are widely used to increase efficiency: GPS

and RFID allow containers to be tracked in real time (Cimino et al., 2017), TOS optimizes the selection of storage locations (Hervás-Peralta et al., 2019), and automated control systems speed up processes and reduce manual labor (Custodio & Machado, 2020).

Artificial intelligence solutions help to distribute equipment, reduce downtime, congestion, and the risk of accidents (Tsolakis et al., 2022). Scanners and planning programs are also being implemented to prevent errors and speed up processes (Heikkilä, Saarni & Saurama, 2022). Electronic data interchange (EDI) systems improve communication and coordination in the supply chain (Vrbová et al., 2018).

Efficient warehousing is important for saving time and resources. In cases of limited space, stacking containers on top of each other increases the need for additional work and costs, so it is necessary to apply optimized layout methods (Galle, Barnhart & Jaillet, 2018). Automated transport equipment and forklifts are increasingly being used (Hu et al., 2019). With increasing flows, it is necessary to develop effective storage schemes (Abdul Rahman, Ismail & Lun, 2016).

Loading efficiency also depends on the choice of equipment. Rail-mounted gantry cranes and container quay cranes are mainly used at quays (Stoilova & Martinov, 2019), which are widely used in rail and road transport due to their power and versatility (Zhang et al., 2020). Martinov, 2019), which are widely used in rail and road transport due to their power and versatility (Zhang et al., 2020). New hybrid control systems reduce the risk of errors and increase crane productivity (Yavuz & Beller, 2021), while automated cranes help achieve higher levels of efficiency (Jobran & Kara, 2022). Terminals also use a variety of equipment, such as reach stackers, straddle carriers, and automated vehicles (Stoilova & Martinov, 2019). Modern equipment, as noted by Gattuso and Pellicanò (2023), is safe, maneuverable, and reduces the need for workers in hazardous areas. Additional GPS and scanning technologies help to speed up processes (Lee et al., 2021). Automation, including remote control of gantry cranes, is becoming an integral part of modern logistics (Gattuso & Pellicanò, 2023).

Sustainability principles are becoming increasingly important in container logistics operations. The electrification and automation of equipment (Hong et al., 2023) helps to reduce CO₂ emissions, air pollution, and noise levels in the working environment. At the same time, optimized container placement in the storage area reduces the operating time of handling equipment, search time, and energy consumption, thus contributing to the achievement of environmental goals (Kizilay & Eliiyi, 2021).

The planning and development of container terminal operations is closely linked to flow monitoring and forecasting. According to Cocuzza et al. (2025), ports are integral elements of the global logistics chain, and their functioning has a direct impact on the stability of supply chains. Terminal capacities must be aligned with peak container flows, and their forecasts become a key tool in decision-making on infrastructure modernization and investment. Su et al. (2024) note that container transport dynamics are closely linked to changes in the global market, so appropriate forecasting tools allow ports to adapt to changing conditions in a timely manner. The authors emphasize that advanced analytical methods, such as data analysis or artificial intelligence, can help not only to optimize operations but also to identify risks in advance.

3. Research objective and methodology

Primary research objective - to develop and apply a multi-scenario forecast of container handling volumes for Klaipėda, Riga, and Tallinn ports up to 2030, and to analyze the competitive interdependency of these ports to provide a foundational basis for regional strategic planning.

This methodology was chosen to achieve this goal due to its simple, quantifiable and scenario-based forecasts combined with regional market interaction analysis. The CAGR model is a simple, easily transferable method for forecasting future volumes based on historical trends, making it ideal for managerial decision-making. By defining three different scenarios (baseline, optimistic, pessimistic), the study goes beyond a single-point estimate and offers a range of possible outcomes, taking into account market uncertainty and strategic interventions. The inclusion of the Pearson correlation coefficient is very important in multi-port studies, as it confirms or refutes the assumption of a single “Baltic ports” market, providing depth to the strategic analysis.

The object of the study is the container handling volumes of the Baltic ports (Klaipeda, Riga, and Tallinn), which directly reflect the scale of operations, competitiveness, and impact of these container terminals on the region's economy. Container flows are one of the most important indicators for assessing port infrastructure load, labor demand, the need for technology implementation, and environmental impact.

However, factual analysis alone does not provide sufficient information for strategic decision-making. Therefore, particular importance is attached to container handling forecasts, which are essential for the sustainable operation of ports. Forecasts allow for the assessment of possible future scenarios – from optimistic ones, where growth is driven by the expansion of international trade, the introduction of green technologies, and investments in infrastructure, to pessimistic ones, where throughput is limited by geopolitical disruptions, global crises, or supply chain disruptions.

Methodology for Container Throughput Forecasting. To estimate container throughput for Klaipeda, Riga, and Tallinn ports up to 2030, a compound annual growth rate (CAGR) model was applied. This approach allows for projecting future values under three scenarios: baseline, optimistic, and pessimistic.

Calculation of CAGR. This rate expresses the average annual growth over the period. The Compound Annual Growth Rate (CAGR) was calculated using the following formula:

$$CAGR = \left(\frac{V_n}{V_o} \right)^{\frac{1}{n-1}} - 1$$

Where:

V_n - throughput in the final available year (2024).

V_o - throughput in the first year of observation (2005).

n - number of years in the observed period.

Baseline Forecast. For the baseline scenario, the CAGR is applied directly to project future values:

$$Baseline\ Forecast(t) = V_{last} \times (1 + CARG)^t$$

Where t represents the number of years after the last observed year.

Optimistic Forecast. The optimistic forecast assumes faster growth by increasing the CAGR by 20%:

$$Optimistic\ Forecast(t) = V_{last} \times (1 + 1.2 \times CARG)^t$$

This reflects potential expansion due to infrastructure investments, improved logistics efficiency, and stronger trade flows.

Pessimistic Forecast. The pessimistic forecast accounts for slower growth by using half of the historical CAGR:

$$Pessimistic\ Forecast(t) = V_{last} \times (1 + 0.5 \times CARG)^t$$

This scenario represents slower growth due to economic downturns, trade restrictions, or supply chain disruptions.

Pearson correlation analysis is used to quantitatively assess the strength and direction of linear relationships between cargo throughput and external variables, allowing for a more accurate selection of significant factors and the refinement of forecasting models (Wu & Gao, 2023; Zhang et al., 2023).

The Pearson correlation coefficient (r) was used to create the correlation graph (heatmap). It allows us to determine how closely related the data sets are – in this case, the annual container throughput of the Baltic ports (Klaipeda, Riga, and Tallinn). This calculation is necessary for several reasons. Container flows in the Baltic region are heavily dependent on general macroeconomic, geopolitical, and trade trends. Correlation analysis allows us to determine whether changes in flows at one port are related to changes at other ports, i.e., whether there is a regional pattern. This is directly related to sustainability – if port flows move synchronously, investment planning, infrastructure modernization, and the implementation of environmental measures can be coordinated at the regional level. This ensures more efficient use of resources, lower emissions, and better

intermodal transport compatibility. When forecasting container flows, correlation analysis allows risks to be assessed: for example, if one port experiences a shock (economic or political), it is possible to predict the probability that other ports will experience the same impact. This makes it possible to develop resilience measures and strengthen sustainable business continuity across the region.

Pearson Correlation Coefficient (r):

$$r_{xy} = \frac{Cov(X, Y)}{\sigma_X \times \sigma_Y}$$

Where:

X, Y – annual container throughput data (TEU) for two ports (e.g., Klaipėda and Riga).

Cov(X, Y) – covariance between the two datasets, showing how strongly they vary together.

σ_X, σ_Y – standard deviations of each dataset, showing the degree of variability.

Covariance (Cov):

$$Cov(X, Y) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})$$

Where:

x_i, y_i – observed values for a given year (e.g., Klaipėda TEU and Riga TEU).

$\bar{x}, \bar{y}$ – the mean values of each dataset.

n – number of observations (years).

Standard Deviation (σ):

$$\sigma_x = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

The interaction between these two methods enables a comprehensive analysis of cargo flows by combining trend evaluation with interdependencies among variables, thereby increasing forecast accuracy and improving the interpretability of results (Eskafi et al., 2021).

For the analysis, statistical data on container throughput from the ports of Klaipėda, Riga, and Tallinn were used. These data made it possible to assess the operational trends of regional ports and compare cargo handling volumes among the selected ports.

4. Results and discussion

Container flows in ports are unevenly distributed throughout the year – seasonality is determined by production, trade demand, or agricultural cycles, which cause cargo handling intensity to peak at certain times (Farhan & Ong, 2018; Ferrari, Christidis & Bolsi, 2023; Alessandria et al., 2023). Economic booms and busts have a direct impact on export and import volumes, and the unevenness of these fluctuations is reflected in container volumes. Flows are particularly sensitive to global supply chain disruptions: pandemics, shipping blockades, route changes, port closures, or crises such as the temporary suspension of traffic in the Suez Canal (Wan et al., 2023; Tran et al., 2025). All these factors destabilize the entire supply chain and reach the ports of the Baltic countries as volatile changes in container flows. The intensity of container flows in the ports of the Baltic region is closely related to transit cargo. Changes in tariffs, sanctions, or the emergence of alternative routes (via other ports or land transport corridors) directly determine changes in flows (Locaitienė, & Čižiūnienė, 2024; Serry, 2025). Regional competition between the ports of Klaipėda, Riga, and Tallinn encourages competition for the same cargo: when one port invests in dredging, modern loading equipment, or digital systems, container flows can be redirected away from competitors.

Based on the container handling results for 2005–2024 in the ports of Klaipeda, Riga, and Tallinn, optimistic and pessimistic calculations for container handling in ports were made, and the results are presented in the graphs (Figure 1, Figure 2, Figure 3).

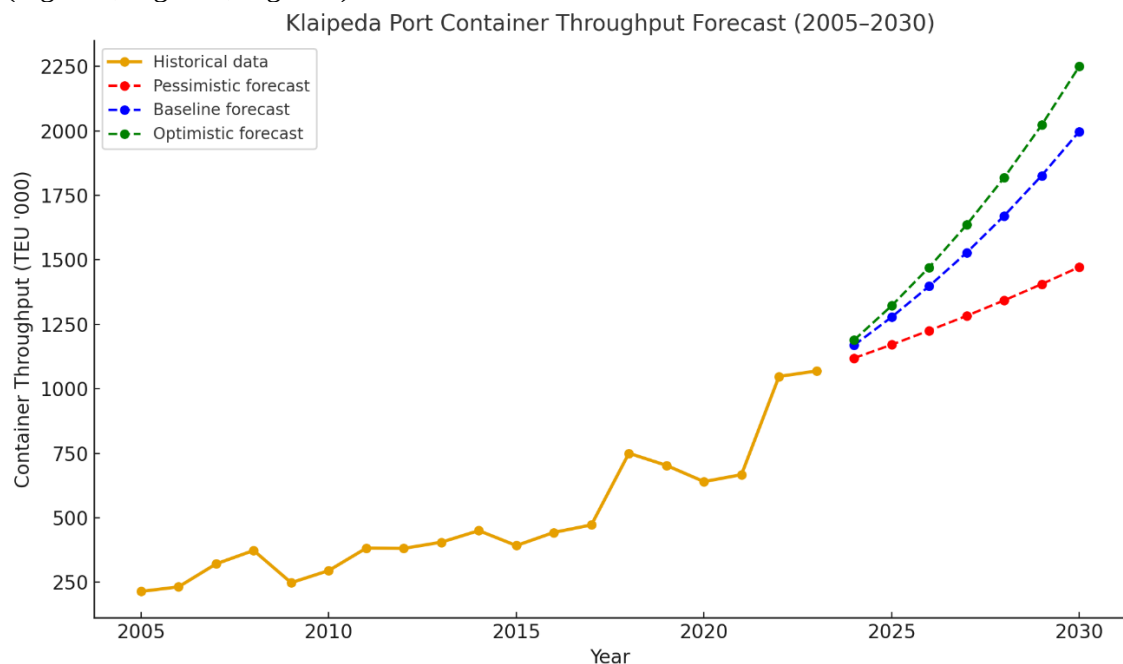


Figure 1. Container flow forecast for the Port of Klaipeda

The Figure 1 shows the dynamics of container handling in the Port of Klaipeda from 2005 to 2023 and forecasts until 2030, distinguishing three possible scenarios: pessimistic, baseline, and optimistic. Analysis of statistical data shows that container handling volumes have grown gradually since 2005, but the growth has been uneven. In 2009, due to the global financial crisis, handling volumes declined, but in subsequent years, container handling at the port stabilized. The period from 2011 to 2017 was marked by stable growth, reaching almost 472,000 TEU. In 2018–2020, there was a rapid jump, with cargo volumes reaching 750,000 TEU, but the impact of the pandemic led to a decline to 640,000 TEU. In recent years, especially in 2022–2023, container handling at the Port of Klaipeda has grown significantly, exceeding the 1 million TEU mark. In recent years, especially in 2022–2023, container handling at the Port of Klaipeda has grown significantly, exceeding the 1 million TEU mark and reaching approximately 1.07 million TEU in 2023.

The forecast chart reveals three forecasts for container handling at the Port of Klaipeda until 2030, which can be assessed in the context of sustainable development. The pessimistic forecast (red line) shows slower growth to approximately 1.5 million TEU. This would mean limited investment in infrastructure, technology, or environmental solutions. In this case, there would be an increased risk that the port would not be able to ensure an efficient logistics process, which would have a negative impact on both economic growth and the environment, as inefficient cargo handling increases energy consumption and emissions. The baseline forecast (blue line), which predicts around 2.0 million TEU by 2030, reflects a balanced scenario. This would demonstrate that the Port of Klaipeda is capable of adapting to global changes, ensuring sustainable growth, and gradually implementing environmental measures such as digitization, automation of cargo handling processes, and the use of renewable energy. This would contribute to strengthening a sustainable transport system and maintaining regional competitiveness. The optimistic forecast (green line), which predicts reaching approximately 2.25 million TEU in 2030, is clearly linked to active investments in "green logistics." This would mean the widespread development of electrification, the strengthening of intermodality, the application of modern digital solutions `xml-ph-0000@deepl.internal`, and the more efficient use of renewable energy sources. This would mean extensive electrification, strengthening intermodality, applying modern digital solutions, and using resources more efficiently. In this case, growth would not only be rapid but also sustainable, as the port would reduce CO₂ emissions, improve energy efficiency, and ensure a competitive advantage in the international market.

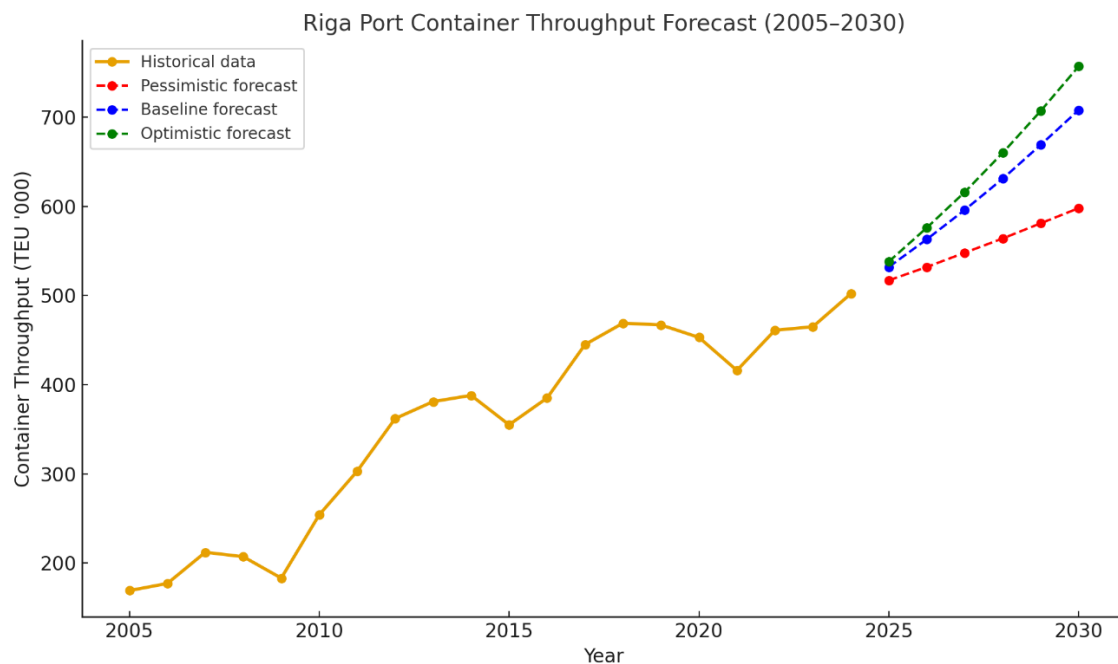


Figure 2. Container traffic forecast for the Port of Riga

The dynamics of container handling at the Port of Riga from 2005 to 2010 showed rather slow growth (Figure 2), and in some years even a decline, which is associated with the impact of the global financial crisis on international trade. The period from 2010 to 2015 was marked by significant growth, with handling exceeding the 400,000 TEU mark. This reflects the recovery after the crisis and the strengthening of regional transit flows. Cargo handling then stabilized, fluctuating between 400,000 and 470,000 TEU, and reaching around 500,000 TEU in recent years. This dynamic shows that the Port of Riga remains competitive, but its sustainability depends on investments in infrastructure, modern technologies, and the application of green logistics principles. A pessimistic baseline and optimistic flow forecast for container handling at the Port of Riga has been made. The pessimistic forecast (red line) shows that by 2030, container handling could reach only around 600,000 TEU. This would be a scenario of limited growth, which could be caused by geopolitical tensions, the diversion of transit cargo to other ports, or insufficient investment in terminal modernization and environmentally friendly solutions. The baseline scenario (blue line) forecasts balanced growth to 700,000 TEU in 2030. This would be a stable development path, based on the assumption that the economic and political environment will remain sufficiently stable and that the port will gradually invest in digital technologies. This would be a stable development path, based on the assumption that the economic and political environment will remain sufficiently stable and that the port will gradually invest in digital technologies, energy efficiency, and environmentally friendly cargo handling systems. In this case, the port's activities would be more in line with the principles of sustainable development. The optimistic forecast (green line) predicts rapid growth – up to approximately 750,000 TEU in 2030. This scenario could be achieved if the Port of Riga successfully implemented a green transformation, invested in electrified cargo handling equipment and smart logistics infrastructure, and developed intermodal transport solutions. In this case, the port would not only increase its competitiveness but also set an example of how sustainable solutions can promote economic growth, reduce CO₂ emissions, and contribute to the development of green logistics in the region.

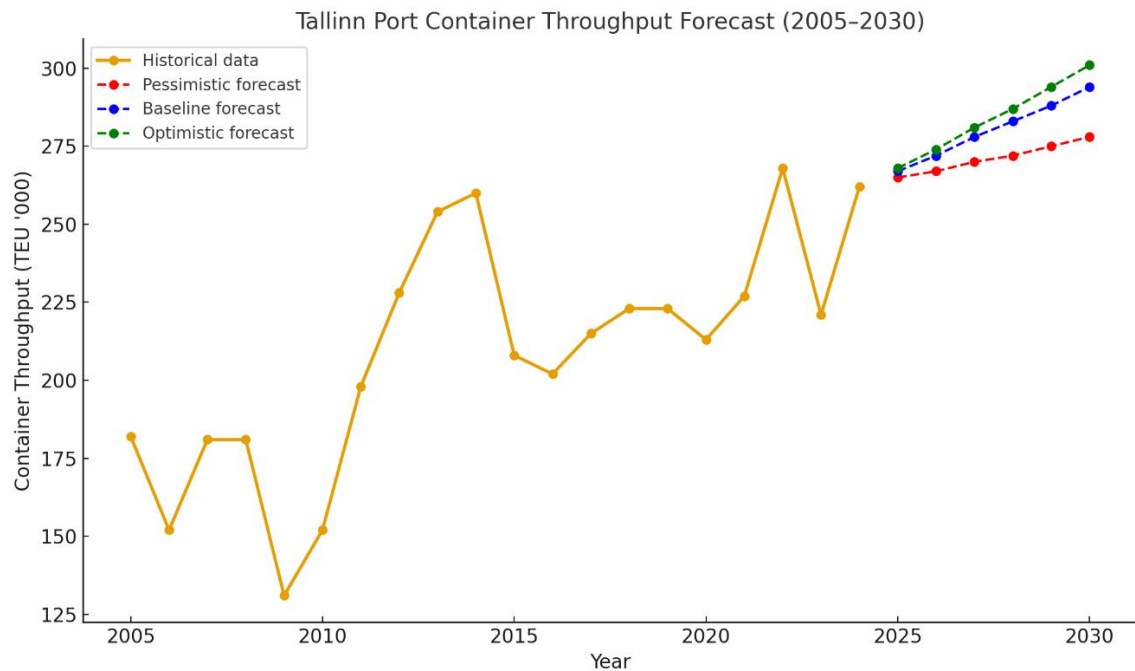


Figure 3. Container flow forecast for the Port of Tallinn

Container flows at the Port of Tallinn (Figure 3) over the past two decades have been characterized by volatility, reflecting the impact of both global and regional economic processes. Between 2005 and 2010, cargo volumes fluctuated significantly and even fell to 130,000 TEU, mainly due to the global financial crisis, which led to a slowdown in international trade. Since 2010, container flows have started to grow, exceeding 250,000 TEU in 2014. However, this growth was not sustainable, and was followed by several downturns reflecting a decline in regional transit cargo, geopolitical disruptions, and competition with neighboring Baltic ports. In recent years, cargo handling has stabilized at around 260,000–270,000 TEU.

The pessimistic forecast (red line) shows that container handling could reach just 280,000 TEU by 2030. This scenario would reflect the negative interaction of economic and geopolitical factors, such as the possible diversion of transit flows to other ports, limited investment in infrastructure, or failure to meet environmental requirements. This situation would have a negative impact on the port's sustainability, as operational efficiency would remain low and environmental modernization would slow down. The baseline scenario (blue line) forecasts moderate but stable growth to approximately 295,000 TEU in 2030. This would be a balanced path of development if the port were able to gradually invest in technological modernization, strengthen intermodality, and adapt to the needs of international trade. This scenario would be in line with sustainable development goals, as it would encompass both economic stability and compliance with environmental standards. The optimistic forecast (green line) shows the possibility of the Port of Tallinn reaching approximately 300,000 TEU by 2030. This scenario would only be feasible if the Port of Tallinn actively implemented green infrastructure, such as electrified handling equipment and expanded green areas. This scenario would only be feasible if the Port of Tallinn actively implemented green infrastructure – electrified cargo handling equipment, expanded intermodal connections, digitized logistics processes, and strengthened environmental monitoring. Such a development path would not only ensure faster cargo growth, but also contribute to long-term sustainability by reducing CO₂ emissions, improving the region's competitiveness, and strengthening Estonia's image as an innovative logistics country.

A comparison of the dynamics and forecasts for container traffic at the ports of Klaipeda, Riga, and Tallinn until 2030 reveals different development trajectories that are closely linked to their sustainability prospects. The port of Klaipeda stands out as the regional leader in terms of container handling growth. Statistical data show a rapid increase, especially after 2018, and forecasts reveal that even in a pessimistic scenario, handling would remain at around 1.5 million TEU by 2030, while in an optimistic scenario it could reach 2.25 million TEU.

This trajectory shows great potential for attracting international flows, but from a sustainability perspective, it also means the need to rapidly implement green technologies. This trajectory shows great potential for attracting international traffic, but from a sustainability perspective, it also means the need to rapidly implement green technologies – electrify equipment, develop intermodality, and ensure that the growing volume of cargo does not increase carbon dioxide emissions. Klaipeda's success can serve as an example of how to combine growth with environmental commitments.

The dynamics of the Port of Riga are more volatile – after rapid growth until 2015, container flows stabilized at around 400-500 thousand TEU. Forecasts show that by 2030, cargo handling could increase from 600,000 TEU (pessimistic scenario) to 750,000 TEU (optimistic scenario). This reveals that Riga's future is highly dependent on transit cargo, regional geopolitical conditions, and investments in terminal modernization. In terms of sustainability, it is particularly important for this port to increase energy efficiency, promote the transition to renewable energy sources, and implement the sustainable electrification of cargo handling equipment so that growth is not achieved at the expense of environmental quality.

The Port of Tallinn has the lowest cargo volume and the greatest fluctuations among the Baltic ports. Its cargo volume has mostly ranged between 200,000 and 270,000 TEU, and forecasts indicate relatively moderate growth: the pessimistic scenario is around 280,000 TEU, while the optimistic scenario is around 300,000 TEU. Although the growth potential here is limited, it provides an opportunity to focus not on quantitative but on qualitative sustainability breakthroughs. Although the growth potential here is limited, this creates opportunities to focus not on quantitative but on qualitative sustainability breakthroughs.

In order to assess how the ports of the Baltic countries operate within the overall logistics system, a correlation analysis was performed between the container flows of the ports of Klaipeda, Riga, and Tallinn, using annual cargo handling figures measured in TEU units for the period 2005–2024 as input data. Basic statistical characteristics were calculated – the mean values and standard deviations for each port, which made it possible to determine the typical volume of flows and how they changed during the period under review. The covariance was calculated for each pair of ports (Klaipeda–Riga, Klaipeda–Tallinn, Riga–Tallinn), showing how changes in the two variables are related to each other. This covariance was normalized by dividing it by the sum of standard deviations, thus obtaining Pearson correlation coefficients, which showed that port container flows are closely related to each other (Figure 4).

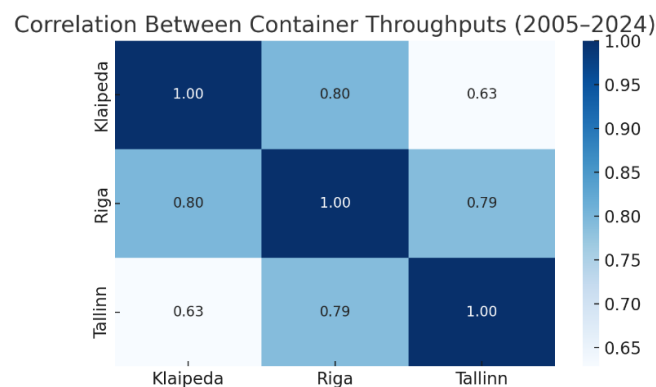


Figure 4. Correlation of container flows

The Figure 4 shows the pairwise Pearson correlation coefficients between container handling in Klaipeda, Riga, and Tallinn in 2005–2024. The value on the diagonal (each port with itself) is 1.00, while Klaipeda–Riga: 0.80, Riga–Tallinn: 0.79, Klaipeda–Tallinn: 0.63. All values obtained are positive, therefore container handling flows at the ports move in the same direction: when one port experiences growth, the other port also records growth in container flows. 0.80 and 0.79 – strong positive correlation (approximately 64% and 62% of the variation in one port is linearly explained by the variation in the other, because $R^2 = \rho^2$). 0.63 – moderate positive correlation (~40% of the variation is explained). The high indicators obtained show a common sensitivity to the same

external factors: global trade cycles (the 2008–2009 crisis, the 2020 pandemic), supply chain disruptions, and geopolitical changes in 2022. The Klaipeda–Tallinn correlation is lower, probably due to different transit dependencies. The surges in container handling at the Port of Klaipeda in 2018 and 2022–2024 were not as pronounced in Tallinn, while the Port of Riga is geographically and functionally located between Klaipeda and Tallinn, so its dynamics are very close to those of its two neighbors. High interdependence means systemic risk: route redistributions or economic downturns simultaneously affect the entire Baltic corridor. This is important from a sustainability perspective, as synchronous peaks increase the risk of congestion, downtime, and additional emissions across the region.

Container handling trends in Baltic ports are directly linked to the principles of sustainable development. The increasing cargo volumes in Klaipeda and Riga show that these ports are using their infrastructure efficiently and investing in modernization, which allows them to optimize energy costs, reduce emissions, and ensure more efficient management of the logistics chain. The projected growth encourages the introduction of more green technologies, such as electrified cargo handling equipment, renewable energy-powered vehicles, and smart terminal management systems. Such solutions help reduce CO₂ emissions per container handled, contributing to the region's climate goals. Meanwhile, the slower growth rate and data volatility of the Port of Tallinn may indicate lower investment in long-term sustainability measures or a more fragmented market. However, it is precisely this result that may serve as an incentive to strengthen sustainability strategies, attract innovative logistics projects, and increase the region's competitiveness in the future.

Conclusions

CAGR analysis shows that between 2005 and 2024, the port of Klaipeda grew the fastest (9.35%), followed by Riga (5.90%) at an average rate, and Tallinn (1.94%) at the slowest rate, which leads to the conclusion that Klaipeda remains the regional leader in terms of growth rate.

The future success of the Port of Klaipeda depends not only on geopolitical and economic factors, but also on strategic decisions to invest in sustainable technologies and logistics innovations that would ensure not only economic growth but also the achievement of environmental goals.

Klaipeda stands out with the highest growth potential, Riga is characterized by moderate growth but is more dependent on transit, and Tallinn, although it has limited potential, is the most suitable for targeted sustainable innovations.

In terms of sustainability, the success of all three ports will depend on how effectively they can balance economic growth aspirations with environmental commitments and social responsibility.

The results of the flow correlation show that there is a very strong positive correlation (close to +1) between the ports of Klaipeda and Riga, which means that changes in cargo handling at these ports usually follow the same direction. The correlation between the ports of Klaipeda and Tallinn is moderately positive – flows in Tallinn move in a similar direction, but less synchronously. The correlation between the ports of Riga and Tallinn is quite strong and positive, indicating that both ports tend to experience similar trends.

References

- Abdul Rahman, N. S. F., Ismail, A., & Lun, V. Y. (2016). Preliminary study on new container stacking/storage system due to space limitations in container yard. *Maritime Business Review*, 1(1), 21-39. <https://doi.org/10.1108/MABR-03-2016-0004>
- Alessandria, G., Khan, S. Y., Khederlarian, A., Mix, C., & Ruhl, K. J. (2023). The aggregate effects of global and local supply chain disruptions: 2020-2022. *Journal of international Economics*, 146, 103788. <https://doi.org/10.1016/j.jinteco.2023.103788>
- Bartosiewicz, A., & Jadczyk, R. (2023). Multi-criteria analysis of the competitiveness of major Baltic Sea container terminals. *Comparative Economic Research*, 26(2), 163-178. <https://doi.org/10.18778/1508-2008.26.18>

Benghalia, A., Ferdjallah, A., Oudani, M., & Boukachour, J. (2025). Machine Learning and Simulation for Efficiency and Sustainability in Container Terminals. *Sustainability*, 17(7), 2927. <https://doi.org/10.3390/su17072927>

Cimino, M. G., Palumbo, F., Vaglini, G., Ferro, E., Celandroni, N., & La Rosa, D. (2017). Evaluating the impact of smart technologies on harbor's logistics via BPMN modeling and simulation. *Information Technology and Management*, 18(3), 223-239. <https://doi.org/10.1007/s10799-016-0266-4>

Cocuzza, E., Ignaccolo, M., Marinacci, C., Ricci, S., Twrdy, E., & Zanne, M. (2025). Sustainable Strategies for Ports and Maritime Logistics: A Methodological Approach to Green Transition. *Sustainability*, 17(13), 5739. <https://doi.org/10.3390/su17135739>

Custodio, L., & Machado, R. (2020). Flexible automated warehouse: a literature review and an innovative framework. *The International Journal of Advanced Manufacturing Technology*, 106, 533-558. <https://doi.org/10.1007/s00170-019-04588-z>

Galle, V., Barnhart, C., & Jaillet, P. (2018). Yard crane scheduling for container storage, retrieval, and relocation. *European Journal of Operational Research*, 271(1), 288-316. <https://doi.org/10.1016/j.ejor.2018.05.007>

Gattuso, D., & Pellicanò, D. S. (2023). Perspectives for ports development, based on automated container handling technologies. *Transportation Research Procedia*, 69, 360-367. <https://doi.org/10.1016/j.trpro.2023.02.183>

Eskafi, M., Kowsari, M., Dastgheib, A., Ulfarsson, G. F., Stefansson, G., Taneja, P., & Thorarinsdottir, R. I. (2021). A model for port throughput forecasting using bayesian estimation. *Maritime economics and logistics*, 23(2), 1-21. <https://doi.org/10.1057/S41278-021-00190-X>

Farhan, J., & Ong, G. P. (2018). Forecasting seasonal container throughput at international ports using SARIMA models. *Maritime Economics & Logistics*, 20(1), 131-148. <https://doi.org/10.1057/mel.2016.13>

Ferrari, E., Christidis, P., & Bolsi, P. (2023). The impact of rising maritime transport costs on international trade: Estimation using a multi-region general equilibrium model. *Transportation Research Interdisciplinary Perspectives*, 22, 100985. <https://doi.org/10.1016/j.trip.2023.100985>

Hasan, K. R., Zhang, W., & Shi, W. (2023). A sustainable port-hinterland container transport system: The simulation-based scenarios for CO2 emission reduction. *Sustainability*, 15(12), 9444. <https://doi.org/10.3390/su15129444>

Heikkilä, M., Saarni, J., & Saurama, A. (2022). Innovation in Smart Ports: Future Directions of Digitalization in Container Ports. *Journal of Marine Science and Engineering*, 10(12), 1925. <https://doi.org/10.3390/jmse10121925>

Hervás-Peralta, M., Poveda-Reyes, S., Molero, G. D., Santarremigia, F. E., & Pastor-Ferrando, J.-P. (2019). Improving the Performance of Dry and Maritime Ports by Increasing Knowledge about the Most Relevant Functionalities of the Terminal Operating System (TOS). *Sustainability*, 11(6), 1648. <https://doi.org/10.3390/su11061648>

Hong, C., Guo, Y., Wang, Y., & Li, T. (2023). The Integrated Scheduling Optimization for Container Handling by Using Driverless Electric Truck in Automated Container Terminal. *Sustainability*, 15(6), 5536. <https://doi.org/10.3390/su15065536>

Ilesaliev, D. I., Abdvakhitov, S. R., Ismatullaev, A. F., & Makhmatkulov, S. G. (2019). Research of the main storage area of the container terminal. *International Journal of Engineering and Advanced Technology (IJEAT)*, 9(1), 4625-4630. <https://doi.org/10.35940/ijeat.A2923.109119>

Jobran, Y., & Kara, G. (2022). Examining the Efficiency of Automation in Container Terminals. *Journal of Transportation and Logistics*, 7(1), 137-155. <https://doi.org/10.26650/JTL.2022.1039692>

Kamara, T. A. R., Souldan, S. M., Paul, D. J., Smith, D., & Smith, V. (2025). Impact of Infrastructure Investment on Port Efficiency: A Case Study of Queen Elizabeth II Quay, Sierra Leone. *Journal of Transportation Technologies*, 15(2), 203-221. <https://doi.org/10.4236/jtts.2025.152011>

Kerbiriou, R. (2024). Modernisation of Container Ship Fleets: State of Play and Consequences for the Baltic Sea. *TransNav, The International Journal on Marine Navigation and Safety of Sea Transportation*, 18(1), 211-217. <https://doi.org/10.12716/1001.18.01.22>

Kim, K. H., Lee, K. M., & Hwang, H. (2003). Sequencing delivery and receiving operations for yard cranes in port container terminals. *International Journal of Production Economics*, 84(3), 283-292. [https://doi.org/10.1016/S0925-5273\(02\)00466-8](https://doi.org/10.1016/S0925-5273(02)00466-8)

Kizilay, D., & Eliyi, D. T. (2021). A comprehensive review of quay crane scheduling, yard operations and integrations thereof in container terminals. *Flexible Services and Manufacturing Journal*, 33(1), 1-42. <https://doi.org/10.1007/s10696-020-09385-5>

Lee, H., Lee, J., An, M., Park, G., & Choi, S. (2021). Machine learning approach to analyze the status of forklift vehicles with irregular movement in a shipyard. *Computers in Industry*, 133, 103544. <https://doi.org/10.1016/j.compind.2021.103544>

Locaitienė, V., & Čižiūnienė, K. (2024). Assessing the Logistics Efficiency of Baltic Region Seaports Through DEA-BCC and Spatial Analysis. *Journal of Marine Science and Engineering*, 13(1), 50. <https://doi.org/10.3390/jmse13010050>

Luo, J., & Wu, Y. (2020). Scheduling of container-handling equipment during the loading process at an automated container terminal. *Computers & Industrial Engineering*, 149, 106848. <https://doi.org/10.1016/j.cie.2020.106848>

Mohite, A. A., & Mathew, E. (2025). Exploring the necessary upgrades in port infrastructure to accommodate and support the operation of the next-generation green ships. *Marine Systems & Ocean Technology*, 20(2), 26. <https://doi.org/10.1007/s40868-025-00171-2>

Serry, A. (2025). From Crisis to Resilience: The Port of Klaipeda and the Reshaping of Baltic Trade Flows (2014-2023). *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, 19. <https://doi.org/10.12716/1001.19.01.16>

Stoilova, S. D., & Martinov, S. V. (2019). Choosing the container handling equipment in a rail-road intermodal terminal through multi-criteria methods. In *IOP Conference Series: Materials Science and Engineering* (Vol. 664, No. 1, p. 012032). IOP Publishing. <https://doi.org/10.1088/1757-899X/664/1/012032>

Su, Z., Liu, Y., Gao, Y., Park, K.-S., & Su, M. (2024). Critical Success Factors for Green Port Transformation Using Digital Technology. *Journal of Marine Science and Engineering*, 12(12), 2128. <https://doi.org/10.3390/jmse12122128>

Tan, C., He, J., & Wang, Y. (2017). Storage yard management based on flexible yard template in container terminal. *Advanced Engineering Informatics*, 34, 101-113. <https://doi.org/10.1016/j.aei.2017.10.003>

Tang, P., Postolache, O. A., Hao, Y., & Zhong, M. (2019). Reefer container monitoring system. In *2019 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE)* (pp. 1-6). IEEE. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8724950&casa_token=mqt3kpUhdFUAAAAA:PxA3Usxt7fk7HybXCyqyS-oOOctlFGIrAubCOIKrfA7AxGXMq-3GwaKuYnjPibKj44Cz-a-ioc4y

Tran, N. K., & Lam, J. S. L. (2024). CO2 emissions in a global container shipping network and policy implications. *Maritime Economics & Logistics*, 26(1), 151-167. <https://doi.org/10.1057/s41278-022-00242-w>

Tran, N. K., Haralambides, H., Notteboom, T., & Cullinane, K. (2025). The costs of maritime supply chain disruptions: The case of the Suez Canal blockage by the 'Ever Given' megaship. *International Journal of Production Economics*, 279, 109464. <https://doi.org/10.1016/j.ijpe.2024.109464>

Tsolakis, N., Zissis, D., Papaefthimiou, S., & Korfiatis, N. (2022). Towards AI driven environmental sustainability: an application of automated logistics in container port terminals. *International Journal of Production Research*, 60(14), 4508-4528. <https://doi.org/10.1080/00207543.2021.1914355>

Vis, I. F., de Koster, R. M. B., & Savelsbergh, M. W. (2005). Minimum vehicle fleet size under time-window constraints at a container terminal. *Transportation Science*, 39(2), 249-260. <https://doi.org/10.1287/trsc.1030.0063>

Vrbová, P., Cempírek, V., Stopková, M., & Bartuška, L. (2018). Various electronic data interchange (EDI) usage options and possible substitution. *NÁŠE MORE: znanstveni časopis za more i pomorstvo*, 65(4 Special issue), 187-191. <https://doi.org/10.17818/NM/2018/4SI.4>

Wan, Z., Su, Y., Li, Z., Zhang, X., Zhang, Q., & Chen, J. (2023). Analysis of the impact of Suez Canal blockage on the global shipping network. *Ocean & Coastal Management*, 245, 106868. <https://doi.org/10.1016/j.ocecoaman.2023.106868>

Weerasinghe, B. A., Perera, H. N., & Bai, X. (2024). Optimizing container terminal operations: a systematic review of operations research applications. *Maritime Economics & Logistics*, 26(2), 307-341. <https://doi.org/10.1057/s41278-023-00254-0>

Wu, W., & Gao, S. (2023). Port container throughput prediction method based on SSA-SVM. *Highlights in Business, Economics and Management*, 12 null, 88-95. <https://doi.org/10.54097/hbem.v12i.8326>

Yavuz, H., & Beller, S. (2021). An intelligent serial connected hybrid control method for gantry cranes. *Mechanical Systems and Signal Processing*, 146, 107011. <https://doi.org/10.1016/j.ymssp.2020.107011>

Zhang, Q., Dong, H., Ling, M., Duan, L., & Wei, Y. (2020). Optimization of gantry cranes' operation path for transshipment based on improved TSP. *Journal of Advanced Transportation*, 2020(1), 9861370. <https://doi.org/10.1155/2020/9861370>

Zhuang, X., Li, W., & Xu, Y. (2022). Port Planning and Sustainable Development Based on Prediction Modelling of Port Throughput: A Case Study of the Deep-Water Dongjiakou Port. *Sustainability*, 14(7), 4276. <https://doi.org/10.3390/su14074276>

Zhang, H., Di, X., & Yang, L. (2023, June). An improvement of Pearson correlation coefficient for variable importance analysis. In *2023 8th International Conference on Computational Intelligence and Applications (ICCIA)* (pp. 83-90). IEEE. <https://doi.org/10.1109/iccia59741.2023.00023>

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