Journal of *Marine Science and Engineering*

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Analysis of Damage to Shipping Container Sides During Port Handling Operations

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Abstract: The damage to shipping containers during port handling operations continues to pose a significant challenge that adversely affects operational efficiency, equipment integrity, and supply chain accountability. This study utilises real-world measurement data gathered through accelerometers to examine the occurrence and dynamics of physical impacts, particularly side and rear collisions, during the handling of containers at Klaipėda City Port. The research prioritises two critical scenarios: side impacts during stacking operations with reach stackers and rear impacts during trailer loading procedures. Impact events are meticulously recorded and analysed to ascertain the magnitudes of acceleration across multiple axes. This reveals that side impacts produce significantly greater forces, particularly in the lateral direction, than rear impacts. This study employs sensor-based monitoring, advanced data visualisation techniques, and structured scenario analysis to delineate the variability and intensity of mechanical interactions during these operations. The findings emphasise the structural stress that containers experience and underscore the importance of embedded monitoring technologies for real-time event detection and damage prevention. The results contribute to the expanding body of knowledge that supports the digital transformation of container terminals and furnish actionable insights for enhancing handling protocols, informing insurance assessments, and improving safety measures within both automated and conventional port environments.

Keywords: container handling operations; impact detection; port terminal monitoring; smart sensor systems

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Academic Editors: Nam Kyu Park, Livia Maglić, Ana Peric Hadzic, Marina Zanne and Lovro Maglić

Received: 21 April 2025
Revised: 13 May 2025
Accepted: 16 May 2025
Published: 19 May 2025

Citation: Jakovlev, S.; Eglynas, T.; Jankunas, V.; Jusis, M.; Voznak, M. Analysis of Damage to Shipping Container Sides During Port Handling Operations. *J. Mar. Sci. Eng.* **2025**, *13*, 982. https://doi.org/10.3390/jmse13050982

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1. Introduction

Shipping containers are the structural cornerstone of modern global trade [1,2], enabling the standardised, modular transportation of goods across continents with unmatched efficiency. With millions of twenty-foot equivalent units (TEUs) processed annually, container ports have become high-throughput environments where speed, coordination, and mechanical precision are vital for maintaining global supply chains [3,4]. Yet, within this highly optimised system, container damage during handling operations remains a persistent and costly issue [5,6]. From operational delays and insurance disputes to equipment failure and safety risks, the consequences of mishandled containers ripple through the entire logistics network [7].

Container damage in port environments typically occurs during loading, unloading, and transhipment procedures. These operations often involve heavy machinery such as

quay cranes, gantry cranes, reach stackers, and automated guided vehicles (AGVs), all interacting with containers dynamically and sometimes unpredictably [8]. Containers are lifted, swung, aligned, and lowered within confined spaces, often under tight time constraints and in variable weather conditions. While containers are designed to withstand harsh conditions, their structural integrity is often compromised by high-impact forces, repeated stress cycles, and unintentional collisions with port infrastructure or other containers. Key points of vulnerability include the corner castings, sidewalls, and bottom rails, which may suffer crushing, denting, or bending due to poor alignment during crane engagement, excessive swing during lifting, or uncontrolled descent during placement [9]. This damage is not merely cosmetic; it can compromise the container's ability to seal correctly, reduce its load-bearing capacity, or interfere with stacking mechanisms on board ships and within container yards (see Figure 1).



Figure 1. Examples of container damage resulting from bad handling operations.

Furthermore, when damaged containers go undetected, they pose risks to cargo security, terminal personnel, the overall structural integrity of the port, and other valuable equipment. Given the scale and pace of containerised logistics [10], relying solely on visual inspection and manual reporting to detect damage is increasingly inadequate. Human-based assessments are limited by visibility, access, time, and subjective judgement. As a result, many damage events go unnoticed until significant deterioration or secondary complications arise [11]. This delay in detection often leads to more extensive repair costs, shipment delays, and disputes between shippers, terminal operators, and insurers. Moreover, visual inspections fail to provide forensic insight into when, where, or how the damage occurred, as data are essential for accountability, process optimisation, and preventive measures.

This is where intelligent event monitoring emerges as a crucial component of modern container handling [12–15]. In this context, event monitoring refers to the real-time or near-real-time tracking of physical interactions and impact events involving containers during handling operations. Using sensors, data acquisition systems, and signal processing algorithms enables detecting, classifying, and logging events such as collisions, hard landings, excessive swings, and other anomalies during crane or AGV operations. The availability of these data allows operators to gain a deeper understanding of operational dynamics, identify risky procedures [16–20], and take proactive measures to mitigate future damage. Event monitoring systems generally depend on accelerometers, gyroscopes, vibration sensors, or other non-invasive measurement tools that can be integrated into existing port equipment (see Figure 2).

These systems collect high-resolution motion and impact data, automatically classifying events based on severity, direction, frequency, and duration. Advanced systems can even correlate these events with specific handling procedures, container IDs, operator actions, or crane paths, creating a digital audit trail of container movements within the

terminal. The significance of such systems extends beyond operational efficiency [21,22]. From a safety perspective [23], undetected container damage can lead to lifting, stacking, or transportation accidents. A weakened corner fitting or misaligned frame may cause load instability or equipment malfunction, putting workers and cargo at risk [24]. From a financial standpoint, demonstrating when and where damage occurred can aid in resolving insurance disputes, enforcing liability clauses, and reducing the incidence of false claims.

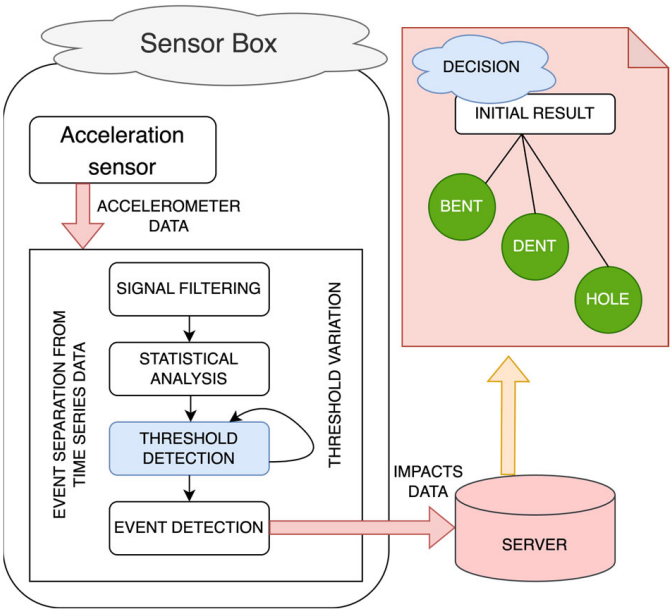


Figure 2. This figure presents an example of a container damage detection system previously used by the authors. The scheme illustrates the principle of critical incident detection when a device is mounted on the container's door by acquiring real-time acceleration data and checking whether it has reached the predetermined threshold value.

In a data-driven terminal environment, this level of transparency also fosters enhanced operational awareness, facilitates more informed decision-making, and enables the implementation of predictive maintenance practices. By continuously collecting and analysing data from handling equipment and container movements, terminal operators can identify emerging patterns, anticipate equipment failures, and schedule maintenance activities based on real-time usage and stress indicators, rather than relying on static time intervals. This transition from reactive to proactive maintenance significantly reduces unexpected downtime, prolongs the service life of critical assets, and enhances overall terminal efficiency. Moreover, such transparency bolsters continuous improvement strategies by systematically identifying inefficiencies, recurring operational bottlenecks, and sources of damage, which can be addressed through process re-engineering or targeted training programmes. Event monitoring also aligns closely with the broader objectives of digitalisation and automation currently reshaping the maritime and logistics sectors. As ports transform into intelligent infrastructure ecosystems, integrating event monitoring data with terminal operating systems (TOSs), enterprise resource planning (ERP) tools, and digital twin platforms lays a crucial foundation for more adaptive and intelligent control systems. This integration provides real-time situational awareness and promotes data fusion across various operational layers, encompassing crane dynamics, container flow, safety management, and asset tracking. Event monitoring supports the creation of predictive algorithms that evaluate risk levels and anticipate potential disruptions before they occur. For example, identifying unusual impact frequencies or force levels among similar equipment may indicate systemic alignment problems or mechanical wear, leading to the

necessary recalibration of crane operations, adjustment of spreader arms, or modifications of control sequences. Likewise, recurring error patterns tied to specific shifts or personnel may reveal the necessity for retraining, updating procedures, or altering user interfaces.

In fully or semi-automated terminals, these data prove to be particularly significant in enhancing robotic systems' motion profiles and control logic, including automated stacking cranes (ASCs), automated guided vehicles (AGVs), and quay cranes equipped with intelligent spreaders. By integrating feedback from event monitoring systems, these automated components can adjust movement trajectories, acceleration rates, and engagement timings to mitigate collision risks and mechanical stress, thereby enhancing operational precision and decreasing the probability of container damage. Ultimately, the amalgamation of event-based data analytics and automation promotes a safer, more resilient, and highly optimised port environment, enabling terminals to address the escalating demands of global trade with agility and intelligence. Importantly, the benefits of event monitoring are not confined to high-end, fully automated ports [25–27]. Even in traditional or semi-automated terminals, retrofitting handling equipment with affordable sensors and utilising cloud-based analysis tools can significantly improve visibility and responsiveness. Modular systems can be deployed selectively at high-risk handling points, during pilot phases, or for especially valuable cargo, facilitating a scalable adoption that aligns with the terminal's operational and budgetary constraints. However, challenges remain in standardising the data formats, threshold criteria, and interpretation frameworks associated with event monitoring. Questions about sensor calibration, false positives, data overload, and real-time processing must be addressed to ensure operational usability. Moreover, privacy, cybersecurity, and data governance must be carefully managed, especially as ports begin to integrate such systems into broader logistics platforms and supply chain networks. In summary, although the issue of shipping container damage at ports has long been recognised (making it the primary goal of our research group, see Figure 3), the tools available to detect, prevent, and learn from these incidents have fallen behind in operational complexity.

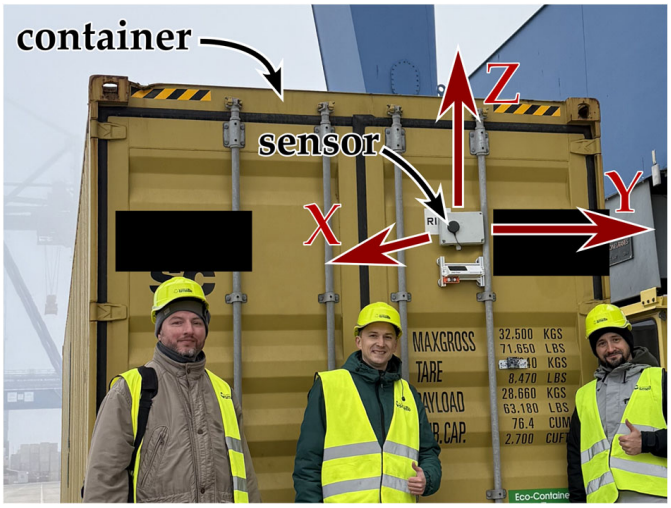


Figure 3. Research performed at Klaipeda City Port Container Terminal-Limited Liability Stevedoring Company "Klaipėdos Smeltė" (here the X-, Y-, and Z-axes show the orientation of the sensor box).

Event monitoring represents a crucial advancement in this regard, providing detailed visibility into handling dynamics and a pathway toward more resilient, safe, and accountable terminal operations [28–30]. As global trade continues to grow [31] and terminals strive to balance throughput with safety, the widespread adoption of real-time impact detection and event logging [32–35] will become advantageous and essential.

This article further examines the problem of container side impacts that occur during stacking operations in port environments. Specifically, it investigates the mechanical interactions and misalignments that arise when containers are positioned within ship hulls or stacked vertically in yards, where precision and synchronisation between crane systems and container guides are critical. These side impacts, often resulting from lateral sway, misaligned vertical cell guides, or improper spreader positioning, represent some of the most underreported yet structurally significant forms of container damage.

By analysing the causes, frequency, and consequences of these impacts, the study aims to provide a deeper understanding of the operational dynamics that contribute to such events and to explore technological solutions—such as sensor-based monitoring and data-driven detection algorithms—that can mitigate their occurrence and enhance the overall safety and efficiency of container handling systems, investigating the causes of the most critical events.

2. Analysis of Damage Causes and On-Shore Impact Scenarios

2.1. Background Statistics

Analysis of container damage in global port operations highlights critical trends that underscore the importance of enhanced monitoring and detection systems. Improper packing and inadequate container cargo securing are the primary causes of damage, accounting for approximately 65% of all reported incidents. This includes issues such as poor load distribution, insufficient bracing, and failure to follow standard packing procedures, which can shift cargo, cause crushing, or lead to collapse during handling and transit. Additionally, physical damage from container handling activities, such as impacts from cranes, yard vehicles, and other machinery, contributes to around 25% of the damages recorded. These incidents frequently occur during lifting, aligning, or lowering operations and are exacerbated by environmental factors, human error, and constraints due to time pressures.

Moreover, thermal damage to temperature-sensitive cargo, especially in refrigerated (reefer) containers, accounts for roughly 14% of damage incidents. Such issues generally result from equipment failures or the inability to maintain necessary temperature ranges while the cargo is in terminals or transit phases. Beyond these causes, theft and shortage-related incidents collectively contribute to a significant portion of container damage-related claims, with approximately 9% attributed to cargo theft and a further 8% to discrepancies in inventory upon arrival, often due to miscounts, pilferage, or administrative errors during port handling procedures. Container losses at sea, while often associated with vessel transit, also reflect vulnerabilities introduced during port stacking and loading. Between 2008 and 2019, the average number of containers lost annually at sea was approximately 1382 units, with a substantial proportion—nearly 57%—directly linked to adverse weather conditions and improper stacking protocols. These figures illustrate the need for more robust securing methods, weather-responsive loading plans, and real-time monitoring of shipboard stability during container transfer operations.

Incidents occurring within port boundaries illustrate the intricate risks associated with terminal operations. In 2022, roughly 2400 maritime incidents were documented at ports and terminals worldwide, with nearly half occurring during berthing, loading, and unloading activities. Over 800 of these incidents were linked to vessels docked at berths or manoeuvring in harbour areas, underscoring the frequency of accidents in high-density operations. Supporting this, major terminal operators like APM Terminals have reported over 1200 container handling-related incidents in one operational year, emphasising the issue's magnitude, even in high-tech environments. Furthermore, the situation is exacerbated by significant underreporting. Minor impacts and surface deformations, which may not be visibly apparent or initially considered critical, are frequently omitted from official

incident records. Nonetheless, such damage is known to diminish container value by about 2–5%, which impacts asset utilisation and heightens downstream logistical risks. These statistics (summarised in Table 1) strongly support implementing continuous, data-driven monitoring systems in port operations.

The significant impact-related damage rate, environmental unpredictability, and the shortcomings of manual inspections call for a shift towards smart detection, threshold-based alerts, and detailed logging of container handling activities. By adopting these strategies, the port logistics industry can effectively decrease the frequency and severity of container damage and its hidden costs.

Table 1. Statistics of events.

Cause of Damage	Statistic	Source
Improper packing and securing	65% of cargo damage claims are due to poor packing and securing	Officially provided by the Global Trade Magazine "https://globaltrademag.com/"
Physical damage during handling	25% of cargo damages are attributed to physical handling damage	Officially provided by IFA Forwarding "https://ifa-forwarding.net/"
Containers lost overboard	11% of cargo damage claims are due to containers lost at sea	Officially provided by Container xChange "https://www.container-xchange.com/"
Temperature-related damages	14% of cargo damages are due to incorrect temperatures	Officially provided by IFA Forwarding "https://ifa-forwarding.net/"
Theft-related damages	9% of cargo damages are due to theft	Officially provided by IFA Forwarding "https://ifa-forwarding.net/"
Shortage-related damages	8% of cargo damages are due to shortages	Officially provided by IFA Forwarding "https://ifa-forwarding.net/"
Maritime incidents in ports and terminals	2400 incidents recorded in 2022; ~50% occurred within port boundaries	Officially provided by Port Technology "https://www.porttechnology.org/"
Incidents at berth or harbour	813 incidents occurred while docked in ports and harbours in 2022	Officially provided by Port Technology "https://www.porttechnology.org/"
APM Terminal incidents	Over 1200 incidents reported globally in 2019	Officially provided by BoxOnWheel "https://boxonwheel.com/"
Unreported container damages	Minor damages can reduce container value by 2–5%; many incidents go unreported	Officially provided by Identec Solutions "https://www.identecsolutions.com/"
Average annual containers lost at sea	Approximately 1382 containers were lost annually between 2008 and 2019	Officially provided by Standard Club "https://www.standard-club.com/"
Adverse weather as a cause of container loss	57.14% of container loss incidents are attributed to adverse weather conditions	Yi et al. [36]

2.2. Use Cases with Stacking Operations On-Shore

A use case study examined the dynamics occurring during container stacking operations at the terminal when containers placed side by side collided. In this study, two primary types of container collisions were analysed: side collisions and rear collisions. Side collisions occur during stacking operations, typically when a moving container sways or is misaligned laterally, leading to contact with adjacent containers or vertical cell guides. These lateral impacts are often driven by dynamic forces introduced by the reach stacker's movement or wind-induced sway, especially in high-stacking environments. In contrast, rear collisions primarily take place during trailer loading procedures when a container makes longitudinal contact with stationary surfaces, such as the end wall of a trailer or another container. These impacts often result from insufficient deceleration or alignment errors during final placement. Understanding these distinct mechanisms is essential for

designing scenario-specific detection strategies and interpreting sensor data accurately. The experimental field is presented in Figure 4.

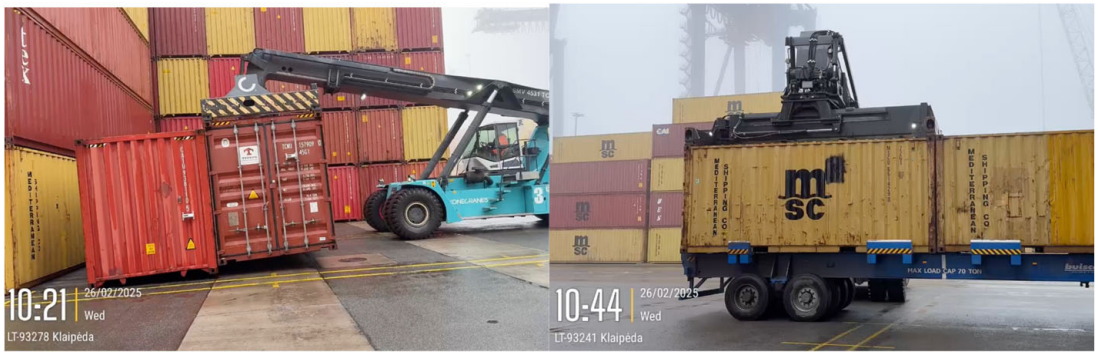


Figure 4. Examples of experiments conducted at the port, with detailed schematics presented in Figures 5 and 6.

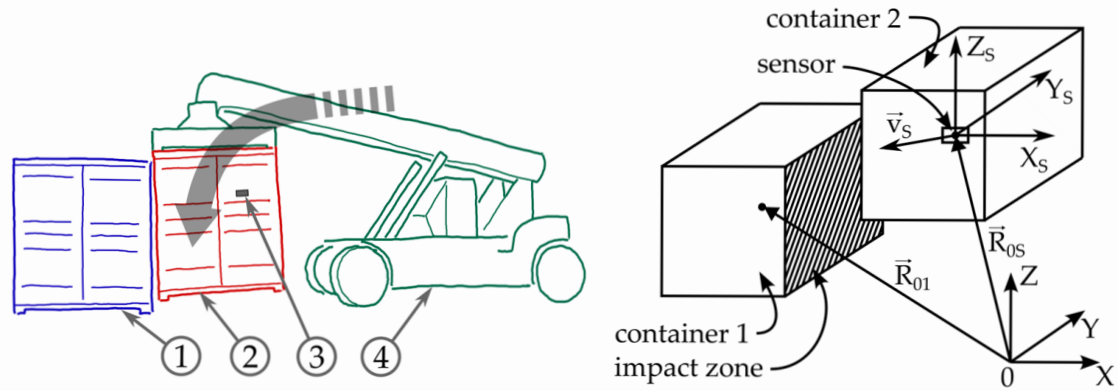


Figure 5. Schematic illustration of side impact during container stacking using a reach stacker (here 1 illustrates the stacked container; 2 illustrates the container being handled; 3 the smart container device "Slam stick (enDAQ: S3-D16)"; 4 is the reach stacker-type handler).

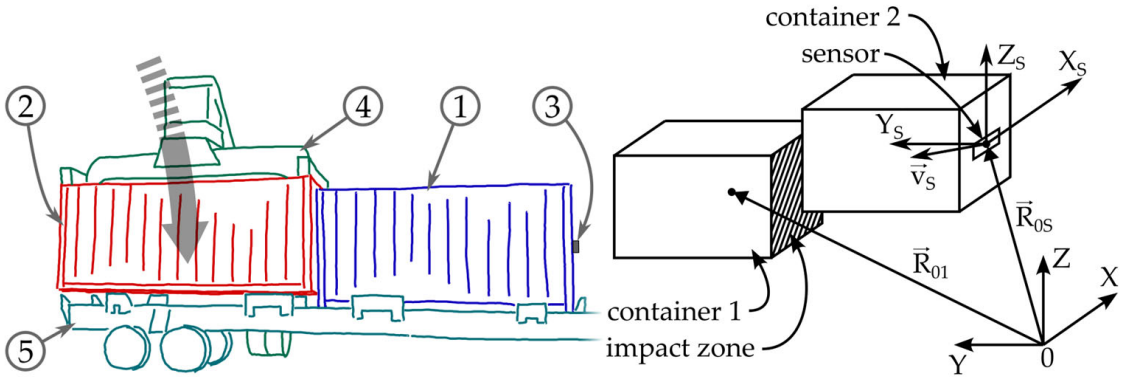


Figure 6. Rear impact between containers during loading onto a truck trailer platform (here 1 illustrates the stacked container; 2 illustrates the container being handled; 3 is the smart container device "Slam stick (enDAQ: S3-D16)"; 4 is the reach stacker-type handler; 5 is the truck platform).

In the first scenario, the containers were transported using a reach stacker-type handler (see Figure 5). Vibrations resulting from these impacts were measured using an accelerometer (Slam stick (enDAQ: S3-D16), Woburn, MA, USA). The measurements took place within the Klaipeda city port area.

The second observed scenario involved rear impacts when containers contacted their rear walls (see Figure 6). These collisions typically occurred during loading operations onto truck trailer platforms within the terminal and, in most cases, during other logistics operations on land.

These real-world observations emphasised the frequency and variability of impact events during routine container handling operations, reinforcing the need for continuous monitoring and data-driven analysis to enhance safety and minimise structural damage, particularly within terminal environments. This approach empowers engineers and port operators to make informed, evidence-based decisions in customs inspections, insurance claims, and compliance monitoring.

3. Results

This section presents the findings of a use case study conducted at the Klaipėda City Port container terminal, operated by Klaipėdos Smeltė, in 2025. The study aimed to capture real-world impact dynamics during container handling operations. Measurements focused on two typical scenarios using a reach stacker container handler:

- Firstly, the side impacts during stacking in container yards, shown in Figure 5.
- Secondly, the rear impacts during loading onto truck trailers, shown in Figure 6.

In terms of signal clarity, it is important to note that the noise amplitude of the sensor in a stationary (idle) state was approximately 0.015 g. In contrast, the amplitudes of vibrations caused by impact events were significantly higher than this baseline noise level. Moreover, the frequency content of vibrations generated by collisions was substantially higher than the frequency of normal operational accelerations encountered during container handling. As a result, the segments corresponding to impact events were easily distinguishable from background noise and could be reliably detected.

3.1. Side Impact Measurements

Side impacts were observed as containers were stacked side by side, causing collisions along their longitudinal walls. An accelerometer (Slam stick (enDAQ: S3-D16)) was mounted on the moving container to record impact-induced vibrations. The sensor was factory-calibrated, with the last calibration performed less than three months before the experiments. The sampling rate was set to 100 Hz, and the dynamic range of the sensor was $\pm$16 g. Four distinct impact events were recorded (see Figure 7):

- Between the 69th and 70th (see Figure 7a)—Peak acceleration: X = 4.1 g, Y = 3.8 g, Z = 3.9 g.
- Between the 155th and 156th (see Figure 7b)—Peak acceleration: X = 7.2 g, Y = 3.2 g, Z = 4.2 g.
- Between the 21st and 22nd (see Figure 7c)—Peak acceleration: X = 2.3 g, Y = 5.1 g, Z = 2.7 g.
- Between the 78th and 80th (see Figure 7d)—Peak acceleration: X = 3.2 g, Y = 3.8 g, Z = 2.3 g.

These results indicate that lateral collisions during stacking can induce substantial multi-axial accelerations, with peak values reaching up to 7.2 g.

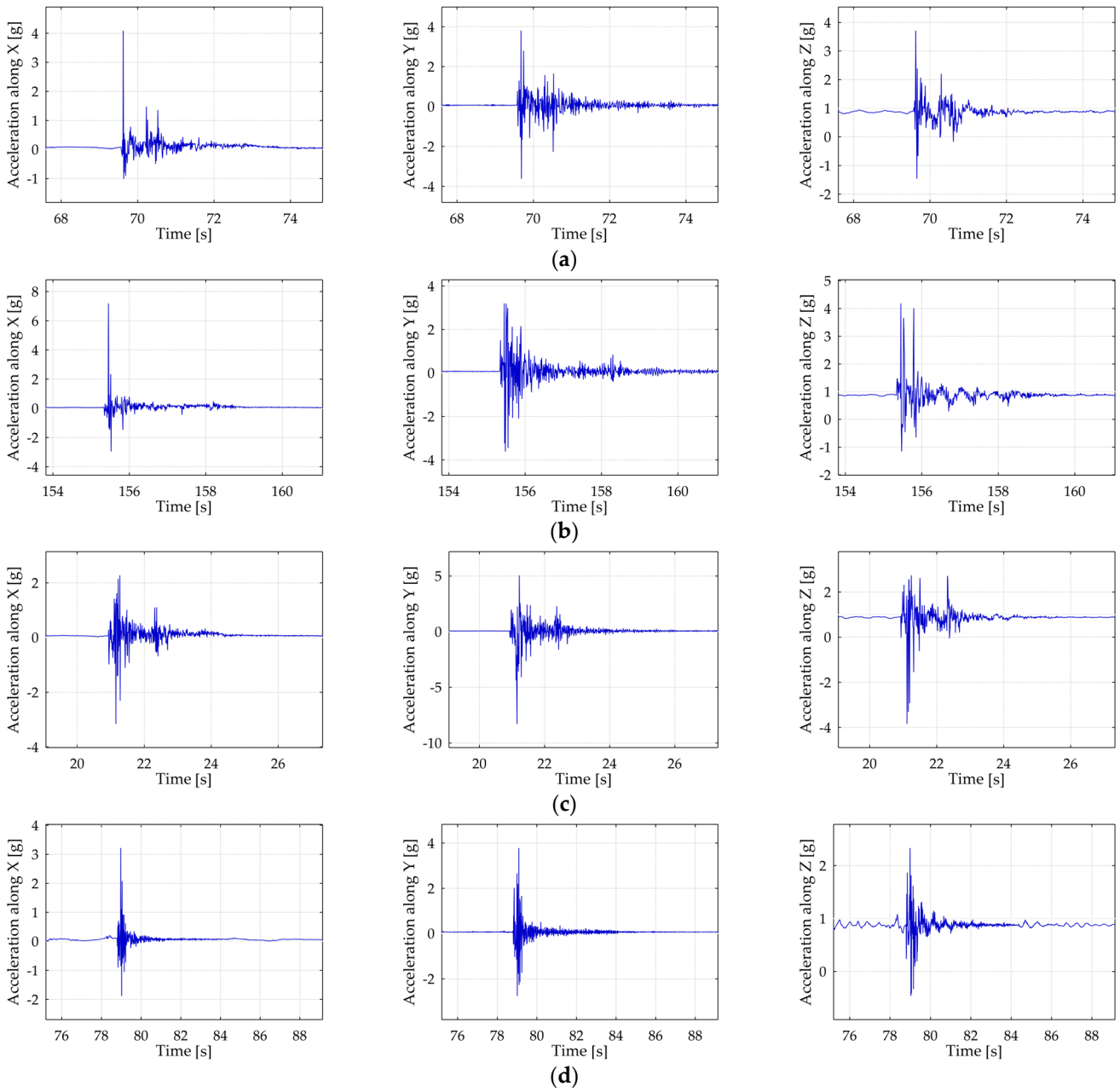


Figure 7. Side impact measurements (**a**–**d**).

3.2. Rear Impact Measurements

Rear impacts were identified when containers contacted each other or infrastructure at their rear walls—most frequently during loading onto truck trailers. Accelerometers were attached to either the moving or stationary container, depending on the test (see Figure 8a–e).

Five impact events were analysed:

- Between the 91st and 92nd (mild impact, see Figure 8a)—X = 0.4 g, Y = 1.2 g, Z = 1.2 g.
- Between the 102nd and 103rd (aggressive impact, see Figure 8b)—X = 3.4 g, Y = 6.2 g, Z = 3.7 g.
- Between the 90th and 91st (mild impact, see Figure 8c)—X = 1.0 g, Y = 1.4 g, Z = 2.4 g.
- Between the 144th and 145th (aggressive impact, see Figure 8d)—X = 1.1 g, Y = 1.6 g, Z = 3.2 g.
- Between the 208th and 209th (mild impact, see Figure 8e)—X = 0.8 g, Y = 1.1 g, Z = 3.4 g.

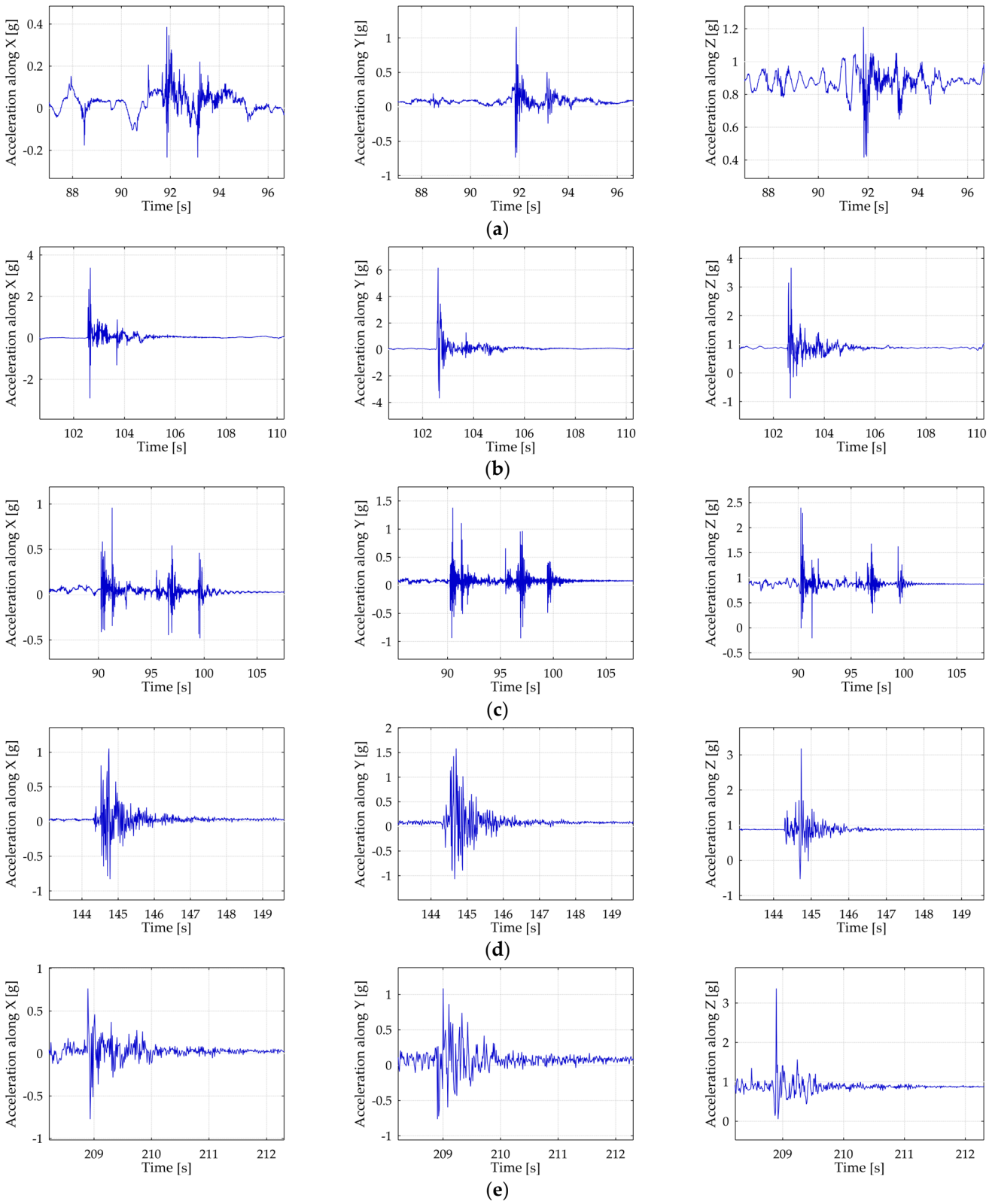


Figure 8. Rear impact measurements (**a**–**e**).

Compared to side impacts, rear impacts generally produced lower acceleration values, though certain aggressive collisions exceeded 6 g on the Y-axis.

3.3. Qualitative Analysis of Impact-Induced Acceleration Signals

Figure 7a illustrates the acceleration profile recorded on the Z-axis during a container handling event in which the container was transported toward a stationary one. Before the collision, low-frequency acceleration components (see Figure 9) were observed in the 1–1.5 Hz range, corresponding to the suspended container's sway-induced motion. In the 1.5–10 Hz range, vibrations were attributed to the mechanical operation of the reach stacker transporting the container. Notably, in the frequency spectrum above 10 Hz, the signal showed minimal vibration, indicating that high-frequency background noise was negligible.

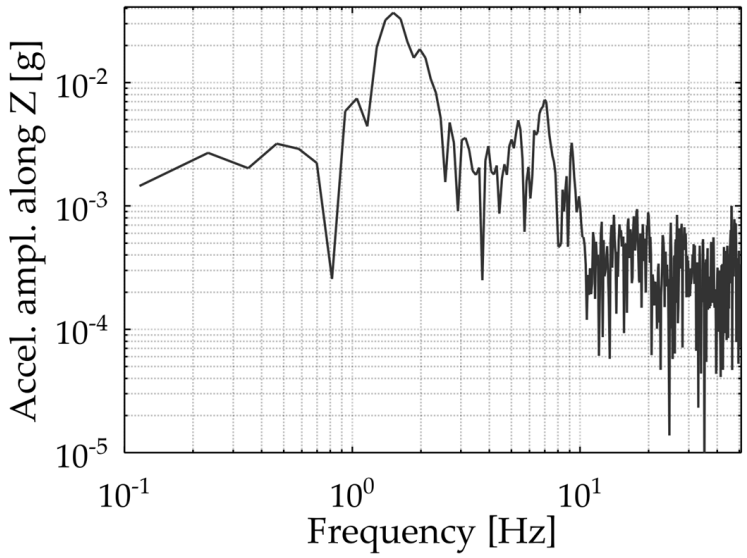


Figure 9. Frequency components of the acceleration before impact.

At the moment of impact, the acceleration signal exhibited a sharp rise, reaching a peak amplitude (in this case, 4.1 g), which reflected the forceful contact between the container and a rigid object—typically another container, a trailer, or port infrastructure. This collision induced high-frequency vibrations (see Figure 10) that were distinguishable from the pre-impact motion, both in amplitude and frequency characteristics.

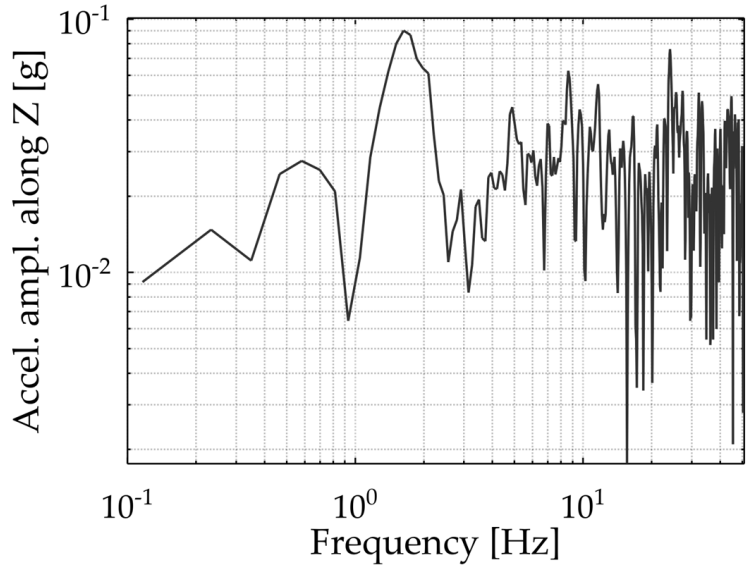


Figure 10. Frequency components of the acceleration during impact.

These vibrations were evident across all three sensor axes and were similar in their envelope shape, as shown in Figures 7 and 8. The amplitude of the acceleration signal decayed rapidly after the initial contact, illustrating the transient nature of the mechanical shock. This study used the peak acceleration value as the key metric to characterise the severity of impact events, providing a reliable indicator for identifying and classifying physical collisions during port handling operations.

3.4. Interpretation

The recorded data demonstrated the range of forces containers are subjected to during typical handling operations. Side impacts yielded the highest accelerations, particularly on the horizontal axes, while rear impacts showed notable but generally lower forces, as seen in Figure 11. These insights highlight the structural stress containers endure in real-world conditions and reinforce the value of embedded sensor technologies for event detection and operational diagnostics. Continuing the presented results, the radar chart compared the average acceleration values recorded across the X-, Y-, and Z-axes for both side and rear impact scenarios. Side impacts exhibited consistently higher average accelerations, particularly along the X-axis, indicative of the strong lateral forces generated during stacking operations.

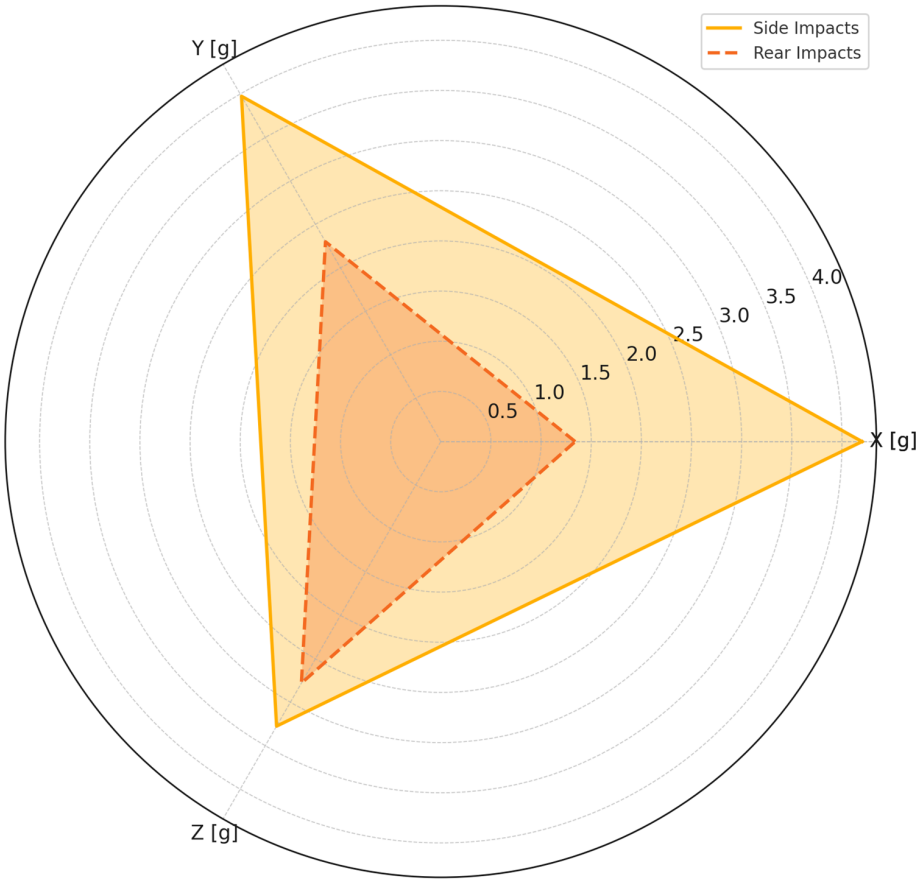


Figure 11. Radar chart of average accelerations by scenario.

Rear impacts, in contrast, displayed a more compact profile, with generally lower acceleration values, except for a moderate increase along the Y-axis—likely due to vertical motion during container placement onto truck trailers. This contrast in impact profiles highlights the varying mechanical stresses containers are subjected to depending on the specific handling scenario, further underscoring the importance of scenario-aware monitoring and mitigation strategies within terminal operations.

4. Discussion

The findings of this study align with the previous literature emphasising the vulnerability of containers during mechanical handling, particularly under the high-throughput conditions common in modern terminals. While prior work has broadly addressed damage detection systems and risk mitigation frameworks, this research offers an empirical contribution by quantifying real-world impact forces through embedded sensor technology. The measured accelerations in side impact events exceed those recorded in rear impacts by a substantial margin, particularly along the X-axis. This confirms the operational hypothesis that lateral misalignments during stacking are among the most damaging handling events. These insights correlate with incident data suggesting the underreporting of such impacts are often underreported due to their non-visible external consequences. The radar visualisations further reinforce the multidirectional nature of container stress and illustrate the potential for pattern recognition and predictive alerting within innovative terminal environments. Moreover, the distinction between aggressive and mild impacts, as documented in stacking and trailer loading scenarios, demonstrates the sensitivity and capability of embedded sensors to classify severity levels—a key requirement for scalable event monitoring systems. While this study focuses on specific handling cases using a reach stacker, the findings suggest a broader applicability for similar sensor-driven frameworks across different terminal configurations and equipment types. Future research may extend these insights through long-term deployment, multi-sensor fusion, and integration with terminal operating systems to enable automated responses.

It is acknowledged that the current study is based on a limited sample size and data collected from a single port environment, which may constrain the generalizability of the conclusions. While the results highlight key trends and offer valuable insights into typical handling scenarios, broader validation is required to account for variability across different terminals, equipment configurations, and operational practices. Future work will address these limitations by incorporating larger datasets and multi-site comparisons to strengthen the reliability and external validity of the findings.

5. Conclusions

This study presented a use case analysis of container damage mechanisms during port handling operations, focusing on side and rear impacts as recorded by onboard accelerometer devices. The results show that side impacts during stacking generate higher and more variable acceleration profiles than rear impacts during trailer loading. These differences emphasise the importance of distinguishing between handling scenarios when evaluating structural risk and designing monitoring solutions. The successful capturing and classification of impact data demonstrate the feasibility of implementing innovative sensor-based systems in real operational contexts. Such systems can provide actionable intelligence for operators, insurers, and terminal managers by supporting damage documentation, liability resolution, and preventive decision-making. Integrating these insights into broader digital port infrastructure can help foster safer, more efficient, data-driven container handling practices. As container logistics continues evolving, real-time impact detection will be essential for optimising performance, maintaining asset value, and enhancing resilience in automated and manually operated terminal environments.

While this study provides theoretical insights and practical value for container damage detection, future research should focus on verifying the universality of the findings across multiple ports and equipment types. Expanding the analysis to diverse terminal configurations and machinery will help assess the scalability and broader applicability of the proposed monitoring approach.

Author Contributions: Conceptualisation, S.J. and T.E.; methodology, T.E. and M.V.; software, M.J. and V.J.; validation, V.J.; formal analysis, S.J. and T.E.; investigation, T.E.; resources, V.J. and M.V.; data curation, S.J., M.J. and T.E.; writing—original draft preparation, S.J.; writing—review and editing, T.E.; visualisation, M.J.; supervision, V.J. and M.V.; project administration, M.V.; funding acquisition, S.J. and M.V. All authors have read and agreed to the published version of the manuscript.

Funding: The research was co-funded by the European Union (EU) within the REFRESH project—Research Excellence For Region Sustainability and High-tech Industries—ID No. CZ.10.03.01/00/22_003/0000048 of the European Just Transition Fund and also supported by the Ministry of Education, Youth and Sports of the Czech Republic (MEYS CZ), within a Student Grant Competition in the VSB–Technical University of Ostrava under project ID No. SGS SP2025/013.

Data Availability Statement: The datasets used in this research can be partially provided upon the submission of a formal request to sergej.jakovlev@ku.lt.

Acknowledgments: During the preparation of this manuscript/study, the authors used the Grammarly (6.8.263) and QuillBot (v23.0.4) software tools for text correction and rephrasing. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: Tomas Eglynas, Mindaugas Jusis and Valdas Jankunas were employed by Inotecha Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TEU	Twenty-foot equivalent units
AGVJ	Automated guided vehicle
TOS	Terminal operating system
ERP	Enterprise resource planning
ASC	Automated stacking crane

References

1. Nguyen, P.N.; Kim, H.; Son, Y.M. Challenges and Opportunities for Southeast Asia's Container Ports throughout the COVID-19 Pandemic. *Res. Transp. Bus. Manag.* **2024**, *52*, 101074. [CrossRef]
2. Zhou, C.; Zhu, S.; Bell, M.G.H.; Lee, L.H.; Chew, E.P. Emerging Technology and Management Research in the Container Terminals: Trends and the COVID-19 Pandemic Impacts. *Ocean Coast. Manag.* **2022**, *230*, 106318. [CrossRef]
3. Brooks, L.; Gendron-Carrier, N.; Rua, G. The Local Impact of Containerization. *J. Urban. Econ.* **2021**, *126*, 103388. [CrossRef]
4. del Rosal, I.; Moura, T.G.Z. The Effect of Shipping Connectivity on Seaborne Containerised Export Flows. *Transp. Policy* **2022**, *118*, 143–151. [CrossRef]
5. Cha, S.-H.; Noh, C.-K. A Case Study of Automation Management System of Damaged Container in the Port Gate. *J. Navig. Port Res.* **2017**, *41*, 119–126. [CrossRef]
6. Jakovlev, S.; Eglynas, T.; Voznak, M.; Jusis, M.; Partila, P.; Tovarek, J.; Jankunas, V. Detection of Physical Impacts of Shipping Containers during Handling Operations Using the Impact Detection Methodology. *J. Mar. Sci. Eng.* **2022**, *10*, 1250. [CrossRef]
7. Styliadis, T.; Chlomoudis, C. Analysing the Evolution of Concentration within Containerized Transport Chains through a Circuitist Approach: The Role of Innovations in Accelerating the Circuits of Liner and Container Terminal Operators. *Asian J. Shipp. Logist.* **2021**, *37*, 321–328. [CrossRef]
8. Liang, C.; Fan, L.; Xu, D.; Ding, Y.; Gen, M. Research on Coupling Scheduling of Quay Crane Dispatch and Configuration in the Container Terminal. *Comput. Ind. Eng.* **2018**, *125*, 649–657. [CrossRef]
9. Jakovlev, S.; Eglynas, T.; Voznak, M.; Jusis, M.; Partila, P.; Tovarek, J.; Jankunas, V. Detecting Shipping Container Impacts with Vertical Cell Guides inside Container Ships during Handling Operations. *Sensors* **2022**, *22*, 2752. [CrossRef]
10. Imai, A.; Nishimura, E.; Papadimitriou, S. Marine Container Terminal Configurations for Efficient Handling of Mega-Containerships. *Transp. Res. E Logist. Transp. Rev.* **2013**, *49*, 141–158. [CrossRef]

11. Hoffmann, N.; Stahlbock, R.; Voß, S. A Decision Model on the Repair and Maintenance of Shipping Containers. *J. Shipp. Trade* **2020**, *5*, 22. [CrossRef]
12. Carn, J. Smart Container Management: Creating Value from Real-Time Container Security Device Data. In Proceedings of the 2011 IEEE International Conference on Technologies for Homeland Security, HST 2011, Waltham, MA, USA, 15–17 November 2011; pp. 457–465. [CrossRef]
13. Mahmood, S.; Hasan, R.; Ullah, A.; Sarker, K.U. SMART Security Alert System for Monitoring and Controlling Container Transportation. In Proceedings of the 2019 4th MEC International Conference on Big Data and Smart City, ICBDSC 2019, Muscat, Oman, 15–16 January 2019. [CrossRef]
14. Nexxiot. *Smart Containers: Safe, Secure and Compliant Supply Chains*; Nexxiot: Frisco, TX, USA, 2023.
15. Tovarek, J.; Partila, P.; Jakovlev, S.; Voznak, M.; Eglynas, T.; Jusis, M. A New Approach for Early Detection of Biological Self-Ignition in Shipping Container Based on IoT Technology for the Smart Logistics Domain. In Proceedings of the 29th Telecommunications Forum (TELFOR 2021), Belgrade, Serbia, 23–24 November 2021.
16. Beaumont, P. Cybersecurity Risks and Automated Maritime Container Terminals in the Age of 4IR. In *Handbook of Research on Information and Cyber Security in the Fourth Industrial Revolution*; IGI Global: Hershey, PA, USA, 2018; pp. 497–516.
17. Gunes, B.; Kayisoglu, G.; Bolat, P. Cyber Security Risk Assessment for Seaports: A Case Study of a Container Port. *Comput. Secur.* **2021**, *103*, 102196. [CrossRef]
18. Yang, Y.; Sun, J.; Tang, L. Research on the Model of Risk Identification of Container Logistics Outsourcing Based Factor Analysis. In Proceedings of the 2008 IEEE International Conference on Service Operations and Logistics, and Informatics, Beijing, China, 12–15 October 2008; pp. 1680–1685. [CrossRef]
19. Budiyanto, M.A.; Fernanda, H. Risk Assessment of Work Accident in Container Terminals Using the Fault Tree Analysis Method. *J. Mar. Sci. Eng.* **2020**, *8*, 466. [CrossRef]
20. Wan, S.; Yang, X.; Chen, X.; Qu, Z.; An, C.; Zhang, B.; Lee, K.; Bi, H. Emerging Marine Pollution from Container Ship Accidents: Risk Characteristics, Response Strategies, and Regulation Advancements. *J. Clean. Prod.* **2022**, *376*, 134266. [CrossRef]
21. Zhou, G.; Li, D.; Bian, J.; Zhang, Y. Airfreight Forwarder's Shipment Planning: Shipment Consolidation and Containerisation. *Comput. Oper. Res.* **2024**, *161*, 106443. [CrossRef]
22. Maritime, N.K. RFID-Based RTLS for Improvement of Operation System in Container Terminals. In Proceedings of the 2006 Asia-Pacific Conference on Communications, Busan, Republic of Korea, 31 August–1 September 2006; pp. 1–5.
23. Chang, C.H.; Xu, J.; Song, D.P. An Analysis of Safety and Security Risks in Container Shipping Operations: A Case Study of Taiwan. *Saf. Sci.* **2014**, *63*, 168–178. [CrossRef]
24. Jakovlev, S.; Voznak, M. Auto-Encoder-Enabled Anomaly Detection in Acceleration Data: Use Case Study in Container Handling Operations. *Machines* **2022**, *10*, 734. [CrossRef]
25. Yuan, S.; Skinner, B.T.; Huang, S.; Liu, D.K.; Dissanayake, G.; Lau, H.; Pagac, D.; Pratley, T. Mathematical Modelling of Container Transfers for a Fleet of Autonomous Straddle Carriers. In Proceedings of the 2010 IEEE International Conference on Robotics and Automation, Anchorage, AK, USA, 3–7 May 2010; pp. 1261–1266. [CrossRef]
26. Gelareh, S.; Merzouki, R.; McGinley, K.; Murray, R. Scheduling of Intelligent and Autonomous Vehicles under Pairing/Unpairing Collaboration Strategy in Container Terminals. *Transp. Res. Part C Emerg. Technol.* **2013**, *33*, 1–21. [CrossRef]
27. Bahnes, N.; Kechar, B.; Haffaf, H. Cooperation between Intelligent Autonomous Vehicles to Enhance Container Terminal Operations. *J. Innov. Digit. Ecosyst.* **2016**, *3*, 22–29. [CrossRef]
28. Liu, C.I.; Jula, H.; Vukadinovic, K.; Ioannou, P. Automated Guided Vehicle System for Two Container Yard Layouts. *Transp. Res. Part C Emerg. Technol.* **2004**, *12*, 349–368. [CrossRef]
29. Jung, S.-H.; Lim, D.-S.; Nam, K.-C. An Economic Analysis of Transportation Equipments at Container Terminals. *J. Navig. Port Res.* **2011**, *35*, 167–172. [CrossRef]
30. Sharif, O.; Huynh, N. Storage Space Allocation at Marine Container Terminals Using Ant-Based Control. *Expert. Syst. Appl.* **2013**, *40*, 2323–2330. [CrossRef]
31. UNECE. *White Paper Smart Containers Real-Time Smart Container Data for Supply Chain Excellence. Simple, Transparent and Effective Processes for Global Commerce*; United Nations: Geneva, Switzerland, 2020.
32. Ting, S.L.; Wang, L.X.; Ip, W.H. A Study of RFID Adoption for Vehicle Tracking in a Container Terminal. *J. Ind. Eng. Manag.* **2012**, *5*, 22–52. [CrossRef]
33. American Bureau of Shipping. *Certification of Container Securing Systems*; American Bureau of Shipping: Spring, TX, USA, 2021.
34. Caballini, C.; Gracia, M.D.; Mar-Ortiz, J.; Sacone, S. A Combined Data Mining—Optimisation Approach to Manage Trucks Operations in Container Terminals with the Use of a TAS: Application to an Italian and a Mexican Port. *Transp. Res. E Logist. Transp. Rev.* **2020**, *142*, 102054. [CrossRef]

35. Choi, S.G.; Kim, S.K.; Kim, C.H. A Study on the Cost Allocation of the Container Terminal Operator Coalition through a Game-Theoretic Approach: Focusing on Busan New Port. *J. Korean Navig. Port Res.* **2020**, *44*, 211–218.
36. Yi, M.S.; Lee, B.K.; Park, J.S. Data-Driven Analysis of Causes and Risk Assessment of Marine Container Losses: Development of a Predictive Model Using Machine Learning and Statistical Approaches. *J. Mar. Sci. Eng.* **2025**, *13*, 420. [CrossRef]

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