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Digitalization and Sustainability Integration in Container Terminal Operations: Evidence from a Lithuanian Port Case Study

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Abstract

Digitalization and sustainability have become key priorities in the development of container terminals. However, existing research has largely examined smart port technologies and sustainability initiatives separately, while empirical evidence regarding their integration in medium-sized container terminals remains limited. This study investigates the relationship between digitalization and sustainability in container terminal operations through a qualitative case study conducted at a medium-sized container terminal in the Port of Klaipėda, Lithuania. Data were collected through document analysis and semi-structured interviews with employees involved in terminal operations, planning activities, and digitalization and sustainability initiatives. Qualitative content analysis was applied to identify key themes related to technological implementation, operational efficiency, environmental performance, and organizational challenges. The findings indicate that digital technologies, including the Terminal Operating System, Vehicle Booking System, automated gate solutions, and the Port Community System, contribute to improved operational efficiency, enhanced information exchange, reduced congestion, and more effective resource utilization. Sustainability initiatives, including equipment electrification, renewable energy adoption, and energy-efficient infrastructure, support reductions in energy consumption and environmental impacts. Nevertheless, challenges related to system interoperability, fragmented information flows, organizational adaptation, and employee competencies continue to limit the full realization of these benefits. The results demonstrate that digitalization and sustainability should be viewed as interconnected dimensions of container terminal development rather than independent strategic objectives. The study contributes empirical evidence from a medium-sized Baltic Sea container terminal and provides practical insights for ports seeking to advance digital and sustainable transformation simultaneously.

Keywords: container terminal; digitalization; sustainability; smart port; green port; digital transformation; Port of Klaipeda

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1. Introduction

Container terminals are critical nodes of global logistics systems because they connect maritime transport with inland transport networks and determine the speed, reliability and cost of cargo flows within international supply chains [1–3]. Their operational performance affects not only terminal productivity but also the competitiveness of port regions and the resilience of wider logistics corridors [4,5]. At the same time, terminals operate under increasing pressure caused by growing cargo volumes, higher service expectations, infrastructure constraints, labour limitations and stricter environmental requirements [2,3,5]. These pressures have made digitalization and sustainability two central priorities in contemporary port and terminal development.

Digitalization in container terminal operations refers to the use of information and communication technologies to automate processes, improve information exchange, increase operational visibility and support data-driven decision-making [6–9]. The main technologies discussed in the literature include terminal operating systems (TOS), port community systems (PCS), vehicle booking systems (VBS), automated gate systems, Internet of Things (IoT) applications, big data analytics, artificial intelligence (AI), blockchain and digital twins [8–18]. These technologies are expected to improve planning accuracy, reduce waiting times, support equipment allocation, enhance cargo tracking and strengthen coordination between terminal operators, shipping lines, customs authorities, freight forwarders and inland transport providers [9–15]. Therefore, digitalization is no longer considered only a technical modernization process; it is increasingly treated as an organizational transformation that changes information flows, decision-making routines and stakeholder relationships in port logistics [6,7,14,15].

The smart port concept has emerged from this broader digital transformation agenda. Smart ports use connected technologies, data infrastructures and intelligent management systems to improve operational efficiency, transparency, safety, security and stakeholder collaboration [10,14–18]. Recent systematic and bibliometric reviews show that smart port research has expanded rapidly, with digitalization, automation, IoT, AI, performance indicators and sustainability becoming dominant themes [14–18]. However, the literature also indicates that smart port development is uneven: large hub ports usually have stronger financial capacity, technological maturity and institutional support, whereas medium-sized and regional terminals often face more limited resources, fragmented systems and slower organizational adaptation [15,18]. This creates a need for more empirical research on how digital transformation unfolds in operationally constrained terminal environments.

Sustainability has developed in parallel as a core objective of port and terminal management. Ports contribute to economic development but also generate negative externalities, including greenhouse gas emissions, local air pollution, noise, water contamination, land-use pressure and energy consumption [19–26]. Green port and sustainable port approaches therefore emphasize emission reduction, energy efficiency, renewable energy use, electrification of cargo-handling equipment, environmental monitoring, waste reduction and structured environmental management [20–29]. Existing studies show that energy management, electrified equipment, environmental performance indicators and formal management systems can support both environmental improvement and operational efficiency [21–28]. In addition, international strategies and policy initiatives increasingly frame ports as important actors in maritime decarbonization and climate transition [37–39].

Despite the growing attention to both smart ports and green ports, these two research streams have often developed separately. Digitalization studies tend to focus on operational efficiency, automation and information systems, while sustainability studies often focus on energy, emissions, environmental indicators and governance mechanisms [6–14,20–29]. This separation limits understanding of how digital technologies can actively support sustainability-related outcomes in everyday terminal operations. Recent research increasingly argues that digitalization can be an enabler of sustainability because it improves data availability, supports environmental monitoring, optimizes equipment use, reduces truck congestion, decreases unnecessary container movements and strengthens evidence-based decision-making [18,30–40]. Nevertheless, empirical evidence remains fragmented, particularly in medium-sized container terminals where system integration, data quality, investment capacity and employee competencies may constrain implementation [15,18,40].

This study addresses this gap by investigating the integration of digitalization and sustainability in container terminal operations through an exploratory case study of a medium-sized terminal operating in the Lithuanian seaport. In this article, integration is understood as the extent to which digital systems support sustainability-related objectives through process automation, information sharing, operational optimization, environmental monitoring and resource-efficient decision-

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making. The study contributes to the literature in three ways. First, it provides empirical evidence on the interaction between digitalization and sustainability in a medium-sized terminal context. Second, it identifies technological and organizational challenges affecting implementation, including system fragmentation, data transfer problems, employee adaptation and investment uncertainty. Third, it extends smart port and green port research by examining a Baltic Sea region terminal, a context that remains underrepresented compared with large international hub ports.

2. Literature Review

2.1. Digitalization in Container Terminal Operations

Digitalization has become a key mechanism through which container terminals seek to improve operational performance and respond to increasing logistics complexity. The literature emphasizes that digital technologies improve the availability, speed and reliability of operational information, which is essential for coordinating vessel, yard, gate and hinterland activities [6–9]. TOS platforms are usually regarded as the backbone of terminal digitalization because they support vessel planning, container tracking, yard management, equipment allocation and reporting [8,12]. PCS and single-window systems extend digitalization beyond the terminal by connecting public and private actors and reducing fragmented administrative procedures [8,13]. VBS and automated gates further support the synchronization of truck arrivals and gate operations, reducing bottlenecks and improving the predictability of landside flows [13,18].

The smart port literature expands this operational perspective by linking digitalization with broader organizational and strategic change. Molavi et al. [10] propose that smart port development requires technological infrastructure, data integration, governance and performance measurement. Li et al. [14] show that smart port research is strongly associated with IoT, big data, cloud computing, AI and performance indicators. Belmoukari et al. [15] further argue that the smart port should be understood as a connected, sustainable, safe and automated port supported by smart infrastructure, skilled personnel and smart managerial practices. These studies indicate that technology alone is insufficient; smart port development depends on the alignment of digital tools, organizational capabilities and stakeholder collaboration.

AI, data analytics and digital twins have recently become important topics in terminal digitalization research. AI-based approaches can support berth allocation, equipment scheduling, predictive maintenance and traffic forecasting, while digital twins create virtual representations of port or terminal operations that can be used for simulation, scenario assessment and data-driven planning [16–18]. Digital twin research is especially relevant because it connects operational modelling with sustainability assessment: by simulating alternative operational scenarios, terminal managers can evaluate not only productivity effects but also resource consumption, congestion and emission-related outcomes [16,17]. This makes digital twins particularly important for the emerging smart-green port agenda.

However, the benefits of digitalization are not automatic. Studies repeatedly identify barriers such as interoperability problems, legacy systems, data fragmentation, cybersecurity risks, high investment costs and insufficient employee skills [7,13,15,18]. In many terminals, digital systems are introduced incrementally rather than as part of a fully integrated architecture. This can create parallel platforms, duplicated data entry and manual data transfers, reducing the expected benefits of automation and information visibility. Therefore, digitalization should be analysed as a socio-technical transformation rather than as a simple adoption of technologies.

2.2. Sustainability in Container Terminal Operations

Sustainability in ports and terminals is usually discussed through the green port, sustainable port and port decarbonization perspectives. These approaches share the assumption that terminals must reduce environmental externalities while maintaining economic performance and service reliability [19–29]. The environmental dimension is particularly important because terminal

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operations involve energy-intensive cargo-handling equipment, trucks, lighting, storage areas and infrastructure that can generate emissions, noise and other local impacts [20–28].

Energy management is one of the most developed sustainability themes in the literature. Acciaro et al. [21] argue that ports can play an active role in energy transition by managing energy demand, introducing renewable energy and coordinating stakeholders. Acciaro et al. [22] further show that energy efficiency in seaports is linked to operational planning, equipment choices and infrastructure investments. Electrification of rubber-tyred gantry cranes and other handling equipment is often identified as a practical measure for reducing fuel consumption and emissions [27]. Renewable energy systems, LED lighting, shore-side electricity and environmental monitoring technologies are also widely discussed as measures that support green port development [23–29].

Environmental management systems and indicators form another important part of sustainability implementation. Darbra et al. [25] and Puig et al. [23,24] show that ports require structured indicators and management methods to measure environmental performance, identify risks and support continuous improvement. Schipper et al. [26] stress that sustainability assessment should include not only environmental indicators but also planning and governance dimensions. Recent reviews of port sustainability and decarbonization confirm that the literature has expanded, but also remains fragmented across technologies, indicators, governance tools and implementation mechanisms [39–46].

Decarbonization has become a particularly important theme in recent years. IMO and ESPO policy documents emphasize greenhouse gas reduction, energy transition and environmental performance measurement as key priorities for maritime and port sectors [37,38]. Recent reviews show that port decarbonization requires a combination of technological measures, energy management, regulatory instruments, stakeholder coordination and business strategy [39,44]. These findings are relevant for container terminals because many sustainability measures depend on operational decisions made at the terminal level, including equipment deployment, truck flow management, yard planning and energy use.

2.3. Integration of Digitalization and Sustainability

The integration of digitalization and sustainability is the central theoretical issue of this study. Earlier literature often treated smart port and green port concepts separately: smart port research emphasized operational efficiency and digital technologies, whereas green port research emphasized emissions, energy and environmental governance [6–15,20–29]. More recent studies increasingly challenge this separation by arguing that digital technologies can support sustainability through data generation, monitoring, optimization and decision support [18,30–40].

Several operational mechanisms explain this relationship. First, TOS platforms can reduce unnecessary container re-handling and equipment movements by improving yard planning and container location accuracy [8,12]. Second, VBS and automated gate systems can reduce truck queues, idling and congestion-related emissions by coordinating arrivals and improving gate processing [13,18]. Third, PCS and single-window systems can reduce administrative duplication, support paperless operations and improve information flow across logistics actors [8,13]. Fourth, IoT sensors and smart monitoring systems can collect data on energy use, equipment utilization, emissions and environmental conditions [18,32]. Fifth, AI and digital twins can support predictive maintenance, scenario modelling and resource optimization, linking operational planning with environmental outcomes [16,17].

The literature therefore suggests that digitalization can contribute to sustainability not only indirectly through efficiency but also directly through monitoring, reporting and environmental decision-making [18,30–40]. However, this potential depends on the integration of systems, the quality of data, employee capabilities and managerial commitment. If digital systems remain fragmented, the sustainability benefits of digitalization may be limited because operational data cannot be transformed into coherent environmental indicators or optimization routines [7,13,15]. This is particularly relevant for medium-sized terminals, where investment capacity and digital maturity are often lower than in major hub ports.

Recent systematic reviews support the need for more empirical research in this area. Smart port reviews identify digitalization, sustainability and governance as increasingly connected but still unevenly studied themes [14,15]. Reviews on smart port sustainability show that research is growing but remains concentrated on conceptual frameworks and large-port examples, with less attention to implementation in smaller operational contexts [40]. Reviews of port sustainability and decarbonization similarly show that actions and measures are fragmented and that implementation mechanisms require further investigation [39,41,44–46]. Therefore, there remains a clear gap concerning how digital and sustainable practices are jointly implemented in everyday terminal operations.

2.4. Research Gap and Conceptual Position of the Study

The reviewed literature demonstrates that digitalization and sustainability are both essential for contemporary container terminal development. However, the interaction between these dimensions remains insufficiently explained at the operational level. Existing research provides strong evidence that digital technologies can improve information exchange, planning and operational efficiency [6–18], and that sustainability measures can reduce environmental impacts and improve energy performance [20–29,37–46]. Yet fewer studies examine how these two agendas interact in a single terminal context, how employees experience implementation, and how technological fragmentation affects sustainability-oriented outcomes.

This study addresses this gap by analysing digitalization and sustainability as interconnected rather than independent dimensions of terminal development. The conceptual position is that digital systems support sustainability when they enable process automation, information sharing, resource optimization, environmental monitoring and evidence-based decision-making. This perspective is particularly relevant for medium-sized container terminals, where integration challenges may be more visible than in highly automated global hubs. By focusing on a Lithuanian port case, the study contributes empirical evidence from a Baltic Sea regional context and provides practical insights for terminals pursuing digital and environmental transformation simultaneously.

Table 1. Relationship between digitalization and sustainability in container terminal operations.

Digital technology	Operational function	Sustainability contribution
Terminal Operating System (TOS)	Container and equipment management	Reduced unnecessary movements, re-handling and fuel consumption
Vehicle Booking System (VBS)	Truck arrival coordination	Reduced gate congestion, truck waiting time and idling emissions
Automated gate system	Vehicle identification and gate processing	Faster processing, fewer queues and better data capture
Port Community System (PCS)	Stakeholder information exchange	Paperless operations and reduced administrative duplication
IoT monitoring systems	Real-time monitoring of equipment and environment	Improved energy, emission and environmental performance management
AI and predictive analytics	Forecasting, optimization and predictive maintenance	Lower resource waste and improved equipment reliability

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The literature suggests that digitalization and sustainability should not be viewed as independent development pathways. Instead, digital technologies increasingly function as enablers of sustainability through process optimization, environmental monitoring, resource efficiency, and data-driven decision-making. However, existing studies remain largely conceptual and provide limited empirical evidence on how these interactions occur in medium-sized container terminals.

Therefore, this study adopts an integrated perspective and investigates how digitalization contributes to sustainability objectives within a Lithuanian container terminal. Particular attention is given to implementation practices, organizational challenges, and the operational mechanisms linking digital technologies with sustainability outcomes.

3. Materials and Methods

3.1. Research Design

This study employed a qualitative case study approach to investigate the integration of digitalization and sustainability in container terminal operations. Case study research is particularly suitable for examining contemporary phenomena within their real-life context, especially when the boundaries between the phenomenon and its context are not clearly evident [51]. The approach enables an in-depth understanding of organizational processes, technological implementation practices, and contextual factors influencing operational performance.

A qualitative research design was selected because it allows researchers to explore participants' experiences, perceptions, and interpretations regarding digitalization and sustainability initiatives [52]. Qualitative methods are particularly appropriate when investigating complex organizational processes that cannot be adequately explained through quantitative indicators alone.

The empirical investigation focused on a medium-sized container terminal operating in the Port of Klaipeda, Lithuania. The case was selected using purposive sampling because the terminal has implemented several digital technologies and sustainability initiatives, making it suitable for examining the interaction between these two dimensions [53].

3.2. Data Collection

Data collection was conducted using two complementary qualitative methods: document analysis and semi-structured interviews. The use of multiple data sources enabled methodological triangulation and contributed to a more comprehensive understanding of the investigated phenomenon [57].

Document analysis. Document analysis was conducted to obtain contextual and operational information regarding terminal activities, digital technologies, sustainability initiatives, and organizational practices. The analysed materials included operational reports, environmental documentation, internal procedures, technical descriptions of information systems, investment-related documentation, and publicly available information related to terminal operations.

Document analysis is recognized as an important qualitative research method because it enables researchers to examine organizational processes through existing records while providing contextual understanding and supporting data triangulation [54]. The analysed documentation covered operational, technical, and environmental aspects of terminal activities, including information related to digital systems, sustainability measures, infrastructure development, and organizational processes. The use of documentary evidence provided an additional source of information for validating interview findings and identifying consistencies and discrepancies between formal procedures and operational practices [54].

The findings obtained from document analysis were subsequently used to support data interpretation and refine the interview protocol.

Semi-structured interviews. Semi-structured interviews were conducted with employees representing different operational and managerial perspectives within the container terminal. Participants were selected using purposive sampling based on their involvement in operational

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processes, digital system utilization, planning activities, and sustainability-related initiatives [53]. This approach ensured that the collected data reflected practical experience and organizational knowledge regarding the implementation and use of digital and sustainable solutions.

The interview protocol was developed based on the findings of the literature review and the results obtained during the document analysis stage. Particular attention was given to topics related to digital technology implementation, operational efficiency, information sharing, environmental performance, sustainability initiatives, and organizational challenges. The final interview guide consisted of open-ended questions designed to encourage respondents to describe their experiences and perceptions regarding digital technologies, sustainability practices, implementation barriers, and future development opportunities [55].

The interview questions were organized around four thematic areas:

1. Digital technologies and information systems;
2. Operational efficiency and process integration;
3. Sustainability practices and environmental initiatives;
4. Implementation challenges, organizational adaptation, and future development opportunities.

Semi-structured interviewing was selected because it enables the collection of comparable information across participants while allowing sufficient flexibility to explore context-specific experiences and emerging themes [55]. All interviews were conducted individually, audio-recorded with participant consent, transcribed verbatim, and anonymized before analysis. To ensure confidentiality, respondents were assigned identification codes and all personally identifiable information was removed from the transcripts.

3.3. Data Analysis

The collected data were analysed using qualitative content analysis, a method widely applied in organizational and management research for the systematic interpretation of textual information [56].

The analytical process consisted of four stages. First, interview transcripts and documentary materials were reviewed repeatedly to obtain a comprehensive understanding of the collected data. Second, meaningful statements related to digitalization and sustainability were identified and assigned initial codes. Third, the codes were grouped into subcategories and broader thematic categories according to conceptual similarities. Finally, relationships among categories were interpreted and compared with findings reported in previous studies.

An inductive coding approach was employed, allowing themes and categories to emerge directly from the empirical material rather than being imposed through a predefined theoretical framework [56]. Particular attention was given to identifying recurring patterns associated with digital technology implementation, operational efficiency, sustainability initiatives, environmental performance, organizational capabilities, and implementation barriers.

Category Development

The coding process resulted in the identification of several higher-order categories reflecting the relationship between digitalization and sustainability within container terminal operations. Initial codes were progressively grouped into subcategories and broader thematic categories based on conceptual similarities and their relevance to the study objectives [56].

The final analytical framework consisted of five main categories:

1. Digital system performance and operational efficiency;
2. Information flow and system interoperability;
3. Sustainability practices and environmental performance;
4. Strategic integration of digitalization and sustainability;
5. Implementation challenges and organizational adaptation.

These categories provided the basis for the interpretation of findings and the development of the results section.

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3.4. Research Quality and Trustworthiness

Several procedures were applied to enhance the credibility, dependability, and trustworthiness of the study [57]. First, methodological triangulation was achieved through the integration of document analysis and interview data. The use of multiple data sources enabled the validation of findings and reduced the risk of relying on a single source of evidence.

Second, all interview data were transcribed and analysed systematically following clearly defined coding and categorization procedures. Third, analytical decisions and category development processes were documented throughout the study to ensure transparency and consistency. Fourth, the interpretation of findings was continuously compared with insights from the scientific literature to strengthen analytical validity.

Furthermore, triangulation was applied not only through the use of multiple data sources but also through the comparison of empirical findings with insights derived from the scientific literature. The integration of documentary evidence and interview data enabled the validation of recurring themes and reduced the likelihood of single-source bias. Such an approach is considered particularly important in qualitative case study research, where credibility depends on the convergence of evidence from different sources [51,57].

Although the study is based on a single case, the objective was analytical rather than statistical generalization. Consistent with case study research principles, the findings provide in-depth insights into the mechanisms through which digitalization and sustainability interact within a real operational environment [51]. Consequently, the study contributes to the development of knowledge regarding digital and sustainable transformation in container terminal operations and provides practical implications for similar terminal contexts.

4. Results and Discussion

The results of the case study demonstrate that the integration of digitalization and sustainability in the analyzed container terminal leads to measurable improvements in operational efficiency; however, these benefits remain constrained by technological and organizational limitations. The findings are discussed across four key dimensions: operational efficiency of digital systems, system integration challenges, sustainability performance, and implementation risks.

4.1. Digital Systems and Operational Efficiency

The terminal utilizes several core digital systems, including the terminal operating system Autostore, the vehicle booking system (VBS), the automated gate control system, and the port community system KIPIS. These systems support real-time container tracking, yard management, and traffic coordination.

The Autostore system has been in operation for approximately 18 years and remains central to container flow management. The evaluation of Autostore (Table 2) reveals a clear divergence in employee perceptions. Operational users emphasize its reliability, adaptability, and effectiveness in tracking container movements and managing inventory. In contrast, other employees highlight limitations such as outdated functionality, system instability, and restricted access to information.

Table 2. Evaluation of Autostore and implementation of additional digital technologies.

Category	Subcategory	Supporting statements
“Evaluation of the Autostore programme	Excellent	R-C “The Autostore app is excellent, <..> tracking the location of the container <..>, the app offers <..> inventory updates <..> reports on the movement of containers”.
	Positive	R-A “I have nothing but positive things to say about Autostore”. R-A “<...> no longer does the RTG shoreman have to think about where to park, <...> the Autostore app can show these locations”.

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	Tailored to your needs	R-A "the programme can be adapted to our needs<..>".
	Negative	R-B "Autostore is an old application <..> makes it difficult to disseminate information <..>". R-B "<..> incomplete view of the system <..> driver dissatisfaction<..>". R-B "program malfunctions <..> make the program stuck, <..> complicate <..> the work being done, <..> affect the loading processes <..>".
Development of digital technologies	Work allocation	R-A "<..> introduce a programme to automatically allocate work <..> fewer planners would be needed <..> fewer mistakes would occur".
	Sharing information	R-B "<..> additional information sharing system <..> regarding changes in loading operations and procedures
	Not planned	R-C "we have no plans to introduce new programmes, <..>".

This divergence indicates that system effectiveness depends strongly on user roles and access to real-time data. As a result, digital system performance is uneven across the organization. While Autostore continues to support core operations, its limited integration and lack of advanced functionalities reduce its contribution to further efficiency gains.

The findings presented in Table 2 indicate that the benefits of digitalization are perceived differently depending on employees' responsibilities and interaction with the system. While operational personnel emphasize the contribution of Autostore to container tracking, inventory management, and workflow coordination, other respondents identify limitations associated with information accessibility and system functionality. This suggests that the effectiveness of digital technologies is influenced not only by technical capabilities but also by how information is distributed across organizational functions.

Similar observations have been reported by Heilig and Voß [6,8], who argue that digital technologies create value only when operational information is available to relevant stakeholders in a timely manner. Fragmented access to information may reduce the potential benefits of digital systems and negatively affect decision-making processes. The findings also support the conclusions of Belmoukari et al. [15], who identified interoperability and information-sharing challenges as persistent barriers to smart port development.

Furthermore, the results demonstrate that digitalization should be understood as an organizational transformation rather than solely a technological investment. As highlighted by Fruth and Teuteberg [7], successful digital transformation requires alignment between technological infrastructure, operational processes, and employee capabilities. Therefore, future improvements should focus not only on introducing new digital tools but also on enhancing system usability and information accessibility.

At the same time, newer systems such as VBS have introduced measurable improvements. The VBS enables pre-registration of vehicle arrivals, reducing congestion and waiting times at terminal gates. Similarly, the automated gate system improves vehicle processing speed and enhances data collection. These findings confirm that digital technologies contribute to improved operational efficiency, consistent with previous research highlighting the role of digital maturity in port performance [18,22,23].

4.2. System Integration and Data Fragmentation

A critical issue identified in the study is the lack of interoperability between digital systems. The absence of integration between Autostore and KIPIS requires manual data transfer, increasing administrative workload and the risk of human error. This fragmentation significantly reduces the effectiveness of digitalization and limits the potential of data-driven decision-making.

The implementation of the automated gate system further illustrates the importance of organizational factors. As shown in Table 3, the system itself is evaluated positively and functions according to operational requirements. However, the main challenges are related to staff training and user adaptation.

Table 3. Evaluation of the automatic gate system and operational problems.

Category	Subcategory	Supporting statements
Evaluation of automatic gates	Positive evaluation	R-C “<..> is now running smoothly”. R-A “<...> the idea is a good one, and it looks like it will definitely be implemented”.
	System installation underway	R-A “It would be difficult to comment <...> briefly on how the system is used”.
Problems	Weaknesses in staff training	R-B “<..> Lack of staff training” R-C “<..> staff training, <..> was not targeted, showing actions that would not be required R-C “<...> staff were lost<..>”.
	Drivers’ mistakes	R-B “<...> drivers often enter the wrong lane, causing congestion”.

The analysis indicates that the primary barrier is not technological performance but insufficiently targeted training and lack of practical user preparation. Training processes were characterized by information overload and limited focus on operational tasks, which reduced system usability and required repeated training efforts. In addition, user-related errors, particularly incorrect lane selection by drivers, continue to disrupt traffic flow.

These findings demonstrate that the success of digital systems depends not only on technological capabilities but also on effective implementation processes, employee competencies, and organizational readiness, as emphasized in previous studies.

The results summarized in Table 3 reveal that implementation challenges are primarily associated with organizational factors rather than technological deficiencies. Respondents generally evaluated the automated gate system positively; however, difficulties emerged during the adaptation process due to insufficiently targeted training and limited practical preparation. This finding confirms that technological investments alone cannot guarantee successful digital transformation.

Previous studies have similarly emphasized the importance of human and organizational dimensions in digitalization projects. Fruth and Teuteberg [7] identified employee competencies and resistance to change as significant barriers to digital adoption in maritime logistics. Likewise, Belmoukari et al. [15] argue that smart port initiatives require not only technological infrastructure but also organizational learning and stakeholder engagement.

Another important issue highlighted by the respondents is the lack of integration between Autostore and KIPIS. The necessity of manual data transfer creates inefficiencies, increases administrative workload, and raises the risk of human error. Similar interoperability challenges have been widely documented in port digitalization research [8,13,15]. Consequently, improving system integration should be considered one of the key priorities for strengthening digital maturity and supporting data-driven decision-making.

4.3. Sustainability Practices and Environmental Performance

The analysis shows that the terminal actively implements sustainability measures aimed at reducing environmental impact and improving resource efficiency. As presented in Table 4, these

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measures can be grouped into three main categories: operational optimization, technological solutions, and environmental monitoring.

Table 4. Pollution abatement measures for the marine container terminal.

Tarsha	Pollution reduction techniques
Air pollution	Organise handling operations so that the same container is handled as little as possible; In the terminal area, vehicles must switch off their engines during loading; Employees are not allowed to drive loading equipment when loading processes are not taking place; Installing electric cranes and other handling equipment; In windy weather, the area is irrigated.
Water pollution	The surface of the site is covered with a hard waterproof coating; Collection and treatment of surface water from operational loading and storage areas.
Noise/vibration pollution	Vehicle speeds are limited to 20 km/h; Container storage pavement replacement with a smooth surface; Container barriers for sound insulation

Operational measures focus on minimizing unnecessary container handling and reducing equipment idling, while technological solutions include electrified and hybrid handling equipment, LED lighting, and renewable energy systems. Environmental monitoring ensures compliance with regulatory requirements and control of pollution levels.

Significant investments have been made to support these initiatives. In 2023, approximately EUR 800,000 was invested in energy-efficient LED lighting systems, reducing electricity consumption and light pollution. Additionally, EUR 350,000 was allocated to solar energy infrastructure, which currently generates around 13% of the terminal's electricity demand and reduces CO_2 emissions by approximately 250 tons per year.

These results demonstrate that sustainability measures provide both environmental and operational benefits. Similar findings are reported in the literature, where energy efficiency and renewable energy integration are key elements of green port development.

However, the analysis also shows that sustainability practices remain primarily operational. The absence of a certified environmental management system, such as ISO 14001, indicates that sustainability is not fully integrated into a structured management framework. This limits the potential for systematic performance improvement and aligns with previous research emphasizing the importance of formal sustainability management systems. The sustainability measures presented in Table 3 demonstrate that environmental considerations are increasingly embedded within everyday terminal operations. The combination of operational optimization, equipment electrification, renewable energy utilization, and environmental monitoring reflects a transition from reactive environmental compliance towards a more proactive sustainability approach.

These findings are consistent with previous studies emphasizing energy efficiency and renewable energy integration as essential components of green port development [21,22,28]. Acciaro et al. [21] argue that ports can play a significant role in the energy transition through investments in renewable energy infrastructure and improved energy management practices. Similarly, Lam and Notteboom [28] identify technological modernization as one of the most effective approaches for reducing environmental impacts while maintaining operational efficiency.

The investments in LED lighting and solar energy systems are particularly important because they generate both environmental and economic benefits. In addition to reducing emissions and electricity consumption, such measures contribute to long-term operational resilience by lowering

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dependence on conventional energy sources. Similar benefits have been identified in recent studies on port decarbonization and sustainable infrastructure development [39,46].

4.4. Sustainability Integration and Strategic Orientation

The analysis of sustainability objectives (Table 5) indicates that the terminal prioritizes the electrification of handling equipment, increased use of renewable energy, and reduction of energy consumption. Additional measures include pollution monitoring, process optimization, and investments in green technologies.

Table 5. Objectives and measures set by the terminal to implement the Green Port concept.

Category	Subcategory	Supporting statements
Objectives	Electrified handling equipment	R-B "<..> use of electrified and hybrid handling equipment". R-C "<..>we will electrify the fleet as far as possible <..>".
	Renewable energy	R-C "<...> 100% switch to renewable electricity".
Measures to be applied	Monitoring	R-A "<..> pollution control, monitoring <..>". R-B "<..> we measure wastewater treatment<..>". R-C "<..>we have carried out pollution measurements <..>".
	LED lighting	R-A "<..> we have changed the lighting, we are now using LED lights <..>".
	Solar batteries	R-A "<..> we have installed solar panels <..>" R-B: "<..> the installation of solar power plants <..> has improved sustainability and reduced fuel use". R-C "<..> we have invested in solar power<..>".
	Process organisation	R-A "<..> to organise processes in such a way as to minimise environmental impacts".
	Technique differentiation	R-B "<..>we strictly allocate machinery to jobs". R-B "We plan loading operations <...> Avoid reloading the container and idling the machinery".
	Cleaning works	R-B "<..>Terminal cleaning work in progress<..>"
	Reducing energy consumption	R-C "<..>reduce energy consumption".
	Purchasing green energy	R-C "<..> signing a contract <..> for the purchase of green energy.

While these initiatives demonstrate a clear commitment to sustainability, their implementation remains fragmented. Sustainability is embedded in individual operational practices rather than integrated into a comprehensive strategic framework. This limits the ability to achieve higher levels of environmental performance and alignment with international standards.

The findings suggest that the integration of digitalization and sustainability requires not only technological adoption but also strategic coordination. This supports previous research highlighting the need for integrated approaches to smart and green port development.

The evidence presented in Table 5 indicates that sustainability objectives are increasingly influencing operational and investment decisions within the terminal. However, the findings also suggest that sustainability initiatives remain predominantly project-based and operationally oriented rather than being embedded within a comprehensive strategic management framework.

This observation corresponds with previous sustainability research, which has shown that many ports implement environmental initiatives incrementally through individual projects rather than through integrated sustainability strategies [41,42]. Although such initiatives contribute positively to environmental performance, their long-term effectiveness may be constrained by the absence of clearly defined sustainability indicators, governance structures, and performance monitoring systems.

The findings further demonstrate that sustainability and digitalization are becoming increasingly interconnected. Several sustainability-related activities, including environmental monitoring, energy management, process optimization, and operational planning, depend on digital technologies and data availability. This supports recent studies suggesting that digitalization functions as an enabler of sustainability by improving transparency, resource efficiency, and evidence-based decision-making [18,39,40].

4.5. Implementation Challenges and Risks

The study identifies several key risks associated with the implementation of digital and sustainable technologies. As shown in Table 6, these risks can be categorized into three main groups: knowledge-related, technological, and financial risks.

Table 6. Challenges and solutions for investing in new technologies.

Category	Subcategory	Supporting statements
Risks	Lack of knowledge	R-A “Buying a product and often not knowing <..>”.
	Lack of experience	R-A “<..> sustainable technologies are <..> unexplored, we have no experience <..>”.
	Eligibility	R-A “<..>will it fit in our terminal <..>”.
	Compatibility	R-B “<..> difficult to reconcile with the needs of the terminal”.
	Unmet expectations	R-B “ <...> will not live up to expectations <...>”.
Risk management	Installing well-known handling equipment	R-A “<..> invest in technology with which we are already familiar <..>”. R-B “<..> we choose equipment that is already known or very similar <..>”.
	Staff training	R-B “<..> invest in training<..>”.
	Terms of the contract	R-A: “<..> when we conclude the purchase contract, we shall include conditions <..> for its return”.
	Return of equipment	R-B “<..> the equipment has been returned”.
	Assessing the reliability of the technology	R-C “<..> assess the reliability of the technology <..>”.
	Ergonomics	R-C “<...> we take into account innovation, ergonomics, environmental friendliness, <...> maintenance costs”.
	Loading speed parameters	R-C “<..> when purchasing equipment, we compare loading speed parameters<..>”.
	Sustainability	R-C “<..> we take into account <..> environmental friendliness”.
	Maintenance costs	R-C “<...> we take into account <...> maintenance costs”.

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Knowledge-related risks include limited experience with new technologies and insufficient understanding of their operational implications. Technological risks are associated with system compatibility and uncertainty regarding performance in the specific terminal context. Financial risks relate to uncertainty about return on investment and long-term cost efficiency.

To mitigate these risks, the terminal adopts a cautious investment strategy, prioritizing proven technologies and evaluating solutions based on reliability, performance, sustainability, and maintenance costs. While this approach reduces uncertainty, it also limits the adoption of more advanced innovations.

These findings indicate that risk aversion significantly influences technological development in container terminals. Although it supports operational stability, it may slow digital transformation and reduce long-term competitiveness, as also highlighted in previous studies.

Table 6 illustrates that uncertainty remains a major factor influencing investment decisions related to digital and sustainable technologies. The identified risks extend beyond financial considerations and include concerns regarding technological compatibility, operational suitability, and the ability of employees to adapt to new systems and working methods.

Similar challenges have been reported in studies examining innovation adoption within maritime logistics and port environments [15,18,49]. Organizations often prefer established technologies because they provide greater certainty regarding performance outcomes and operational reliability. However, excessive reliance on proven solutions may simultaneously reduce innovation capacity and slow the implementation of emerging technologies capable of generating substantial operational and environmental benefits.

The risk mitigation measures identified by respondents—including technology assessment, pilot implementation, staff training, contractual safeguards, and performance evaluation—are consistent with recommendations found in the literature [15,49]. These measures help reduce uncertainty and support more informed investment decisions. Nevertheless, balancing innovation and risk management remains one of the most significant challenges for medium-sized container terminals pursuing digital and sustainable transformation.

4.6. Synthesis of Findings

The integrated analysis highlights three key insights. First, digital technologies generate measurable improvements in operational efficiency but remain constrained by system fragmentation and limited integration. Second, sustainability measures contribute to environmental performance but are primarily operational and not fully embedded in strategic management systems. Third, the successful implementation of digital and sustainable solutions depends on organizational capabilities, including employee competencies, training quality, and process alignment.

Overall, the findings demonstrate that the integration of digitalization and sustainability in container terminal operations is a complex and non-linear process shaped by both technological and organizational factors.

4.7. Discussion

The findings of this study demonstrate that digitalization and sustainability are increasingly interconnected dimensions of container terminal development. While digital technologies primarily support operational efficiency, their influence extends beyond productivity improvements and contributes to environmental performance through enhanced planning, reduced congestion, optimized resource utilization, and improved monitoring capabilities.

The results confirm previous research suggesting that digital technologies can serve as important enablers of sustainability [18,30–40]. However, the study also demonstrates that these benefits are not generated automatically. Their realization depends on system interoperability, information quality, organizational readiness, and employee competencies. Consequently, digital transformation should be viewed as a socio-technical process requiring both technological and organizational adaptation.

Another important finding concerns the role of organizational capabilities. The implementation challenges identified in this study indicate that employee training, change management, and process alignment remain critical determinants of successful technology adoption. This supports the arguments presented by Fruth and Teuteberg [7] and Belmoukari et al. [15], who emphasize that organizational factors often represent a greater barrier to digital transformation than technological limitations.

From a sustainability perspective, the findings reveal that environmental initiatives are increasingly integrated into terminal operations but remain only partially embedded within strategic management processes. Although significant investments have been made in renewable energy, electrification, and energy efficiency measures, the absence of formal sustainability management frameworks limits opportunities for systematic performance improvement.

Overall, the study extends smart port and green port research by demonstrating that sustainability outcomes emerge not only from dedicated environmental initiatives but also from the effective integration and utilization of digital technologies within everyday terminal operations.

5. Conclusions

This study examined the integration of digitalization and sustainability in container terminal operations through a qualitative case study conducted at a medium-sized container terminal in the Port of Klaipeda, Lithuania. The findings indicate that digital technologies, including the Terminal Operating System, Vehicle Booking System, automated gate solutions, and the Port Community System, contribute to improved operational efficiency, enhanced information exchange, and more effective resource utilization. At the same time, sustainability initiatives, such as equipment electrification, renewable energy adoption, environmental monitoring, and energy-efficient infrastructure, support reductions in environmental impacts and energy consumption.

However, the results demonstrate that the full benefits of digitalization and sustainability are constrained by several challenges. The most significant barriers include limited interoperability between information systems, fragmented data flows, organizational adaptation difficulties, and employee competency-related issues. These findings suggest that technological investments alone are insufficient to achieve effective digital and sustainable transformation.

A key contribution of this study is the demonstration that digitalization and sustainability should be viewed as interconnected rather than independent dimensions of container terminal development. Digital technologies support sustainability not only through operational efficiency improvements but also through enhanced monitoring, resource optimization, and data-driven decision-making. Consequently, sustainability outcomes increasingly depend on the effective integration and utilization of digital systems.

From a theoretical perspective, the study contributes to smart port and green port literature by providing empirical evidence from a medium-sized Baltic Sea container terminal, a context that remains underrepresented in previous research. The findings support recent studies emphasizing the growing convergence of digital transformation and sustainability agendas within maritime logistics and port management.

From a practical perspective, terminal operators should prioritize system interoperability, information integration, employee capability development, and the alignment of digitalization and sustainability objectives. Strengthening these areas may improve both operational performance and environmental outcomes.

The study is limited by its single-case design and qualitative research approach. Future research could investigate multiple terminals, compare different operational contexts, and incorporate quantitative performance indicators to further explore the relationship between digitalization and sustainability in port and terminal operations.

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