

Article

Resilient Port Operations in Limassol Port, Cyprus: Evaluating the Impact of Global Disruptions on Short Sea Shipping

Georgios Baltatzidis , Michalis Michaelides  and Herodotos Herodotou * 

Department of Electrical Engineering and Computer Science and Engineering, Cyprus University of Technology, 30 Arch. Kyprianou Street, Limassol 3036, Cyprus; ga.baltatzidis@edu.cut.ac.cy (G.B.); michalis.michaelides@cut.ac.cy (M.M.)

* Correspondence: herodotos.herodotou@cut.ac.cy

Abstract

This study examines the operational resilience of Limassol Port, Cyprus's primary maritime hub, amid disruptions caused mainly by the COVID-19 pandemic. Utilizing high-resolution port-level data from 2018 to 2025, we evaluate performance across five key performance indicators: port calls, anchorage utilization, berth utilization, waiting times, and arrival punctuality. The analysis adopts a longitudinal approach, spanning pre-pandemic, peak-pandemic, post-pandemic, and recent phases, while differentiating impacts across vessel categories. Unlike many regional ports, Limassol's cruise sector exhibited unique counter-cyclical growth, with calls doubling during the pandemic as the port transitioned into a strategic safe haven and repositioning base. This surge normalized over the 2024–2025 period as temporary operational disruptions resolved. Conversely, container and Ro-Ro (roll-on/roll-off) segments demonstrated robust stability, achieving rapid post-pandemic normalization, while bulk and tanker operations exhibited higher volatility linked to shifting commodity demands. These findings, validated through one-way analysis of variance (ANOVA) and Cohen's *d* effect sizes, underscore the adaptive capacity of mid-sized Mediterranean hubs. The study concludes that operational flexibility, coupled with enhanced digital coordination and strategic capacity planning, is essential for maintaining the resilience of short sea shipping networks during global crises.

Keywords: port performance; short sea shipping; COVID-19; berth utilization; anchorage utilization; arrival punctuality; operational resilience; sustainable development goals

1. Introduction

Cyprus occupies a pivotal strategic position in the Eastern Mediterranean, serving as a maritime gateway connecting Europe, the Middle East, and North Africa [1]. This geographic advantage deeply integrates the island into European Short Sea Shipping (SSS) networks, positioning its ports, most notably Limassol, as critical nodes for regional trade and maritime connectivity. Consequently, maritime transport serves as a cornerstone of the Cypriot economy, sustaining domestic supply chains, facilitating external trade, and contributing substantially to national economic output [2].

The European Commission defines SSS as the maritime transport of cargo and passengers over relatively short distances between European ports or between the EU and neighboring regions, excluding intercontinental voyages [3]. Within the European policy framework, SSS is a prioritized modality designed to alleviate road congestion, mitigate carbon emissions, and enhance territorial cohesion [4]. For peripheral and island member



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states like Cyprus, these networks are not merely a logistics preference but a fundamental lifeline for economic survival and integration into the Single Market. Critically, these policy objectives are themselves expressions of the United Nations 2030 Agenda for Sustainable Development [5]: by shifting freight from road to sea, SSS advances climate action (SDG 13) and sustainable transport systems (SDG 11), while the resilient port infrastructure that enables it underpins industry and innovation (SDG 9) and the decent work and economic growth (SDG 8) that seaborne trade sustains in island economies. Preserving the operational resilience of such infrastructure against systemic shocks is therefore a direct prerequisite for meeting these sustainability targets.

However, the onset of the COVID-19 pandemic in early 2020 introduced an era of unprecedented disruption to global and intra-European logistics systems. The implementation of mobility restrictions, labor shortages, and stringent health protocols precipitated a wave of service suspensions, schedule instability, and port congestion [6–8]. SSS networks were particularly vulnerable to these shocks due to their reliance on high-frequency operations and rapid vessel turnaround times. Despite EU-level emergency interventions, such as the Green Lanes initiative aimed at preserving essential freight flows, port performance deteriorated across the continent, exposing systemic vulnerabilities in maritime infrastructure and highlighting the need for deeper empirical analysis of port-level resilience [9–12].

The purpose of this article is to empirically assess the impact of the COVID-19 pandemic on the operational performance of Limassol Port, Cyprus' principal maritime hub. Specifically, this study seeks to answer the following research question: How did the specific operational role and vessel mix of a mid-sized Mediterranean hub influence its disruption-response and recovery trajectory relative to broader regional trends? Using granular, official port-level data from 2018 to 2025, the study evaluates performance across five key performance indicators (KPIs), namely, port calls, anchorage and berth utilization, waiting times, and punctuality, spanning pre-pandemic, peak-pandemic, post-pandemic, and recent phases. By framing the analysis within a disruption-response-recovery perspective, this research offers three primary contributions to the field.

1. It provides a rare longitudinal case study of a short sea shipping hub that served as a safe haven, offering a counter-narrative to the standard passenger-sector collapse observed globally.
2. It quantifies the heterogeneous effects of the pandemic across diverse vessel categories, identifying which segments drove resilience versus those that mirrored global volatility.
3. The study advances the empirical understanding of port resilience by correlating fluctuations in operational KPIs with specific policy and maritime shifts, providing a data-driven framework for capacity planning in the face of future global supply chain shocks.

This paper is organized as follows. Section 2 presents related work and Section 3 outlines the research methodology. Sections 4 and 5 present and discuss the findings, respectively. Section 6 offers policy recommendations and future work. Finally, Section 7 concludes the paper.

2. Related Work

The COVID-19 pandemic caused unprecedented disruptions to European port operations and short sea shipping. In 2020, EU ports recorded approximately 10% fewer ship calls than in 2019, with the most severe effects observed in the passenger and Ro-Ro ferry segments. Cruise ship port calls virtually collapsed, declining by around 85% over the year, and by over 90% during the second quarter, while Ro-Pax (roll-on/roll-off passenger) services fell by 19% annually, with peak reductions reaching 36% during lockdown periods [13,14]. Passenger volumes at European ports dropped by nearly 80%, reflecting the

suspension of cruise and ferry operations under travel restrictions [15]. This collapse was particularly pronounced in the Mediterranean basin: across the Spanish Mediterranean port cities of Barcelona, Valencia, Málaga, Palma de Mallorca, Alicante, Almería, and Tarragona, cruise passenger traffic practically disappeared in 2020, with reduction rates exceeding 90% relative to the 2019 peak [16]. By contrast, freight flows demonstrated relative resilience: container shipping in major EU ports experienced only modest throughput contractions, despite blank sailings, supply–demand shocks, and operational disruptions. Nevertheless, pandemic-related labor shortages, health measures, and equipment disruptions led to increased congestion and longer dwell times across many ports [17].

Globally, maritime supply chains faced severe bottlenecks as vessel backlogs accumulated and capacities were strained [18]. European ports largely avoided total shutdowns, but the crisis highlighted the vulnerability of maritime logistics. Short sea shipping emerged as a critical mechanism for sustaining intra-European trade, allowing ports to retain cargo traffic when other modes or long-haul routes were disrupted [19]. To mitigate the pandemic’s impact, the European Commission introduced “Green Lanes” to expedite border crossings and issued guidelines facilitating seafarer mobility and crew changes, designating seafarers as key workers [18,20]. Port authorities implemented complementary measures, including enhanced sanitary protocols, financial relief, and extended storage periods [17,21]. Over time, coordination improved through EU contingency planning, information sharing via the European Maritime Safety Agency (EMSA), and guidance from industry bodies, maintaining essential cargo flows and avoiding a collapse of short sea trade lanes [18,22].

The pandemic accelerated the adoption of digital coordination tools, highlighting the importance of port resilience. Port Community Systems, Single Windows, and Port Collaborative Decision Making enabled real-time sharing of port call information, while emerging technologies such as blockchain and virtual inspections reduced physical contact and improved operational efficiency [15,23]. Studies emphasize that ports with strong governance and adaptive capacities fared better, sustaining throughput and minimizing congestion [22]. Collectively, these developments demonstrate that agility, digitalization, and short sea alternatives are essential for mitigating systemic shocks and enhancing the robustness of European port operations [18].

A growing body of literature has employed quantitative methods to analyze the impact of COVID-19 on port performance and vessel behavior, frequently utilizing Automatic Identification System (AIS) data as a primary source. For instance, Millefiori et al. [24] used AIS to map traffic density fluctuations in the Mediterranean, revealing a total collapse in passenger vessel movements, in contrast to a more mixed impact on cargo sectors. Similarly, Wang et al. [25] derived vessel anchoring and berthing durations from AIS data in China’s Beibu Gulf, observing that tankers experienced significantly more disruption than traditional cargo ships. In the Oslo port area, an AIS-based behavioral analysis identified abnormal ship patterns, confirming that passenger vessels were more severely affected by pandemic restrictions than cargo vessels [26].

Beyond regional studies, AIS data have been instrumental in estimating the incidence of port call cancellations along the Europe–Far East corridor, highlighting non-trivial effects correlated with vessel size [27]. Furthermore, Kim et al. [28] leveraged AIS datasets to measure congestion across 19 major container hubs and examined how port-specific characteristics and local events influenced operational delays. However, while AIS provides high-frequency spatial insights, it is often hampered by significant rates of missing or erroneous data, vulnerability to intentional manipulation, and substantial computational requirements. In contrast, the present study uses official port-call records from the Cyprus Ports Authority (CPA). These sources are best seen as complementary: AIS provides cross-port breadth, whereas verified administrative records provide event-accurate depth, with

arrival, berthing, and departure times logged directly rather than inferred. By exploiting this depth, the present study delivers a resilience assessment of a port type (mid-sized, multipurpose) and an operational role (safe haven) that the predominantly AIS-based literature has not captured.

3. Methodology

Situated in the Eastern Mediterranean, the island nation of Cyprus occupies a strategically vital position as a member state of the European Union (Figure 1), with the Port of Limassol, located on the island's southern coast, serving as the country's primary maritime hub. An analysis of 19,962 port calls recorded between 2018 and 2025 demonstrates Limassol's extensive global connectivity, encompassing 606 unique ports across 98 countries. Macro-level geographic traffic distributions and localized Eastern Mediterranean maritime patterns for this eight-year period are illustrated in Figure 2a and Figure 2b, respectively. Reflecting its regional centrality, 70.8% of Limassol's total traffic is concentrated within the Eastern Mediterranean. On a national level, the port's principal trading partners are Greece (24.4%), Israel (20.2%), Egypt (14.2%), and Lebanon (8.0%). Furthermore, domestic traffic to other Cypriot ports, such as Larnaca and Zygi, accounts for 14.3% of total volume, while connections with Western Mediterranean nations, including Italy and Spain, account for 10.4%.

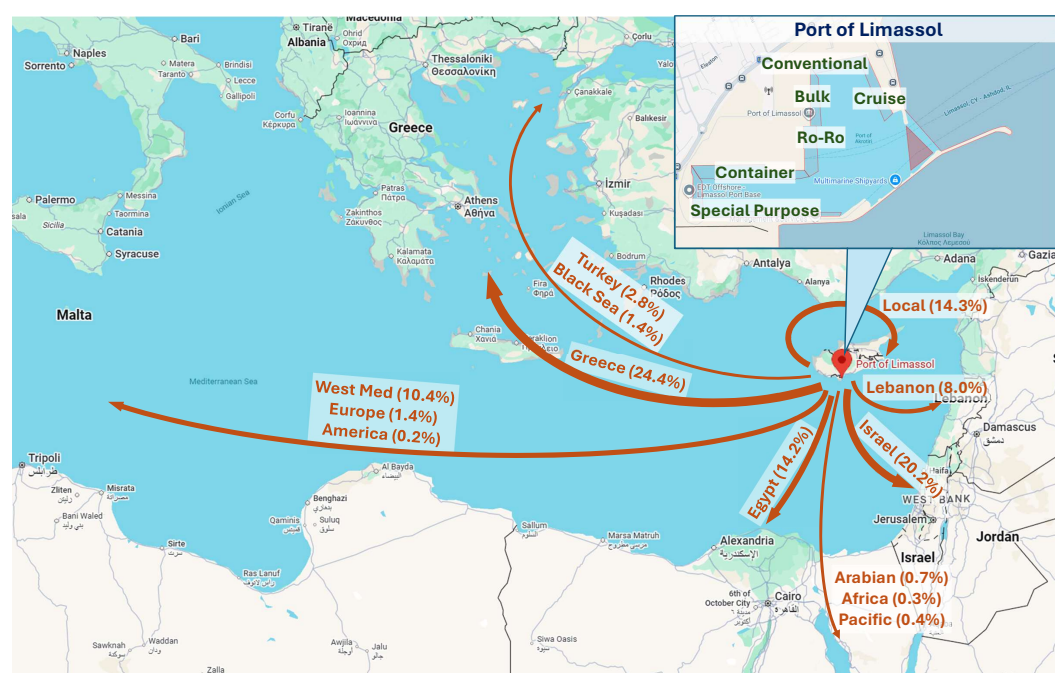


Figure 1. Eastern Mediterranean regional map detailing the spatial distribution of primary maritime traffic, with vectors pointing to key partner nations and trading regions. A zoomed-in layout of the Port of Limassol displays the localized berth orientations and boundaries, along with the main vessel categories served by each berth.

Administratively, the Port of Limassol operates under a landlord-port model following its privatization in 2017. The Cyprus Ports Authority (CPA) retains regulatory oversight, while commercial operations are divided into independent concessions among private entities, primarily Eurogate Container Terminal (handling container logistics) and DP World Limassol (managing multi-purpose and cruise terminals) [12]. Underpinning this decentralized management structure is an integrated Port Community System (PCS) that operates on top of terminal operating systems (TOS). PCS serves as a central digital node that coordinates data among shipping lines, customs officials, port operators, and freight

forwarders. This digital infrastructure facilitates vessel tracking and customs clearances, laying the groundwork for the adaptive, data-driven maritime management frameworks evaluated in this study.

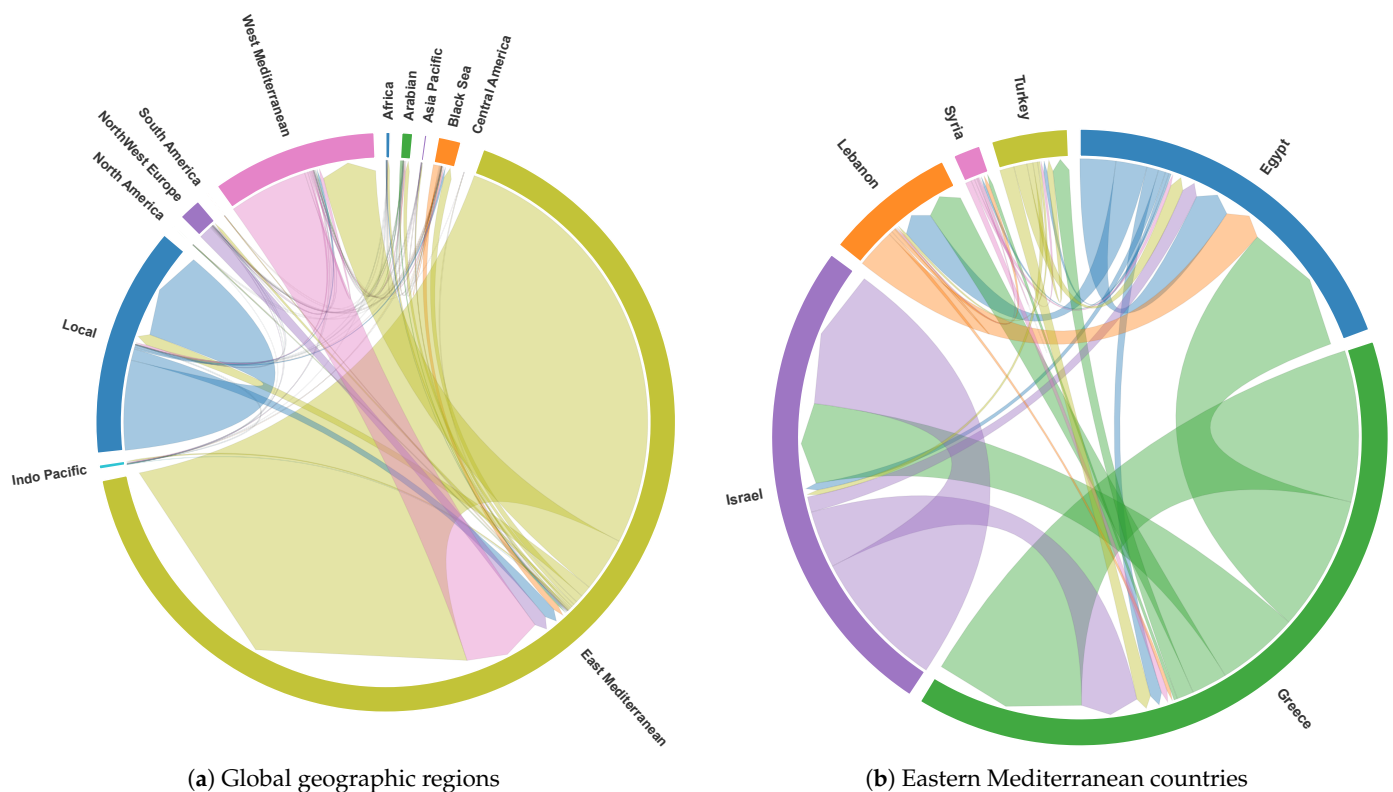


Figure 2. Chord diagrams illustrating the bilateral distribution of maritime traffic volumes (2018–2025): (a) Macro-level directional traffic flows interconnected across global geographic regions; (b) Micro-level port-to-port maritime connectivity patterns specifically within the Eastern Mediterranean region. The width of the connecting chords corresponds to the total volume of traffic shared between the respective nodes. The width of the connecting chords corresponds to the total volume of traffic shared between the respective nodes. Colors serve only to distinguish individual regions and ports and carry no additional meaning.

Port call data from 2018 to 2025 was obtained from PCS, recording vessel arrivals, berthing, unberthing, anchorage, and departures, ensuring a comprehensive dataset of Limassol Port operations. The data are analyzed across four periods: pre-pandemic (2018–2019), peak-pandemic (2020–2021), post-pandemic (2022–2023), and recent (2024–2025). The study hypothesizes that the COVID-19 pandemic produced measurable disruptions, with variation across maritime segments according to demand elasticity. Discretionary traffic (e.g., cruise ships, project cargo) is expected to experience deeper and more prolonged reductions, whereas essential supply chains are expected to remain relatively resilient. Expected operational effects include: increased anchorage utilization due to inspections and crew-change constraints; deteriorated berth-side performance, indicated by longer waiting times, reduced punctuality, and atypical berth utilization; and reduced port call volumes, with recovery patterns mediated by segment-specific elasticity.

The study evaluates operational performance using five key performance indicators (KPIs): port calls, anchorage utilization, berth utilization, berth waiting, and arrival punctuality, which collectively capture throughput, congestion, and schedule reliability [12]. The KPIs are defined using the following timestamp variables: Estimated Time of Arrival (ETA), Actual Time of Arrival (ATA), Actual Time of Berthing (ATB), Actual Time of Unberthing

(ATUB), and Actual Time of Departure (ATD). These abbreviations are defined once here and used consistently in the formulas below.

1. Port Calls (PC): number of fully recorded vessel visits, including the recorded date and time of arrival, berthing, unberthing, and departure.
2. Anchorage Utilization (AU): percentage of total port time spent at anchorage.

$$AU = \frac{\text{Time at Anchorage}}{\text{ATD} - \text{ATA}} \times 100, \quad (1)$$

3. Berth Utilization (BU): percentage of total port time spent moored at berth.

$$BU = \frac{\text{ATUB} - \text{ATB}}{\text{ATD} - \text{ATA}} \times 100, \quad (2)$$

4. Berth Waiting (BW): percentage of vessels delayed more than 60 min before berthing.

$$BW = \frac{\text{Count of port calls with } (\text{ATB} - \text{ATA}) > 60 \text{ min}}{\text{Total port calls}} \times 100, \quad (3)$$

5. Arrival Punctuality (AP): share of vessels arriving within ± 30 min of their estimated time of arrival.

$$AP = \frac{\text{Count of port calls with } |\text{ATA} - \text{ETA}| < 30 \text{ min}}{\text{Total port calls}} \times 100. \quad (4)$$

Together, these five KPIs provide a comprehensive framework for assessing port performance under disruption. High anchorage or berth waiting, low berth utilization, reduced port call frequency, or poor punctuality indicate operational inefficiencies, particularly during crisis periods such as the COVID-19 pandemic. One-way Analysis of Variance (ANOVA) tests were applied to each KPI to identify statistically significant differences across the pre-pandemic, pandemic, post-pandemic, and recent periods for each vessel type. ANOVA was selected because the KPIs are continuous, and it can compare means across multiple groups. It should be noted that one-way ANOVA isolates differences across periods and vessel categories but does not control for concurrent external drivers such as market demand, seasonal cycles, or geopolitical shocks; therefore, the results characterize the magnitude and direction of period-associated change rather than establishing causation. In addition to statistical significance testing, Cohen's *d* was calculated to assess the practical magnitude of the observed differences between periods, allowing statistically significant results to be interpreted in terms of effect size as well as *p*-values. Statistical analyses (one-way ANOVA and Cohen's *d*) were performed using Microsoft Excel (Microsoft 365, Microsoft Corporation, Redmond, WA, USA).

For the purposes of this study, vessel traffic at Limassol Port is classified according to the International Maritime Organization (IMO) definitions [29], which cover more than 95% of all port calls. Minor vessel types, including refrigerated cargo vessels, fishing boats, and dredgers, are excluded because of their negligible contribution to overall operations. The vessel categories used are:

- Bulk—vessel carrying unpackaged dry cargo in bulk (e.g., grains, coal, ore, cement).
- Container—ship designed to transport standardized intermodal containers measured in twenty-foot and forty-foot equivalent units (TEUs and FEUs).
- Conventional—general cargo vessel transporting non-containerized or project cargo, often multipurpose.
- Cruise/Passenger—large cruise ship or ferry (excluding ro-pax vessels).

- Ro-Ro—roll-on/roll-off vessel, including ro-pax vessels, carrying wheeled cargo and passengers.
- Special Purpose—vessel constructed or modified for non-commercial purposes, such as scientific research, subsea operations, or specialized equipment transport.
- Tanker—ship transporting liquid cargoes in bulk, including oil, chemical, and product tankers.

As illustrated in Figure 1, the Limassol Port infrastructure comprises seven functional berthing quays, managed through a multi-operator framework [30]. The two southernmost quays are administered directly by CPA and are dedicated primarily to auxiliary and special-purpose vessels. Commercial container operations are concentrated at the Eurogate Container Terminal, which manages the port's longest continuous quay (800 m). This terminal specializes in container ship handling and is supported by five ship-to-shore (STS) quay cranes. The remaining four berthing quays are operated by DP World Limassol and are segregated by vessel cargo categories: one quay is specifically configured for Ro-Ro vessels, one serves as a dedicated passenger terminal for cruise liners, and the final two accommodate conventional cargo and bulk vessels. Marine services across all terminals, including pilotage, towage, and anchorage support, are centrally provided by P&O Maritime Cyprus to ensure safe navigation and port maneuverability.

To contextualize the scale of Limassol's maritime infrastructure within the broader European port network, its key technical indicators (KTIs) can be benchmarked against both regional Mediterranean hubs and major European gateways (Table 1; data collected for 2024 from Eurostat [31]). With an annual container throughput of approximately 400,000 TEUs and a maximum operational draft of 16 m at its specialized container quay, Limassol functions primarily as a vital regional gateway and domestic feeder node rather than a high-volume transshipment hub. In comparison, prominent Eastern Mediterranean transshipment hubs like Piraeus handle roughly 4.7 million TEUs annually, while Tier-1 European mega-ports like Rotterdam process over 13 million TEUs annually, with drafts exceeding 22 m. This positioning highlights Limassol's specific strategic profile: it is highly connected relative to its local market size, serving as a crucial regional terminal rather than a high-capacity transshipment hub.

Table 1. Comparison of Limassol Port's key technical indicators (container volume, gross weight of goods, and maximum draft) against regional Mediterranean hubs and major European ports.

Port	Country	Container Volume (Million TEU)	Gross Weight (Million Tonnes)	Max Draft (m)
Limassol	Cyprus	0.4	2.6	16.0
Valletta	Malta	0.1	2.7	15.0
Piraeus	Greece	4.7	43.7	18.5
Lisboa	Portugal	0.5	10.2	17.1
Genova	Italy	2.8	47.4	15.0
Barcelona	Spain	3.9	55.5	23.2
Hamburg	Germany	7.8	97.0	16.1
Rotterdam	Netherlands	13.3	397.3	22.5

4. Results

Limassol Port operations from 2018 to 2025 are analyzed to assess the effects of the global disruptions on key performance indicators. Port calls, anchorage and berth utilization, berth waiting, and arrival punctuality are examined across vessel types, with statistical tests applied to identify significant changes and distinguish pandemic-induced disruptions from normal operational variability.

4.1. Port Calls

An analysis of port calls at Limassol from 2018 to 2025 reveals highly heterogeneous impacts of the COVID-19 pandemic and subsequent recovery phases across maritime segments. While certain categories experienced pronounced contractions aligned with global trends, others demonstrated a unique resilience or rapid post-pandemic stabilization, as shown in Figure 3.

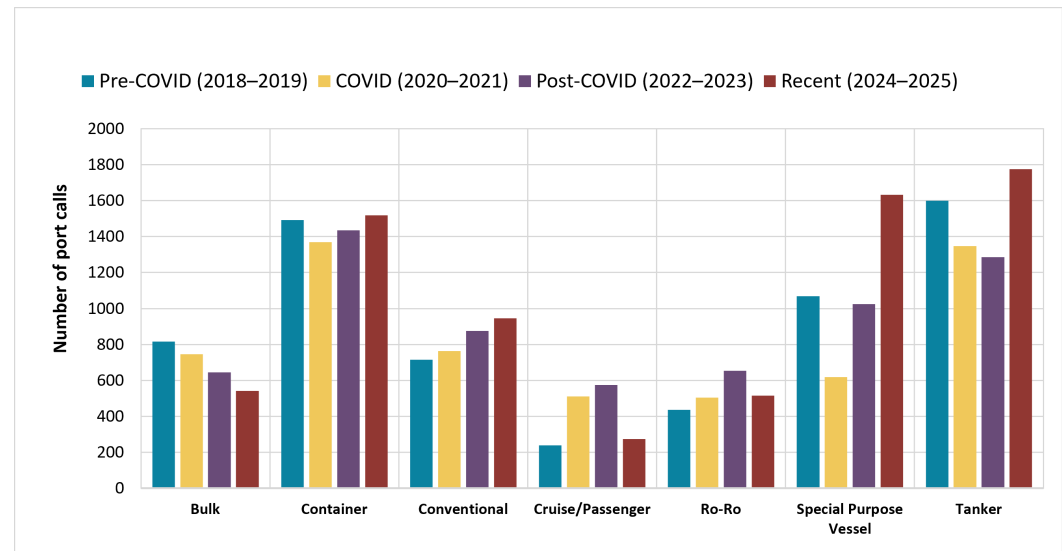


Figure 3. Port calls by vessel type and period at Limassol Port.

Bulk carriers exhibited a sustained downward trend across all study periods. Port calls declined from a pre-pandemic baseline of 816 to 745 during the peak-pandemic period (−8.7%), falling further to 645 post-pandemic (−13.4%). Although initial disruptions were mitigated by the continued flow of essential commodities [11], the subsequent decline reflects broader industrial slowdowns and the geopolitical volatility introduced by the Russia–Ukraine conflict and the Israel– Hamas (Gaza) War [32]. The downward trajectory persisted into the normalization period, with calls falling a further 16.1% to 541, leaving the segment 33.7% below its pre-pandemic baseline.

In contrast, container vessels followed a “U-shaped” recovery trajectory. Port calls shifted from 1492 pre-COVID to 1368 during the pandemic (−8.3%) before rebounding to 1434 post-pandemic (+4.8%). The initial downturn in 2020–2021 was a direct consequence of global schedule disruptions and equipment imbalances [33,34], while the 2023 resurgence aligns with the normalization of liner services and a broader recovery in global container trade [35]. In 2024–2025, the segment edged past its pre-pandemic baseline for the first time (1519 calls, +5.9% over the post-pandemic period), completing the U-shaped recovery.

Conventional (general cargo) vessels displayed a consistent upward trend, effectively acting as a buffer for the port. Port calls rose from 715 pre-COVID to 763 during the pandemic (+6.7%), reaching 875 post-pandemic, a 22.4% increase over the baseline. This surge likely reflects the diversion of cargo from constrained container liners to multipurpose vessels during periods of peak logistical friction [33]. The expansion continued through the normalization period (945 calls, +8.0%), bringing the cumulative increase to 32.2% over the pre-COVID baseline and indicating structural rather than transitory growth.

Cruise and passenger vessels followed a trajectory distinct from the global collapse of the tourism sector. Despite widespread regional closures, calls in Limassol actually rose from 128 in 2019 to 145 in 2020 (+13.3%) as the port served as a critical lay-up and repositioning base. Following the implementation of mass vaccination protocols [36], calls surged by 152% in 2021 to 365 calls and continued to grow by an additional 12.7% post-

pandemic. Overall, Limassol successfully leveraged its geographic position to capture displaced cruise traffic, transforming a period of global crisis into a local growth driver. In the recent period, cruise and passenger calls receded to 273 (−52.5% versus 2022–2023), indicating that the safe haven and repositioning surge was a temporary, crisis-specific role rather than a permanent gain in scheduled passenger traffic. The Gaza War in the region may have also contributed to the reduced passenger traffic [37].

Ro-Ro operations remained remarkably stable initially, with a negligible dip in 2020 (214 calls) followed by a sharp increase to 290 in 2021. This growth coincided with the strategic resumption of the Cyprus–Greece ferry link [38], suggesting that renewed ferry connectivity may have contributed to the strengthening of this segment. By the post-pandemic period, Ro-Ro calls averaged 326 per year, representing a 49.4% increase over pre-pandemic levels and signaling a permanent expansion of this segment. The 2024–2025 data temper this interpretation, however: calls moderated to 516 in total (−21.0% versus the post-pandemic period, an average of 258 per year), suggesting a partial normalization of the segment after the post-pandemic surge, while still remaining above the pre-COVID average.

Special-purpose vessels experienced the most severe volatility, collapsing by 42.1% during the pandemic (falling from 534 to 309 calls) due to the suspension of offshore energy projects [34]. However, this sector rebounded sharply post-pandemic (+65.7% over pandemic lows), reflecting the cyclical nature of subsea operations and regional regulatory shifts [39]. This momentum intensified markedly during the recent period, when special-purpose calls climbed to 1632 (+59.4% versus 2022–2023), with 1104 calls recorded in 2025 alone, a development that coincided with the expansion of regional offshore energy and subsea survey activity.

Finally, tankers experienced a protracted decline, resulting in a 29% reduction between 2018 and 2022. This mirrored the 9% global contraction in fuel demand observed in 2020 [40]. Although a 10.7% recovery was recorded in 2023 (675 calls), the segment remained 21.4% below its 2018 baseline, highlighting a slower recovery path for energy-related maritime traffic. The normalization period reversed this trend decisively: tanker calls rose to 1774 (+38.1% versus 2022–2023), with the 1017 calls recorded in 2025 exceeding even the 2018 level, a pattern consistent with the reorientation of regional energy flows rather than with residual pandemic effects.

Taken together, aggregate traffic in the normalization period reached 7200 study-category calls, 13.1% above the pre-COVID baseline (6367) and 10.9% above the post-pandemic period (6491), confirming that the port's overall throughput not only recovered but expanded, albeit with a markedly different segment composition: growth was driven by tanker, special-purpose, conventional, and container traffic, while bulk, Ro-Ro, and cruise activity receded from their respective post-pandemic levels.

4.2. Anchorage Utilization

Average anchorage utilization by vessel type and period is illustrated in Figure 4, with alphabetical notation indicating statistically significant differences ($p < 0.05$) across the pre-COVID, COVID, post-COVID and recent phases.

Bulk carriers exhibited a marginal but steady increase in anchorage utilization, rising from 37.8% pre-COVID to 39.5% during the pandemic, and reaching 41.7% in the post-COVID period. However, a one-way ANOVA across the three periods revealed no statistically significant differences at the 5% level, suggesting that these shifts represent a directional trend rather than a statistically conclusive structural change. The corresponding effect sizes are likewise negligible (Cohen's $d \leq 0.06$ between consecutive periods), reinforcing that this rise is small in practical magnitude. Operationally, this gradual rise likely reflects infrastructure constraints and episodic demand surges for dry bulk com-

modities during the global recovery phase, as supply chain backlogs accumulated. In the normalization period, however, the trend accelerated into a statistically conclusive shift: utilization climbed to 53.4% ($p < 0.0001$, Cohen's $d = 0.30$, a small effect), the first practically detectable change for this segment and an indication that bulk anchorage congestion has intensified beyond pandemic-era levels.

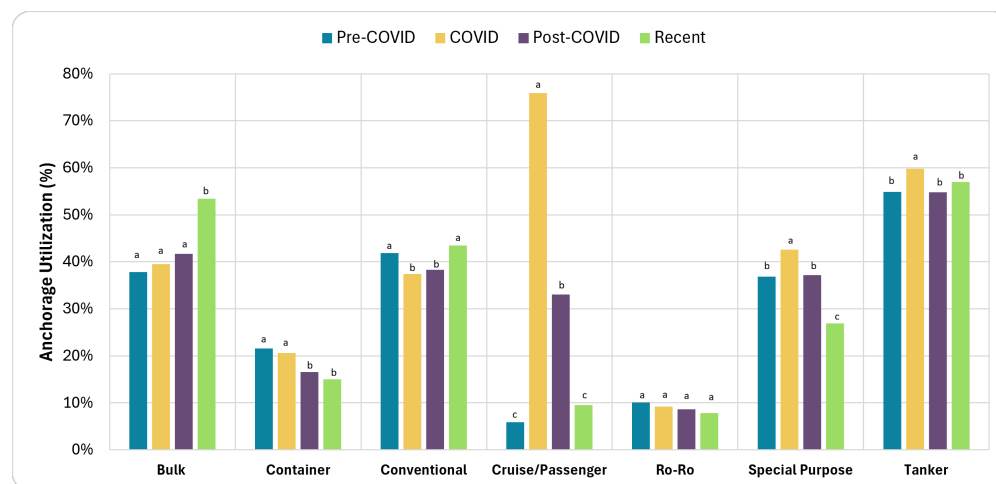


Figure 4. Anchorage utilization by vessel type and period at Limassol Port. Different letters denote statistically significant differences according to one-way ANOVA ($\alpha = 0.05$). For each vessel type, periods sharing a letter are not significantly different at $\alpha = 0.05$.

In contrast, container vessels demonstrated a clear and sustained reduction in anchorage occupancy, declining from 21.57% pre-COVID to 16.54% post-COVID (a 23.3% reduction relative to the baseline). A one-way ANOVA comparing the COVID and post-COVID periods confirms a statistically significant difference ($p < 0.0001$), though the associated effect size is small (Cohen's $d = 0.15$), indicating that the operational improvement, while reliable, is modest in practical magnitude. This trend suggests that the post-pandemic era has been characterized by optimized berth planning, enhanced arrival management, and superior synchronization between feeder and mainline services. These gains were consolidated during 2024–2025, with utilization easing further to 15.0%; the difference from the post-COVID period is not statistically significant ($p = 0.088$, Cohen's $d = 0.06$, negligible), indicating that the efficiency improvements have stabilized as the segment's new operational baseline.

Conventional (general cargo) vessels experienced moderate variability, with anchorage use peaking pre-pandemic before declining to a low of 35.3% in 2021 and stabilizing at 36.9% by 2023. A one-way ANOVA indicates a statistically significant difference between the pre-COVID and COVID periods ($p = 0.0127$), though the effect size is negligible (Cohen's $d = 0.13$), and no significant difference was observed between the COVID and post-COVID phases ($p = 0.55$). This pattern suggests that anchorage volatility in this segment is driven primarily by episodic break-bulk and project-cargo campaigns rather than by a persistent pandemic-induced effect. In the normalization period, utilization rose to 43.5%, a statistically significant increase over the post-COVID phase ($p = 0.0006$), although the associated effect size remains small (Cohen's $d = 0.16$). The rise is therefore consistent with the episodic, campaign-driven character of this segment rather than with a structural deterioration.

Cruise and passenger vessels exhibited the most dramatic fluctuations. Utilization surged from a 5.9% baseline to 75.9% during the pandemic (+1187%), before receding to 33.1% post-COVID. One-way ANOVA confirms statistically significant differences across all periods ($p \approx 0$), with large effect sizes quantifying the magnitude of disruption (Cohen's

$d = 2.00$ for the pre-COVID-to-COVID transition; $d = 1.01$ for the COVID-to-post-COVID recovery), confirming that the pandemic necessitated unprecedented offshore idling for health clearances and vessel repositioning. The normalization period completed this reversion: utilization fell to 9.5%, approaching the pre-pandemic baseline, with the decline from the post-COVID period both statistically significant ($p < 0.0001$) and of medium practical magnitude (Cohen's $d = 0.62$); the largest post-pandemic effect size observed across all segments. This confirms that the elevated anchorage occupancy of 2020–2023 was a crisis-specific phenomenon tied to the port's safe haven role rather than a lasting operational shift.

Ro-Ro vessels maintained the lowest anchorage utilization of all categories, fluctuating narrowly between 7.7% and 10.7%. One-way ANOVA results across the three periods showed no statistically significant differences, and the corresponding effect sizes are uniformly negligible (Cohen's $d \leq 0.10$), confirming that the high-frequency nature and rapid turnaround times characteristic of Ro-Ro operations remained resilient to pandemic-era anchorage congestion. This stability persisted through 2024–2025 (7.8%; $p = 0.28$, $d = 0.06$, negligible), extending the segment's record of insulation from anchorage congestion across all four study periods.

Special-purpose vessels similarly showed significant sensitivity to the crisis, with anchorage use rising to 42.5% during the pandemic (+15.4%) before returning to pre-pandemic levels (37.2%). ANOVA results identified significant differences between pre-COVID/COVID ($p = 0.0067$) and COVID/post-COVID ($p = 0.0169$) phases, although the effect sizes in both cases are negligible (Cohen's $d \leq 0.14$), indicating that pandemic-related offshore project suspensions were statistically detectable but small in practical terms. Notably, despite the sharp expansion of special-purpose traffic during 2024–2025, anchorage utilization declined markedly to 26.9% ($p < 0.0001$, $d = 0.25$, a small effect), suggesting that the port absorbed the surge in offshore-energy-related calls without generating anchorage congestion.

Tankers consistently recorded the highest anchorage utilization, peaking at 63.1% in 2020. Average utilization rose from 54.9% pre-COVID to 59.8% during the pandemic, before normalizing to 54.8% post-COVID. Statistically significant differences between the pre-COVID/COVID ($p = 0.0012$) and COVID/post-COVID ($p = 0.0017$) periods reflect the substantial disruptions to global fuel demand and the subsequent stabilization of energy trades, though the effect sizes in both cases are negligible (Cohen's $d \leq 0.12$), suggesting that the disruption was statistically reliable but limited in operational magnitude. In the normalization period, tanker utilization edged up to 57.0%, remaining the highest of all segments; the change from the post-COVID phase is not statistically significant ($p = 0.135$, $d = 0.06$, negligible), indicating that the strong growth in tanker call volumes during 2024–2025 was accommodated without a meaningful deterioration in anchorage performance.

Overall, aggregate anchorage utilization across all vessel types peaked at 40.5% in 2020 and declined steadily to 32.7% by 2023. This trajectory confirms a period of pronounced pandemic-induced congestion followed by a systematic stabilization of port operations. However, the recovery was non-uniform: while the container and cruise segments achieved marked efficiency gains by 2023, bulk and conventional cargo vessels continue to exhibit elevated or volatile utilization, suggesting that specific trade-related bottlenecks persist in the post-pandemic landscape. The 2024–2025 data sharpen this divergence: aggregate utilization averaged 34.1%, broadly in line with 2023, but beneath this stability, the cruise, container, and special-purpose segments recorded further efficiency gains while bulk and conventional anchorage occupancy rose significantly, confirming that the residual bottlenecks are concentrated in the dry-cargo trades rather than distributed across the port.

4.3. Berth Utilization

Average berth utilization by vessel type and period is summarized in Figure 5, with notation indicating statistically significant differences ($p < 0.05$) across the four study periods.

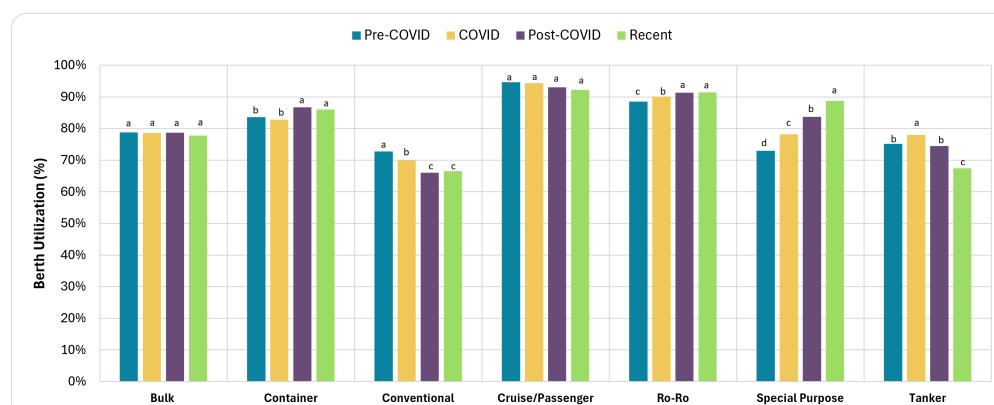


Figure 5. Berth utilization by vessel type and period at Limassol Port. Different letters denote statistically significant differences according to one-way ANOVA ($\alpha = 0.05$). For each vessel type, periods sharing a letter are not significantly different at $\alpha = 0.05$.

Bulk vessel berth utilization remained remarkably constant across all periods, fluctuating minimally between 78.5% and 78.8%. A one-way ANOVA confirms the absence of statistically significant differences ($p = 0.979$), indicating a high degree of structural stability in the bulk segment, a finding corroborated by uniformly negligible Cohen's d values across all period pairs (Cohen's $d \leq 0.01$). While a minor annual dip to 75.6% was observed in 2021, likely reflecting transitory disruptions in global commodity flows, the subsequent recovery by 2023 underscores the port's regional role as a consistent bulk hub. However, utilization levels consistently near 80% suggest that the segment may be approaching its practical capacity limits. The 2024–2025 period confirms this structural stability: berth utilization averaged 77.7%, with no statistically significant change from the post-COVID level ($p = 0.523$, Cohen's $d = 0.04$, negligible), and the four-period ANOVA remains non-significant ($p = 0.886$).

Container vessel berth utilization initially dipped from 83.6% pre-COVID to 82.7% during the pandemic, then rose significantly to 86.7% post-COVID (+4.8%). ANOVA results indicate that while the pre-COVID to COVID shift was not statistically significant ($p = 0.24$, Cohen's $d = 0.04$, negligible), the post-pandemic increase was highly significant ($p < 0.0001$), though the associated effect size is small (Cohen's $d = 0.21$), indicating that the recovery, while reliable, was moderate in practical magnitude. This trajectory reflects a robust recovery in box volumes and improved adherence to berth windows. Sustained utilization above 85% typically signals proximity to saturation, where operational efficiency becomes increasingly dependent on crane gang allocation, yard turnover, and gate flow synchronization. These high levels were maintained in 2024–2025, with berth utilization averaging 86.0%; the change from the post-COVID period is not statistically significant ($p = 0.257$, Cohen's $d = 0.04$, negligible), confirming that the post-pandemic efficiency gains have stabilized as the segment's operational ceiling.

Conventional (general cargo) vessels showed a steady, statistically significant decline in berth utilization, falling from 72.7% pre-COVID to 69.9% during the pandemic ($p = 0.047$, Cohen's $d = 0.10$, negligible) and further to 66.1% post-COVID ($p = 0.0045$, Cohen's $d = 0.14$, negligible). Although each successive step was significant, the consistently negligible effect sizes confirm that the changes were modest in practical terms; the cumulative pre-COVID-to-post-COVID shift yields a small effect (Cohen's $d = 0.24$), suggesting a gradual structural adjustment in Limassol's cargo mix, potentially favoring containerized

or Ro-Ro modalities as project-based break-bulk activities faced pandemic-related postponements. In 2024–2025, berth utilization stabilized at 66.6%, virtually identical to the post-COVID level ($p = 0.701$, Cohen's $d = 0.02$, negligible), indicating that the structural recalibration of this segment has reached a new steady state.

Cruise and passenger berth utilization remained the highest of all segments, averaging 94% throughout the study period and peaking at 98% in 2020. This peak was driven by extended vessel lay-ups during global cruise suspensions. Despite visual fluctuations, ANOVA indicates no statistically significant difference across periods, a finding reinforced by uniformly negligible Cohen's d values across all period pairs ($|d| \leq 0.12$), suggesting a consistently high baseline of berth occupancy for the passenger terminal. The 2024–2025 data extend this pattern: berth utilization averaged 92.2%, and the four-period ANOVA remains non-significant ($p = 0.220$, Cohen's $d = 0.05$ vs post-COVID, negligible), confirming that the passenger terminal has maintained its structurally high occupancy rate regardless of the fluctuations in call volumes documented in earlier sections.

Ro-Ro berth utilization rose significantly from 88.5% pre-pandemic to 91.4% post-pandemic. ANOVA confirms that both the increase during the pandemic ($p = 0.0146$, Cohen's $d = 0.16$, negligible) and the post-pandemic surge ($p = 0.0232$, Cohen's $d = 0.13$, negligible) are statistically significant, though the effect sizes in both cases are negligible, indicating that the upward trend was consistent but incremental rather than dramatic. The cumulative pre-to-post-COVID shift yields a small effect (Cohen's $d = 0.28$). This trend highlights the extreme resilience of the Ro-Ro sector and its close proximity to operational capacity, further bolstered by the 2022 reintroduction of the Cyprus–Greece maritime link [38]. In 2024–2025, Ro-Ro berth utilization held at 91.5%, essentially unchanged from the post-COVID level ($p = 0.837$, Cohen's $d = 0.01$, negligible), extending the segment's record of progressive tightening now approaching a structural ceiling.

Special-purpose vessels experienced a substantial and statistically significant increase in berth occupancy, rising from 73.0% pre-COVID to 78.2% during COVID to 83.7% post-COVID (ANOVA: $p = 0.0024$, Cohen's $d = 0.15$, negligible; and $p = 0.0006$, Cohen's $d = 0.17$, negligible, respectively). The cumulative pre-to-post-COVID shift is small ($d = 0.33$), reflecting a sustained but gradual intensification of project-driven demand within the regional offshore energy and subsea survey sectors. This upward trend continued into 2024–2025, with berth utilization reaching 88.7% ($p < 0.0001$, Cohen's $d = 0.19$, negligible), the highest level recorded across all periods and vessel types combined. The four-period ANOVA is highly significant ($F = 64.0$, $p < 0.001$), and the cumulative pre-COVID-to-recent effect reaches medium magnitude ($d = 0.54$), confirming that the expansion of offshore-energy-related activity has produced a structurally higher berth occupancy profile for this segment.

Tanker berth utilization rose from 75.1% to 77.9% during the pandemic, then receded to 74.5% post-COVID. ANOVA confirms the significance of both the pandemic-era increase ($p = 0.0155$, Cohen's $d = 0.09$, negligible) and the subsequent post-COVID decline ($p = 0.004$, Cohen's $d = 0.11$, negligible); in both cases the effect sizes are negligible, indicating that the fluctuations were statistically detectable but of limited operational significance. These shifts indicate that tanker berth occupancy has largely reverted to its pre-pandemic baseline, with 2023 figures reflecting broader market volatility and regional fuel flow adjustments. The 2024–2025 period marks a more pronounced departure: berth utilization fell to 67.5%, a statistically significant and practically meaningful decline from the post-COVID level ($p < 0.0001$, Cohen's $d = 0.21$, small). This is the first practically detectable shift for the tanker segment and, at 67.5%, the lowest berth utilization recorded for tankers across the entire study window, warranting further investigation into whether

this reflects structural changes in regional energy trade routing or a transient adjustment in vessel scheduling patterns.

Aggregate berth utilization across all vessel types fluctuated only marginally, ranging from 80.9% to 82.0% across the three periods. This remarkable consistency suggests that Limassol Port's internal service efficiency and berth throughput remained largely insulated from the pandemic's external volatility. While the "buffer" for global disruptions was largely absorbed by the anchorage areas (as discussed in Section 4.2), the terminal's core berthing operations maintained a high and stable level of productivity throughout the crisis and recovery phases. In 2024–2025, aggregate berth utilization averaged approximately 80.3%, broadly consistent with the prior three periods. Beneath this aggregate stability, however, the segment-level picture has sharpened: special-purpose vessel berth utilization reached a study-high of 88.7%, tanker berth utilization fell to a study-low of 67.5%, and all other categories remained near their post-COVID baselines. This divergence suggests that the port's aggregate resilience now masks increasingly differentiated capacity pressures across its cargo segments.

4.4. Berth Waiting

The berth waiting KPI, defined as the percentage of vessels waiting more than 60 min to berth, is illustrated in Figure 6. To determine whether observed fluctuations represented statistically meaningful shifts, a one-way ANOVA at a 5% significance level was performed on the raw waiting durations (in minutes) for each vessel call across the pre-COVID, COVID, post-COVID, and the recent 2024–2025 normalization period.

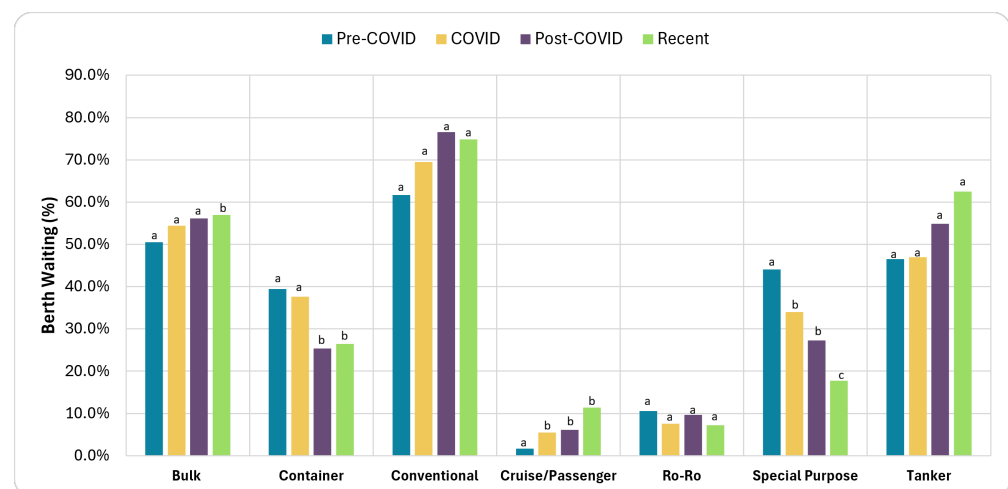


Figure 6. Berth waiting by vessel type and period at Limassol Port. Different letters denote statistically significant differences according to one-way ANOVA ($\alpha = 0.05$). For each vessel type, periods sharing a letter are not significantly different at $\alpha = 0.05$.

Bulk vessels experienced a marginal increase in the percentage of ships waiting, rising from 50.5% pre-COVID to 56.1% post-pandemic. Despite this upward trajectory, the ANOVA results indicated no statistically significant differences in actual waiting times, with effect sizes confirming negligible practical differences across periods (Cohen's $d \leq 0.05$), suggesting that bulk operations maintained a relatively stable, albeit high, baseline of waiting frequency. In 2024–2025, the proportion edged further to 56.9%, while the mean waiting duration increased from 993 to 1419 min—a shift that, for the first time, reached statistical significance (post-COVID vs. 2024–2025: $p = 0.0006$; Cohen's $d = 0.20$, small effect). This indicates that while the incidence of waiting remained similar, the duration of individual waiting episodes lengthened notably in the recent period.

In contrast, the container segment demonstrated a significant improvement in throughput efficiency. The proportion of vessels waiting more than 60 min declined from 39.4% pre-pandemic to 25.4% in the post-COVID era. This 35.6% reduction relative to the baseline was confirmed as statistically significant by the ANOVA ($p = 0.0003$); however, Cohen's $d = 0.14$ indicated a small effect size in raw waiting durations, underscoring that the improvement manifested primarily in the reduction in waiting incidence rather than large changes in mean waiting time. This trend reflects a successful post-pandemic recalibration of terminal operations, likely driven by improved berth window management and reduced schedule volatility. In 2024–2025, container berth waiting stabilised at 26.5%, essentially matching the post-COVID level. Although the ANOVA detected a statistically significant difference between COVID and 2024–2025 ($p = 0.0066$), the negligible effect size ($d = 0.10$) confirms that the operational efficiency gains established in the post-COVID era were sustained throughout the normalization period.

Conventional (break-bulk) cargo exhibited the highest waiting frequency, increasing steadily from 61.7% to 76.6% over the study period. However, these changes were not statistically significant, suggesting that the long waiting times in this segment are a structural characteristic of break-bulk complexity, such as specialized handling requirements, rather than a direct consequence of pandemic-induced systemic failure. The 2024–2025 period showed a marginal improvement to 74.8%, though the difference from the post-COVID phase remained statistically non-significant ($p = 0.055$; Cohen's $d = 0.09$), further underscoring the structural nature of high waiting frequency in this segment.

Cruise and passenger vessels, which historically enjoy high priority and minimal waiting (1.7% baseline), saw a notable peak of 7.7% in 2021. The ANOVA comparison between pre-COVID and COVID periods confirmed this shift as statistically significant ($p = 0.028$), though Cohen's $d = 0.17$ revealed a small effect size in raw waiting durations, consistent with the extreme variance inherent to this vessel type, underscoring the severe operational friction caused by pandemic-era health protocols and the port's role as a temporary lay-up base. The 2024–2025 period recorded a further rise to 11.4%, reflecting the strong rebound in cruise activity and increased port congestion during turnaround operations. The change from the post-COVID level was not statistically significant ($p = 0.145$; Cohen's $d = 0.12$), suggesting that the elevated waiting rate is consistent with increased cruise traffic volumes rather than a systemic deterioration.

Special-purpose vessels showed a paradoxical trend: while the percentage of vessels waiting dropped from 44.0% to 27.2%, the ANOVA indicated a statistically significant difference ($p = 0.0356$) between the pre-COVID and COVID periods. This was largely influenced by high-variance outliers, vessels with unusually long waiting times, which suggest that while fewer specialized ships waited, those that did were subject to significant project-related or regulatory delays. The negligible effect size (Cohen's $d = 0.14$) corroborates this interpretation, as the extreme variance driven by such outliers dilutes the measurable practical impact despite the statistically significant between-group difference. The improvement accelerated in 2024–2025, with the proportion of waiting vessels falling further to 17.7%. This decline was statistically significant relative to the post-COVID period ($p = 0.012$; $d = 0.10$), while the negligible effect size points to a systematic normalization of project scheduling and port coordination rather than a structural shift in vessel handling.

The Ro-Ro and tanker segments remained largely unaffected by the pandemic in terms of berth waiting times. Ro-Ro waiting fluctuated narrowly between 7.5% and 10.5%, while tankers saw a non-significant rise from 46.5% pre-pandemic to 54.9% post-pandemic. In both cases, ANOVA results confirmed that the observed variability fell within the range of normal operational fluctuations, with all consecutive period comparisons yielding negligible effect sizes (Cohen's $d \leq 0.12$). In 2024–2025, Ro-Ro waiting remained stable at

7.2% (post-COVID vs. 2024–2025: $p = 0.213$; $d = 0.07$), while tankers recorded a further, non-significant rise to 62.5% ($p = 0.920$; $d < 0.01$). Both segments continued to operate within their historical range of variability.

A disaggregated view of waiting intervals (Figure 7) reveals that the vast majority of vessels (84.9–87.2%) berthed within 24 hours of arrival. Only a small fraction (5.8–7.3%) experienced delays exceeding three days, a distribution that remained remarkably consistent across the years. Analysis of 2024–2025 vessel records confirms that this distribution pattern was maintained during the normalization period, with no significant structural change in the proportion of extreme waiting episodes.

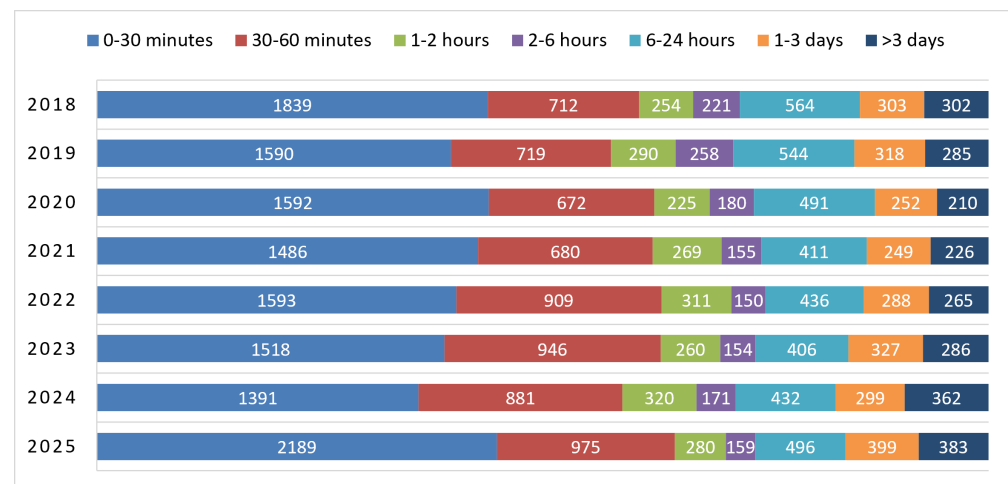


Figure 7. Distribution of berth waiting times (in minutes) by interval.

These trends reflect a successful mitigation of the 2020–2021 global shipping crisis, during which international maritime trade contracted by 3.8% [6]. Limassol's ability to implement continuity measures facilitated a rapid recovery, as evidenced by a 63% increase in cargo tonnage and a 338% surge in cruise passenger volumes in 2022–2023 compared to 2021. The 2024–2025 data reinforces this trajectory: container efficiency gains have been preserved, special purpose vessels waiting has continued its downward trend, and bulk and tanker segments remain structurally stable, collectively indicating a port transitioning toward a mature operational equilibrium. Ultimately, the data suggests that while COVID-19 introduced temporary friction, the port's current waiting patterns are increasingly dictated by structural shifts toward containerization and regional project-driven activities.

4.5. Arrival Punctuality

The arrival punctuality KPI, defined as the percentage of vessels arriving within 30 min of their Estimated Time of Arrival (ETA), is presented in Figure 8. To evaluate the statistical significance of these trends, a one-way ANOVA at a 5% significance level was conducted on the absolute deviation (in minutes) between actual and scheduled arrival times for each vessel call across the four study periods.

For the majority of cargo-carrying segments (i.e., bulk, container, and conventional), arrival punctuality remained statistically stable despite the global supply chain turmoil, with negligible Cohen's d values throughout ($d \leq 0.07$). Bulk vessel punctuality declined from 51.5% pre-COVID to 45.9% post-pandemic, while container vessel punctuality increased slightly to 58.7% during the pandemic, then normalized at 56.1%. Similarly, conventional cargo vessels fluctuated between 38.6% and 43.1%. In all three cases, ANOVA results indicated no statistically significant differences, suggesting that the observed year-to-year variations remained within the bounds of normal operational noise. In 2024–2025, bulk arrival punctuality fell further to 35.3%, with the mean deviation rising sharply to 124.0 min.

This deterioration was statistically significant relative to the post-COVID period ($p = 0.016$; Cohen's $d = 0.14$, negligible), reflecting increased scheduling uncertainty as bulk demand normalized at elevated post-pandemic volumes. Container punctuality also declined to 49.8% (mean deviation 94.7 min), a shift confirmed as significant against the post-COVID benchmark ($p = 0.003$; Cohen's $d = 0.11$, negligible). Despite statistical detection, the negligible effect sizes in both segments underscore that the deterioration represents a gradual drift toward pre-pandemic scheduling variability rather than a structural breakdown. Conventional cargo remained unchanged at 37.0%, with all pairwise comparisons non-significant ($p = 0.308$; $d = 0.05$).

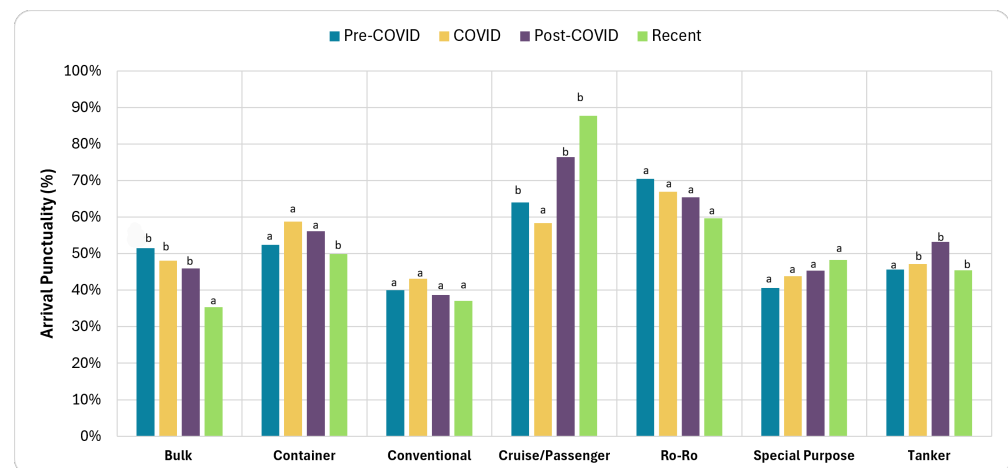


Figure 8. Arrival punctuality by vessel type and period at Limassol Port. Different letters denote statistically significant differences according to one-way ANOVA ($\alpha = 0.05$). For each vessel type, periods sharing a letter are not significantly different at $\alpha = 0.05$.

In contrast, cruise and passenger vessels exhibited highly significant fluctuations ($p < 0.05$). Punctuality in this segment dropped to 58.3% during the pandemic, a direct result of stringent health protocols and irregular “safe haven” call patterns, before surging to a study-high of 76.4% post-pandemic (+31.1%). Cohen's d values of 0.24 (pre-COVID vs. COVID) and 0.28 (COVID vs. post-COVID) confirmed these as small but practically meaningful effects, corroborating that the cruise disruption and subsequent recovery were genuine operational shifts rather than large-sample artifacts. This rapid improvement reflects both the normalization of the cruise industry and the implementation of more robust scheduling protocols in Limassol. In 2024–2025, cruise punctuality rose further to a new study high of 87.7% (mean deviation 27.3 min), marginally above the post-COVID level and statistically indistinguishable from it ($p = 0.699$; Cohen's $d = 0.03$). This continued improvement, while not statistically distinct from post-COVID in pairwise terms, confirms an enduring upward trajectory in cruise scheduling precision, sustaining the pattern that distinguishes COVID as the sole disrupted period ($p < 0.000001$, 4-period ANOVA).

Ro-Ro vessels maintained a high, albeit slightly declining, arrival punctuality rate, moving from 70.5% pre-COVID to 65.4% post-COVID. Special-purpose vessels showed a moderate increase from 40.5% to 45.3% over the same period. For both segments, ANOVA identified no statistically significant shifts, and effect sizes were negligible for all pairwise comparisons (Cohen's $d \leq 0.03$), indicating that their arrival reliability was not fundamentally altered by the pandemic's disruptions. In 2024–2025, Ro-Ro punctuality declined further to 59.7% (mean deviation 56.2 min), a borderline-significant change from post-COVID ($p = 0.052$; Cohen's $d = 0.11$) that fell just short of the 5% threshold. The overall 4-period ANOVA remained non-significant ($p = 0.199$), suggesting the trend is emerging but not yet statistically established. Special-purpose vessels continued their

gradual improvement to 48.2% ($p = 0.519$ vs. post-COVID; $d = 0.03$), with all four periods statistically indistinguishable ($p = 0.924$, 4-period ANOVA), consistent with a structurally stable, project-driven call pattern.

The tanker segment demonstrated a statistically significant improvement ($p < 0.0001$). Arrival punctuality rose from a 45.6% baseline to 53.2% in the post-pandemic period, a 16.7% increase over the 2018–2019 levels. While Cohen’s d indicated negligible effect sizes in raw arrival deviation minutes (pre-COVID vs. COVID: $d = 0.14$; COVID vs. post-COVID: $d = 0.07$), the improvement was statistically robust owing to the large tanker call volume; the practical gain in scheduling discipline was more evident in the binary on-time metric than in mean deviation minutes. This suggests that while tanker volumes were volatile (as discussed in Section 4.1), the remaining calls were executed with higher temporal precision, potentially due to reduced congestion and more structured terminal windows. In 2024–2025, tanker punctuality stood at 45.4% (mean deviation 60.2 min), essentially matching the pre-COVID level in percentage terms, yet remaining statistically indistinguishable from the post-COVID period in raw deviation minutes ($p = 0.383$; Cohen’s $d = 0.03$). The 4-period ANOVA confirms that tankers continue to differ significantly from their pre-pandemic baseline ($p < 0.001$), with COVID, post-COVID, and 2024–2025, all forming a statistically homogeneous cluster that is significantly better than the pre-COVID era in arrival deviation, even as the binary on-time rate has partially reverted.

While the primary KPI strictly defines “on-time” as a ± 30 min window, a disaggregated view of arrival deviations (Figure 9) provides a more nuanced picture of port reliability. A significant proportion of vessels fall within the 30–120 minute delay bands; while technically non-punctual by the 30 min metric, these represent manageable operational delays rather than systemic failures. Notably, the share of ships arriving more than two hours late actually declined from 15.3% pre-COVID to 13.4% post-COVID. This suggests that while strict punctuality is difficult to maintain under recovering demand, the incidence of severe delays has decreased. The analysis of 2024–2025 records indicates that this distribution remained broadly stable during the normalization period, with no significant structural change in the share of severe delays, consistent with the findings for most segments in the 4-period ANOVA. Overall, these results demonstrate that Limassol Port successfully managed the transition from fewer, highly structured calls during the pandemic to a more high-volume, normalized environment, with only the passenger and energy sectors showing statistically permanent shifts in arrival behavior. The 2024–2025 data further reveals a divergence in trajectories: cruise punctuality has continued to reach new highs, reflecting mature post-pandemic scheduling, while bulk and container segments show signs of increasing scheduling pressure as trade volumes recover.

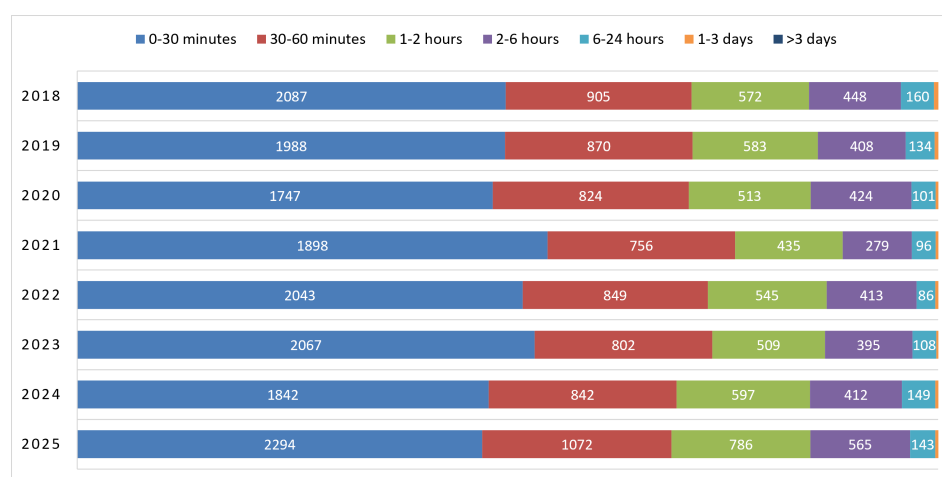


Figure 9. Distribution of arrival deviation times (in minutes) by interval.

5. Discussion

The findings of this study reveal that Limassol Port demonstrated greater resilience than broader European trends. While UNCTAD (United Nations Conference on Trade and Development) [41] noted a 14% global downturn in calls by mid-2020 and EMSA [14] reported an average 5% decline across the EU in 2020, Limassol experienced a total reduction in port calls of 6.8% between 2019 and 2020. While this figure is slightly higher than the EU aggregate, it is significantly lower than the 20% contractions observed in other Mediterranean nations such as Croatia and Spain [42]. This suggests that Limassol's diversified maritime activities partially insulated the hub from the traffic collapses seen elsewhere.

This relative resilience can be benchmarked port-by-port using harmonized vessel-call data rather than qualitative comparison alone (Table 2). Within the container segment, where Limassol recorded an 8.3% contraction in calls during the peak-pandemic period, several Mediterranean ports fared considerably worse on the same metric: Marsaxlokk (Malta) lost 31.9% of container vessel calls between 2018 and 2020, Port Said 24.5%, and Genoa 15.9%, while Barcelona lost approximately 9% of ship calls (11% of volume) and Marseille collapsed by 53.5% in 2020 alone [42]. Piraeus, the largest container hub of the Eastern Mediterranean, registered a comparatively modest decline of 3.8%, consistent with the documented resilience advantage of the very largest hubs [42,43]. Limassol's container trajectory therefore sits at the favorable end of the Mediterranean distribution, closer to that of the major transshipment gateways than to that of comparable mid-sized ports, which declined by approximately 10% on average [43].

Table 2. Quantitative comparison of pandemic-period traffic changes at Limassol Port and selected European comparators. Reference periods and metrics vary across sources (vessel calls, throughput, or passenger volumes). The 'Change' column indicates the relative magnitude and direction of the disruption.

Port/Region	Segment and Metric	Change (Period)	Source
Limassol (Cyprus)	Total port calls	−6.8% (2019–2020)	This study
Limassol (Cyprus)	Container vessel calls	−8.3% (COVID vs. pre-COVID)	This study
Limassol (Cyprus)	Cruise/passenger calls	+13.3% (2020); +152% (2021)	This study
Piraeus (Greece)	Container traffic	−3.8% (2020)	Fedi et al. (2022) [42]
Marsaxlokk (Malta)	Container vessel calls	−31.9% (2018–2020)	Fedi et al. (2022) [42]
Port Said (Egypt)	Container vessel calls	−24.5% (2018–2020)	Fedi et al. (2022) [42]
Barcelona (Spain)	Container calls/volume	≈−9%/−11% (2020)	Fedi et al. (2022) [42]
Genoa (Italy)	Container vessel calls	−15.9% (2018–2020)	Fedi et al. (2022) [42]
Marseille (France)	Container vessel calls	−53.5% (2020)	Fedi et al. (2022) [42]
EU mid-sized ports (3–10 M TEU)	Container throughput	≈−10% (2020)	Notteboom et al. (2021) [43]
Spanish Mediterranean port cities	Cruise passengers	>90% reduction (2020)	Grindlay & Martínez-Hornos (2022) [16]
Oslo (Norway)	Cruise and ferry traffic	−36% (2020)	Wang et al. (2022) [26]
Gdańsk/Gdynia (Poland)	Cruise passengers	>5-fold decrease (2020)	Pioch et al. (2022) [44]
Croatia, Spain (national)	Total port calls	≈−20% (2020)	Fedi et al. (2022) [42]

Furthermore, while the European maritime sector was primarily dragged down by the total cessation of passenger traffic, the specific operational role Limassol adopted during the crisis, serving as a safe haven and repositioning base, buffered the port against more extreme regional volatilities. This contrast is particularly evident when comparing Limassol to other European hubs; for instance, the Oslo port experienced a 36% decrease in cruise and Ferry traffic [26], while Baltic ports of Gdańsk and Gdynia recorded a more than five-fold decrease in cruise passenger volume during 2020 [44]. In contrast, passenger-dependent vessels in Limassol deviated sharply from these broader European trends, with port calls actually doubling in 2020 as Cyprus served as a temporary maritime base. During this period, anchorage utilization for cruise ships rose significantly, suggesting that these vessels

were not engaged in traditional commercial transit but were instead utilizing the port for non-passenger activities, such as maintenance and warm layup.

These dynamics are best understood as functional role substitution, a concrete expression of the adaptive capacity central to resilience theory. Rather than sitting idle, the port's passenger-side assets were reassigned from transit service to staging and warm lay-up: cruise anchorage utilization rose from 5.9% to 75.9%, while cruise berth utilization remained at 94–98%. Critically, this volatility was absorbed by the anchorage buffer while core cargo throughput was preserved, with aggregate berth utilization holding at 80.9–82.0% across all periods. The port thus decoupled its safe haven activity from its core operations. This also explains why a mid-sized multipurpose hub proved resilient where specialized gateways did not: its portfolio of weakly correlated vessel segments meant the global passenger collapse was offset locally by stable cargo and counter-cyclical cruise demand, limiting the 2020 fall in total port calls to 6.8%. Diversification, therefore, acted as a structural resilience buffer rather than an incidental feature.

The global impact of COVID-19 on container ports has been profound, though the severity of these disruptions has largely depended on regional location and port capacity [43,45]. Notably, larger hubs (those handling over 10 million TEUs annually) demonstrated greater resilience with a marginal 4% decrease in traffic, whereas mid-sized ports (3–10 million TEUs) faced more substantial declines of approximately 10% [43]. In this context, the cargo-oriented segments at Limassol Port showed highly heterogeneous responses across vessel types. While container traffic contracted by 8.3% during the peak pandemic period, this sector proved robust, with 2023 volumes ultimately surpassing pre-pandemic levels.

Conversely, Ro-Ro operations followed a distinct upward trajectory, increasing by 15.3% during the pandemic and surging by 29.6% in the post-pandemic era. This growth was significantly bolstered by the strategic resumption of the Cyprus–Greece ferry link [38]. In contrast to these steady recoveries, the bulk and tanker segments remained notably more volatile; their fluctuations appear to align more closely with broader shifts in commodity demand, energy-market volatility, and regional trade patterns than with pandemic restrictions alone.

Global COVID-19 protocols, including mobility restrictions and stringent quarantine mandates, typically resulted in prolonged waiting periods at anchorage. As noted by Kim et al. [28], these restrictions led to an immediate surge in average anchorage wait times, even when service times at the berth remained relatively unaffected. This phenomenon was particularly acute in high-volume regions like China's Beibu Gulf, where anchoring durations for cargo ships and oil tankers rose by 62% and 112%, respectively, in the post-pandemic period [25]. The data from Limassol Port align with this trend of increased reliance on anchorage, with utilization rising by an average of 36.7% during the pandemic compared to the pre-COVID baseline. However, the driver for this increase in Limassol was distinct; it was primarily fueled by the 75.9% surge in anchorage utilization by cruise vessels. This indicates that the anchorage served less as a waiting room for congested berths and more as a long-term staging area for idle passenger fleets. This interpretation is further supported by the remarkably consistent berth utilization rates, which fluctuated only marginally between 80.9% and 82.0% across all study periods. Such stability confirms that despite the external volatility of the pandemic, Limassol's internal service efficiency and berth throughput remained uncompromised, successfully decoupling the safe haven anchorage activity from core cargo operations.

In summary, the maritime ecosystem of Limassol Port demonstrated significant institutional and operational resilience, successfully absorbing the COVID-19 shock and transitioning into a robust recovery phase by the 2022–2023 period. This trajectory is de-

financed by three overarching themes: resilience, specialization, and efficiency. First, the core logistics segments, comprising container, bulk, and Ro-Ro operations, not only returned to pre-pandemic baselines but, in several instances, surpassed them, signaling a full restoration of the port's cargo-handling capacity. Second, the passenger-oriented sectors exhibited a unique form of specialization; rather than a total collapse, these segments adapted to new demand realities by leveraging Limassol as a strategic maritime base, a shift reflected in localized surges in anchorage utilization.

Additionally, the port's internal efficiency remained constant throughout the crisis. The stability of berth utilization, coupled with the rapid normalization of Ro-Ro handling and the eventual easing of anchorage congestion, underscores a high degree of adaptive capacity. These findings are further corroborated by statistically significant patterns in tanker waiting times and container berth adjustments, which represent deliberate operational recalibrations in response to global supply chain shifts. Conversely, the non-significant fluctuations observed in other metrics suggest that Limassol's core infrastructure was sufficiently shielded from the pandemic's most disruptive oscillations. Ultimately, Limassol's experience suggests that mid-sized Mediterranean hubs may leverage diverse vessel roles to buffer against global shocks, ensuring long-term maritime connectivity.

Framed against the United Nations 2030 Agenda [5], these findings carry concrete sustainability implications. Limassol's capacity to preserve reliable cargo throughput and rapidly normalize operations is a direct instance of SDG 9 (Industry, Innovation and Infrastructure), whose Target 9.1 calls for resilient infrastructure, while the uninterrupted seaborne trade that this resilience secured underpins SDG 8 (Decent Work and Economic Growth) in an island economy dependent on maritime supply chains. The port's safe haven role, sustaining crew changes and vessel servicing under stringent health protocols, relates to SDG 3 (Good Health and Well-being), and short sea shipping's function as a lower-carbon alternative to road freight ties the continuity of these networks to SDG 13 (Climate Action) and SDG 11 (Sustainable Cities and Communities). Finally, the multi-stakeholder Port Community System underpinning this analysis, integrating the Cyprus Ports Authority, terminal operators, and government agencies, exemplifies SDG 17 (Partnerships for the Goals). This alignment is not incidental: the Port of Limassol is already listed in the IAPH World Ports Sustainability Program as a port initiative applying the UN SDGs in practice, spanning SDGs 3, 8, 9, 14, and 17 [46]. The present resilience assessment thus extends the sustainability agenda from its original focus on digitalization toward the domain of crisis preparedness and operational continuity.

Several limitations of this study should be acknowledged. First, because this research is structured as a single-port case study, the specific operational magnitudes reported here cannot be directly generalized to maritime ports characterized by different size classes, alternative governance models, or distinct vessel traffic mixes without further empirical validation. Second, the cross-port benchmarking presented in Table 2 is necessarily indirect; the localized operational KPIs were computed using granular, event-level, confidential Port Community System records, whereas equivalent, high-resolution datasets for other Mediterranean ports are publicly unavailable. Consequently, benchmarking relies on aggregated, publicly reported traffic metrics rather than fully harmonized micro-level indicators. Finally, the study period encompasses multiple overlapping geopolitical and socio-economic disruptions, including the COVID-19 pandemic, fuel market shifts, and regional conflicts such as the Gaza crisis. Because the applied one-way ANOVA characterizes broader period-associated changes, it cannot cleanly isolate specific COVID-19 anomalies from these concurrent, compounding factors.

6. Recommendations and Future Research

To translate the lessons learned from the COVID-19 pandemic into long-term institutional resilience, several strategic actions are recommended for the Limassol Port. These initiatives focus on digital transformation, performance transparency, and predictive governance.

Digital Integration and Real-Time Monitoring. First, the port should prioritize implementing continuous, automated KPI monitoring. The development of integrated Digital Dashboards that provide real-time visibility into berth occupancy, anchorage utilization, and arrival punctuality would allow for more agile decision-making during sudden traffic surges. This should be paired with the full consolidation of PCS and advanced digital scheduling, particularly for the high-growth Ro-Ro and container segments. Such integration reduces administrative bottlenecks and ensures that berth waiting times remain insulated from external logistics shocks. The empirical findings provide a direct basis for prioritizing these investments. Bulk vessel arrival punctuality deteriorated to 35.3% in 2024–2025, with mean waiting durations increasing by 43% relative to the post-COVID period, while container punctuality declined to 49.8%—segments where scheduling uncertainty, rather than physical capacity, is the binding constraint. These results highlight the value of Port Collaborative Decision Making (Port CDM) [47], which enables real-time information exchange among port authorities, terminals, shipping agents, and vessel operators. By aligning predicted berth availability with inbound vessel positions, Port CDM creates the conditions for Just-In-Time (JIT) arrivals: vessels slow-steam when a berth is occupied, eliminating idle anchoring time and absorbing schedule variability before it propagates into congestion. The cruise sector’s achievement of 87.7% arrival punctuality in 2024–2025, the highest across the entire study period, demonstrates that structured scheduling coordination can deliver substantive improvements even in operationally complex segments and provides a benchmark for what digitally enabled cargo scheduling could achieve. Consistent with Hsu et al. [48] and Yang & Hsieh [49], who identify rapid berth provision, transparent information integration, and supply chain optimization as leading critical success factors for smart port development in the post-pandemic era, investment in Port CDM infrastructure and AI-assisted berth planning should be treated as operational necessities directly implied by the KPI evidence.

Institutionalizing Crisis Preparedness. To embed the “safe haven” and “base-of-operations” experiences into the port’s DNA, Limassol should institutionalize its pandemic-era adaptations through Scenario Analysis and Operational Drills. Annual performance reviews should be mandated to identify emerging volatilities in bulk and tanker traffic, ensuring that the port’s infrastructure can pivot rapidly between commercial cargo and maritime storage roles. By codifying these responses, the port moves away from ad hoc crisis management toward a structured framework of maritime readiness.

Directions for Future Research. While this study provides a comprehensive baseline of port-level performance, future research should seek to quantify the efficacy of specific technological interventions. There is a clear scholarly need to evaluate the direct impact of AI-driven logistics and Internet of Things (IoT) monitoring on berth productivity and vessel turnaround times. Of particular interest is the measurable impact of Port CDM and JIT arrival schemes on anchorage utilization and berth waiting times in mid-sized multipurpose ports, where the heterogeneity of vessel types makes coordination gains both harder to achieve. Furthermore, investigating the trade-offs of flexible berth management strategies, where berths are dynamically reallocated across vessel types during crises, could provide a blueprint for evidence-based resilience strategies in other mid-sized Mediterranean hubs.

7. Conclusions

The COVID-19 pandemic exerted a profound, multidimensional impact on Limassol Port, disrupting operational efficiency, inflating anchorage wait times, and challenging arrival punctuality. However, these disruptions were notably heterogeneous; the divergent trajectories of passenger and cargo segments underscore the necessity for vessel-specific resilience strategies. While the cruise sector's trajectory highlights Limassol's temporary role as a strategic maritime base, the container and Ro-Ro segments demonstrated strong adaptive capacity, supported by operational normalization, streamlined protocols, and enhanced digital coordination.

The recovery observed in 2022–2025 suggests that targeted operational adjustments and the institutionalization of crisis-era flexibility can effectively restore performance levels. Nevertheless, the persistent variability within the tanker and conventional cargo sectors highlights that true maritime resilience requires a trifecta of technological innovation, real-time data visibility, and adaptive management. Viewed through the lens of the 2030 Agenda, these results demonstrate how resilient port operations (SDG 9) safeguard the economic (SDG 8) and low-carbon (SDG 13) value that short sea shipping networks deliver, even under systemic disruption.

Future research should expand upon the scope of this paper by conducting comparative, multi-port empirical analyses across the Mediterranean basin to establish a fully harmonized benchmarking framework using standardized operational KPIs. In addition, utilizing simulation modeling for scenario-based stress testing will be vital for refining long-term capacity planning and operational risk management under extreme, unpredictable conditions. Ultimately, a holistic, multi-factor analytical approach remains essential for modeling the evolving resilience of Mediterranean maritime hubs against the macroeconomic and geopolitical uncertainties of a globalized supply chain.

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