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Digitalization-Driven Sustainability in a Medium-Sized Container Terminal: Evidence from the Port of Klaipėda, Lithuania

Diana Šateikienė *  and Evelina Jurkutė

Faculty of Business, Klaipėdos Valstybinė Kolegija/Higher Education Institution, LT-91274 Klaipėda, Lithuania; eve.jurkute@kvkedu.lt

* Correspondence: d.sateikiene@kvk.lt

Abstract

Digitalization and sustainability are increasingly important in container terminal development, yet their operational-level integration remains insufficiently explained in medium-sized terminals. This study examines how digital systems support sustainability-related outcomes in a medium-sized container terminal in the Port of Klaipėda, Lithuania. An exploratory qualitative case study was conducted using document analysis and semi-structured interviews with three key informants representing operational, planning/administrative, and technical or sustainability-related functions. Qualitative content analysis was applied to identify digital technologies, operational mechanisms, sustainability outcomes, implementation barriers, and managerial responses. The findings show that the terminal operating system, vehicle booking system, automated gate solutions, and port community system support sustainability mainly indirectly, through improved planning, information exchange, gate coordination, reduced congestion, and more efficient resource use. However, these effects are constrained by system fragmentation, limited interoperability, manual data transfer, uneven access to real-time information, and insufficiently targeted staff training. The strongest documented sustainability effects relate to LED lighting and solar energy infrastructure, while other digital-green links remain mainly qualitative or potential. The study provides exploratory, case-based evidence on how digitalization and sustainability are operationally connected in the analyzed medium-sized container terminal. Rather than proposing a new general theory, the study offers an analytical classification structure that helps distinguish documented, indirect and potential digitalization–sustainability links. The findings provide practical recommendations for system integration, staff training and sustainability performance monitoring.

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



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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.

The main technologies discussed in the literature include terminal operating systems (TOSs), which support vessel planning, yard management, container tracking and equipment allocation [6–8]; port community systems (PCSs) and single-window solutions [6], as well as vehicle booking systems (VBS) and automated gates [7–9], which improve information exchange and landside coordination [6–8]; and more advanced technologies such as IoT and big data analytics [8], digital twins [10,11], and artificial intelligence and blockchain [11–15], which support monitoring [8,10–12], forecasting and optimization [8,10,11,13,14], and scenario-based decision-making [10,11,13]. These technologies are expected to improve planning accuracy [6–8,15], reduce waiting times [8,9,13,14], support equipment allocation [6,8,15], enhance cargo tracking [6,15], and strengthen coordination between terminal operators, shipping lines, customs authorities, freight forwarders and inland transport providers [6,7,9,14,16,17]. Therefore, digitalization is no longer considered only a technical modernization process [7,18]; it is increasingly treated as an organizational transformation [7,16,18] that changes information flows [6,7,16], decision-making routines [7,8,16] and stakeholder relationships in port logistics [7,14,16–18].

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 [8,10–14]. 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 [10–14]. 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 [12,14]. 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 and local air pollution [19–22], noise, water contamination and land-use pressure [23–25], and energy consumption [26]. Green port and sustainable port approaches therefore emphasize emission reduction [19–22], energy efficiency and renewable energy use [26], electrification of cargo-handling equipment [27], environmental monitoring [12,23], waste reduction [28], and structured environmental management [24,29,30]. Existing studies show that energy management [26], electrified equipment [27], environmental performance indicators [23,24] and formal management systems [29,30] can support both environmental improvement and operational efficiency. In addition, international strategies and policy initiatives increasingly frame ports as important actors in maritime decarbonization and climate transition [21,22,31].

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 information systems [6], automation [15,32,33], operational visibility [7,16], data exchange [17,18] and coordination between port stakeholders [8,16,17], while smart port studies emphasize technological infrastructure [8,13,14], data integration [9,14], governance [8,14], performance indicators [8,13] and the use of advanced technologies such as IoT, artificial intelligence [13,14] and digital twins [10,11]. In contrast, sustainability-oriented port research has mainly focused on energy management [26], emission reduction [19–22], en-

vironmental monitoring [12,23], green port practices [28,30,34–37] and decarbonization strategies [5,21,22,31,38,39].

Recent studies increasingly suggest that these two agendas are interconnected. Digital technologies may support sustainability by improving data availability [6,17,18], optimizing equipment and yard operations [15,27,32,33], reducing truck congestion and idling [17,28], supporting environmental monitoring [12,23,24,31], and enabling evidence-based decision-making [8,14,24,40,41]. However, existing research still provides limited empirical evidence on how these links are realized in everyday terminal operations, particularly in medium-sized terminals. This limitation is important because previous studies show that digital transformation in ports is often constrained by legacy systems [6,18], fragmented data flows and interoperability problems [6,14,15,17], investment costs [14,18,33], cybersecurity concerns [9,14], and insufficient employee competencies [9,14,18].

Therefore, the remaining research problem is not only that digitalization and sustainability have been addressed as separate themes, but that the operational mechanisms connecting them remain insufficiently explained. It is still unclear how specific terminal systems, such as TOS, VBS, automated gate solutions and PCS, contribute to sustainability-related outcomes through daily operational practices, and why these effects may remain limited in medium-sized terminals. This study addresses this gap by investigating the operational-level integration of digitalization and sustainability in a medium-sized container terminal operating in the Port of Klaipeda, Lithuania.

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, resource-efficient decision-making and organizational adaptation. The aim of the study is to examine how digital technologies support sustainability-related outcomes in the daily operations of a medium-sized container terminal and to identify the technological and organizational barriers that limit this integration. Accordingly, the study addresses three research questions:

RQ1: How do digital systems support operational and sustainability-related outcomes in a medium-sized container terminal?

RQ2: What technological and organizational barriers limit the integration of digitalization and sustainability?

RQ3: What managerial responses can strengthen digital-green integration in similar terminal contexts?

The contribution of this study is empirical and context-specific rather than broadly theoretical. The study does not claim that factors such as interoperability, information sharing, staff training or operational coordination are previously unknown. Instead, it shows how these already recognized factors interact in one medium-sized Baltic Sea container terminal and how they shape the extent to which digital systems can support sustainability-related outcomes. In this sense, the study modestly refines the operational understanding of digital-green integration by distinguishing between documented, indirect and potential sustainability effects.

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 [6,7,16,18]. TOS platforms are usually regarded as the backbone of terminal digitalization because they support vessel planning, container tracking, yard

management, equipment allocation and reporting [6,15]. PCS and single-window systems extend digitalization beyond the terminal by connecting public and private actors and reducing fragmented administrative procedures [6,17]. VBS and automated gates further support the synchronization of truck arrivals and gate operations, reducing bottlenecks and improving the predictability of landside flows [12,17].

The smart port literature expands this operational perspective by linking digitalization with broader organizational and strategic change. Molavi et al. [8] propose that smart port development requires technological infrastructure, data integration, governance and performance measurement. Li et al. [13] show that smart port research is strongly associated with IoT, big data, cloud computing, AI and performance indicators. Belmoukari et al. [14] 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 [10–12]. 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 [10,11]. 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 [12,14,17,18]. 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 analyzed 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 [23–27,29,30,34,42,43]. The environmental dimension is particularly important because terminal operations involve energy-intensive cargo-handling equipment, trucks, lighting, storage areas and infrastructure that can generate emissions, noise and other local impacts [23–27,29,30,34].

Energy management is one of the most developed sustainability themes in the literature. Acciaro et al. [26] argue that ports can play an active role in energy transition by managing energy demand, introducing renewable energy and coordinating stakeholders. Acciaro et al. [26] 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 [23–25,27,29,30,43].

Environmental management systems and indicators form another important part of sustainability implementation. Darbra et al. [29] 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. [25] 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 [22,35–38,40,41,44].

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 [21,31,45]. Recent reviews show that port decarbonization requires a combination of technological measures, energy management, regulatory instruments, stakeholder coordination and business strategy [22,36]. 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 as separate research streams. Digitalization-oriented studies focused mainly on digital transformation, port information systems and data exchange in maritime logistics [6,7,16,18], while more specific terminal-level studies examined operating system integration and single-window implementation [15,17]. Smart port research further developed this perspective through smart port frameworks, smart port indices and systematic reviews of smart port development [8,9,13,14], including more recent work on digital twins and smart environmental monitoring [10–12]. In contrast, green port and port sustainability research primarily addressed energy management, environmental performance indicators, environmental management practices and the greening of port operations [23–27,29,30,43]. More recent studies and institutional reports have extended this discussion toward decarbonization, greenhouse gas reduction and the sustainability of smart ports [21,22,31,40].

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 [6,15]. Second, VBS and automated gate systems can reduce truck queues, idling and congestion-related emissions by coordinating arrivals and improving gate processing [12,17]. Third, PCS and single-window systems can reduce administrative duplication, support paperless operations and improve information flow across logistics actors [6,17]. Fourth, IoT sensors and smart monitoring systems can collect data on energy use, equipment utilization, emissions and environmental conditions [12,46]. Fifth, AI and digital twins can support predictive maintenance, scenario modelling and resource optimization, linking operational planning with environmental outcomes [10,11].

The literature therefore suggests that digitalization can contribute to sustainability not only indirectly through efficiency [28,43] but also directly through monitoring [12], reporting [31] and environmental decision-making [19–22,40,46]. However, this potential depends on the integration of systems, the quality of data, employee capabilities and managerial commitment [14,15,17,18]. 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 [6,12,14,17,18]. This is

particularly relevant for medium-sized terminals, where investment capacity and digital maturity are often lower than in major hub ports [32,33].

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 [13,14]. 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 [22,36–38,44]. 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 [6,17,18], planning [8,9,13,14] and operational efficiency [7,10,11,15,16], and that sustainability measures can reduce environmental impacts [19,20,23–25,28–30,35–37,44] and improve energy performance [21,22,26,27,38]. 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 analyzing 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). The analytical structure used in this study should be understood as a classification and interpretation tool rather than as a new causal theory. It was developed deductively from the literature on smart ports, green ports and digital-green integration and was subsequently refined through the empirical material obtained from document analysis and interviews. Its purpose is to organize the case evidence and to distinguish between digital technologies, operational mechanisms, sustainability-related outcomes, implementation barriers and managerial responses.

Therefore, the analytical structure does not claim to demonstrate universal causal relationships. Instead, it helps interpret how digitalization and sustainability are connected in the analyzed case and where these links remain documented, indirect or only potential. 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.

Table 1. Analytical classification structure for digitalization-driven sustainability in a medium-sized container terminal.

Framework Element	Meaning in This Study	Digital Technology/ Practice	Operational Mechanism	Sustainability-Related Contribution	Possible Implementation Barrier	Managerial Response
Digital technology	Information systems and digital tools used in terminal operations.	TOS/Autostore, VBS; automated gates, PCS/KIPIS, IoT monitoring systems, and AI and predictive analytics.	Collection, processing and exchange of operational data.	Enables better visibility of terminal processes and creates a basis for resource-efficient decision-making.	Legacy systems, limited interoperability, fragmented data flows, and uneven access to real-time information.	Prioritize system integration, data-exchange interfaces and role-based access to operational information.
Operational mechanism	The way digital tools change daily terminal operations.	TOS/Autostore, VBS, automated gates, and PCS/KIPIS.	Yard planning, container tracking, truck arrival coordination, faster gate processing and reduced manual data transfer.	May reduce unnecessary container movements, truck congestion, waiting time, idling and administrative duplication.	Manual data transfer, incomplete system integration, driver errors, and insufficiently targeted staff training.	Improve workflow design, automate data transfer, strengthen driver guidance and provide practical staff training.
Sustainability-related outcome	Environmental or resource-efficiency effect enabled by operational change.	VBS, automated gates, LED lighting, solar energy infrastructure, and electrified or hybrid handling equipment.	Lower energy use, smoother traffic flows, reduced equipment idling and increased use of renewable electricity.	Reduced electricity consumption, lower CO ₂ emissions, lower congestion-related emissions and improved resource efficiency.	Limited quantitative indicators, fragmented sustainability data, and weak linkage between operational and environmental monitoring.	Develop sustainability KPIs, connect energy and emission data with operational systems, and monitor effects regularly.
Implementation barrier	Technological, organizational or managerial factors limiting digital-green benefits.	Autostore–KIPIS non-integration, outdated system functionality, fragmented information access, and staff training gaps.	Digital systems do not fully support real-time coordination or environmental performance monitoring.	Sustainability effects remain partly qualitative, indirect or potential rather than fully measurable.	Investment constraints, dependence on existing software providers, lack of API-based integration, and limited employee adaptation.	Apply phased implementation, supplier requirements, integration planning, user feedback loops and cost–benefit assessment.
Managerial response	Practical action needed to strengthen the integration between digitalization and sustainability.	System integration projects, role-based training, digital performance dashboards, and environmental monitoring tools.	Converts operational data into managerial and sustainability-related decisions.	Supports measurable digital-green integration and improves transferability to similar medium-sized terminal contexts.	Lack of strategic coordination, cautious investment behaviour, and limited internal capabilities.	Establish a digital-green transformation roadmap, define measurable indicators and align investments with ESPO/IMO-related priorities.

The framework is used in the empirical analysis to move beyond a descriptive list of digital and sustainability initiatives. It enables the identification of how specific digital

technologies influence sustainability-related outcomes through operational mechanisms, and why these effects may remain limited when organizational or technological barriers are present.

To clarify the position of the present study within the existing literature, Table 2 systematizes the main research streams, their limitations, and their relevance to this study.

Table 2. Critical systematization of previous research and positioning of the present study.

Research Stream	Main Focus in Previous Studies	Main Limitation Identified in the Literature	Relevance to the Present Study
Smart port and port digitalization studies	Information systems, automation, operational visibility, data exchange, TOS, PCS, VBS, automated gates, IoT, AI and digital twins [6–18].	Many studies emphasize technological potential and digital maturity, but provide less operational-level evidence on how digital systems generate sustainability-related outcomes in everyday terminal practices [6,12,14,17,18].	This study examines how specific digital systems used in daily terminal operations support planning, information exchange, congestion reduction and resource-efficient decision-making in a medium-sized terminal.
Green port and port sustainability studies	Energy management, emission reduction, environmental monitoring, electrification, renewable energy, environmental indicators and decarbonization strategies [21–27,29–31,34,40,43].	Sustainability measures are often analyzed as separate environmental or energy initiatives, with limited attention to how they are supported by digital systems and operational data [22–24,26,30,34,40].	This study links sustainability practices with the digital systems and operational routines through which environmental and resource-efficiency effects can be achieved or constrained.
Digital-green integration studies	The emerging relationship between digitalization and sustainability, including data-based monitoring, optimization, reduced congestion, lower resource waste and evidence-based decision-making [12,19–22,28,31,40,46–49].	The integration is still frequently discussed at a conceptual or strategic level, while empirical evidence from medium-sized container terminals remains limited [12,14,22,40].	This study provides empirical case evidence on the mechanisms and barriers of digital-green integration in a medium-sized Baltic Sea container terminal.
Medium-sized and regional terminal context	Operationally constrained terminals with more limited investment capacity, legacy systems, fragmented data flows, interoperability problems and employee adaptation challenges [6,12,14,17,18].	Compared with large hub ports, medium-sized terminals remain less represented in empirical smart-green port research, although integration barriers may be especially visible in such settings [12,14,40].	The Port of Klaipėda case is used to analyze how digital-green transformation unfolds in a medium-sized operational environment and what conditions limit transferability to similar terminals.
Methodological gap in previous research	Previous studies include literature reviews, conceptual frameworks, policy discussions and selected empirical port cases [13,14,22,34,40].	There is a need for studies that connect literature-based concepts with empirical evidence from terminal employees, documents, and operational practices.	This study combines document analysis and semi-structured interviews and interprets the results through an operational-level analytical framework linking technologies, mechanisms, outcomes, barriers and managerial responses.

The systematization shows that the novelty of the present study lies not in examining digitalization or sustainability separately, but in analyzing the operational mechanisms through which digital systems support sustainability-related outcomes in a medium-sized terminal context.

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 [50]. 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 [51]. 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 Klaipėda, 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 [52].

The study was designed as an exploratory single-case study. Therefore, its purpose is not statistical generalization, but an in-depth understanding of how digitalization and sustainability are integrated in a specific operational context. The case study approach is suitable for examining complex socio-technical processes where the interaction between digital systems, organizational practices and sustainability objectives cannot be fully captured through quantitative indicators alone. The empirical evidence was interpreted through analytical generalization, meaning that the findings are used to develop an operational-level understanding of digital-green integration that may be relevant to similar medium-sized terminal contexts.

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 [53].

3.2.1. Document Analysis

Document analysis was conducted to obtain contextual and operational information regarding terminal activities, digital technologies, sustainability initiatives, and organizational practices. The analyzed 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 analyzed 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.

3.2.2. 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 processes, digital system utilization, planning activities, and sustainability-related initiatives [52]. 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.

Three key informants were interviewed. The number of respondents was limited because the study focused on employees who had direct knowledge of terminal operations, digital system use, planning processes and sustainability-related initiatives. The respondents were selected purposively rather than randomly, as the aim was to obtain information-rich insights from participants directly involved in the studied processes. The interview sample included representatives of operational, planning/administrative and technical or sustainability-related functions. This enabled the study to capture different perspectives on the same digital and environmental transformation processes.

3.3. Data Analysis

The collected data were analyzed 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 sus-

tainability 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.

To increase transparency, the coding process followed a traceable sequence from raw statements to initial codes, subcategories and higher-order categories. Interview statements were first coded according to their substantive meaning. Similar codes were then grouped into subcategories, which were subsequently linked to broader analytical categories reflecting the relationship between digitalization and sustainability (Table 3).

Table 3. Example of coding procedure used in qualitative content analysis.

Example of Empirical Statement	Initial Code	Subcategory	Analytical Category
"Autostore is an old application. . ."	Outdated system functionality	Digital system limitations	Information flow and system interoperability
"Lack of staff training. . ."	Insufficient practical training	Organizational adaptation	Implementation challenges
"Drivers often enter the wrong lane. . ."	User-related operational error	Gate process disruption	Digital system implementation barriers
"We have installed solar panels. . ."	Renewable energy adoption	Green infrastructure	Sustainability practices and environmental performance
"We choose equipment that is already known. . ."	Risk-averse technology selection	Cautious investment strategy	Implementation risks and managerial responses

An inductive coding approach was employed, allowing themes and categories to emerge directly from the empirical material rather than being imposed through a pre-defined 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.

3.4. Research Quality and Trustworthiness

Several procedures were applied to strengthen the credibility, dependability and transparency of the study [53]. First, methodological triangulation was ensured by combining semi-structured interviews with document analysis. Interview findings were compared with terminal-related documents, environmental information, technical descriptions and publicly available materials. This helped verify whether the issues identified by respon-

dents were also reflected in documentary and operational evidence, thereby reducing the risk of single-source bias.

Second, the interview data were transcribed, anonymized and analyzed using a systematic coding procedure. The coding process followed a traceable sequence from empirical statements to initial codes, subcategories and higher-order analytical categories. This procedure improved the transparency of interpretation and enabled the analytical decisions to be linked back to the empirical material.

Third, the limited number of interviewees was addressed through purposive sampling and functional diversity of respondents. Although only three key informants were interviewed, they represented operational, planning/administrative and technical or sustainability-related perspectives. Therefore, the study does not claim statistical representativeness but relies on information-rich cases and analytical generalization, which is appropriate for exploratory qualitative case study research [50].

Given the exploratory nature of the study, data saturation is interpreted cautiously. The adequacy of the empirical material was assessed through the consistency between interview data and documentary evidence. Recurring themes were identified regarding system interoperability, information fragmentation, staff training, sustainability measures and investment risks. Nevertheless, the limited number of respondents remains a methodological limitation and is explicitly acknowledged.

This study has several limitations. First, it is based on a single terminal case and three key informants; therefore, the findings cannot be statistically generalized to all container terminals. Second, only limited quantitative performance data were available. Third, the relationship between digitalization and sustainability is analyzed through operational mechanisms and perceived or documented effects rather than direct causal measurement. Fourth, the case reflects the specific context of a medium-sized Baltic Sea terminal, and the findings may not fully apply to highly automated global hub ports or small branch terminals. Future research should therefore include comparative multi-terminal studies and combine qualitative insights with quantitative indicators such as gate waiting time, truck idling time, equipment fuel consumption, electricity use, CO₂ emissions, container re-handling rates and return on investment.

Given the limited empirical base, the study does not seek to produce generalized claims about all medium-sized container terminals. The findings are interpreted as case-based evidence from one operational setting. Their relevance to other terminals depends on the presence of comparable contextual conditions, such as similar terminal size, partial digitalization, legacy information systems, limited interoperability, incremental sustainability investments and constrained investment capacity.

4. Results and Discussion

The results of the case study indicate that digitalization supports operational efficiency and sustainability-related objectives in the analyzed terminal. However, only selected sustainability effects are supported by quantitative evidence, while several digital-green links remain qualitative, indirect, or potential. 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 uses 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 container tracking, yard

management, vehicle arrival coordination and information exchange between terminal and port-related actors.

Autostore has been used in the terminal for approximately 18 years and remains one of the central systems for container flow management. The evaluation of Autostore revealed different employee perceptions. Operational users emphasized its reliability, adaptability and usefulness for container location tracking, inventory updates and movement reporting. For example, respondent R-C stated that “the Autostore app is excellent” and highlighted its role in tracking container location, inventory updates and reports on container movements. Respondent R-A also evaluated the system positively, noting that Autostore helps indicate where containers should be placed and can be adapted to terminal needs. In contrast, respondent R-B emphasized several limitations, including outdated functionality, system malfunctions, restricted information visibility and difficulties in information dissemination. These findings are summarized in Table 4.

Table 4. 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”.
	Tailored to your needs	R-A “the programme can be adapted to our needs<..>”. R-B “Autostore is an old application <..> makes it difficult to disseminate information <..>”.
	Negative	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, <..>”.

The results indicate that Autostore performs an important operational function, but its contribution is uneven across user groups. For some employees, the system supports daily decision-making by improving container tracking, yard coordination and inventory control. For others, its value is limited by outdated functionality, insufficient system visibility and interruptions in information flow. This divergence suggests that the effectiveness of Autostore depends not only on the existence of a digital system, but also on user role, access to relevant information and the degree of integration with other systems.

From the perspective of digitalization-driven sustainability, Autostore contributes mainly indirectly. By supporting container tracking, inventory management and yard coordination, it may reduce unnecessary container movements, duplicated work and inefficient use of handling equipment. However, this sustainability effect remains only partly realized because Autostore is not fully integrated with other information systems and does not provide equal real-time information access to all user groups. Similar observations have been made in previous port digitalization studies, which emphasize that digital systems create

value only when operational information is timely, accessible and interoperable [6,16]. The findings also correspond to studies identifying interoperability and information-sharing problems as persistent barriers to smart port development [14].

The results also show that digitalization should be understood as an organizational transformation rather than only as the introduction of individual technologies. As highlighted by Fruth and Teuteberg [18], successful digital transformation in maritime logistics 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 improving system usability, information accessibility and interoperability.

Newer systems, such as the VBS and automated gate solutions, appear to support better coordination of vehicle arrivals and gate operations. The VBS enables pre-registration of vehicle arrivals and may contribute to reduced congestion and waiting times at terminal gates, while automated gate solutions support vehicle processing and data capture. However, these effects were not assessed using before-and-after performance indicators. Therefore, their contribution to operational efficiency and sustainability should be interpreted as qualitative rather than directly measured. This distinction is important because previous studies link digital maturity with port performance, but also emphasize that the benefits of digitalization depend on implementation quality, data integration and organizational readiness [12,23].

4.2. System Integration and Data Fragmentation

A critical issue identified in the study is the limited interoperability between digital systems. The lack of direct integration between Autostore and KIPIS requires manual data transfer, increases administrative workload and raises the risk of human error. This fragmentation reduces the effectiveness of digitalization and limits the potential of data-driven decision-making. It also weakens the connection between operational data and sustainability monitoring, because fragmented information flows make it more difficult to systematically assess congestion, equipment use, waiting time or emission-related effects.

The implementation of the automated gate system further illustrates that digital transformation depends not only on technological performance, but also on user adaptation, training quality and operational readiness. As shown in Table 5, the automated gate system was generally evaluated positively and was considered a useful solution for improving gate processes. However, the main problems were related to insufficiently targeted staff training and driver errors during the use of the system.

Table 5. 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 results show that the main barrier in the automated gate implementation was not the basic functionality of the system, but the way the system was introduced and used in practice. Respondents indicated that training was not sufficiently focused on the actual tasks that employees had to perform. As a result, some users experienced confusion during implementation, and additional adaptation was needed. Driver-related errors, especially incorrect lane selection, also disrupted traffic flow and reduced the expected benefits of automated gate processing.

From the perspective of digitalization-driven sustainability, the VBS and automated gate system demonstrate a more direct link between digital tools and sustainability-related outcomes than Autostore. By coordinating truck arrivals and improving gate processing, these systems can reduce congestion, waiting time and vehicle idling at the terminal entrance. However, this potential is constrained when users are not sufficiently prepared or when external users, such as drivers, do not follow the intended process. Therefore, the environmental value of automated gate solutions depends not only on the technology itself, but also on training, signage, user guidance and process discipline.

The findings also indicate that system fragmentation remains a key limitation. The lack of integration between Autostore and KIPIS creates duplicated work and prevents operational data from being fully used for real-time coordination, performance analysis and environmental monitoring. This confirms that digital-green integration requires more than the introduction of separate digital tools. It requires interoperable systems, clear data flows and organizational routines that allow operational information to be transformed into managerial and sustainability-related decisions.

These results are consistent with previous studies emphasizing that digital transformation in maritime logistics is a socio-technical process. Employee competencies, resistance to change, training quality and organizational readiness may become as important as technological infrastructure itself [18]. Similarly, smart port research shows that interoperability, information sharing and stakeholder engagement remain persistent barriers to the effective use of digital systems in port environments [6,14,17]. In this case, the automated gate system and VBS have the potential to support both operational efficiency and sustainability, but this potential remains partly limited by training weaknesses, driver adaptation problems and incomplete integration between terminal and port information systems.

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

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 CO₂ emissions by approximately 250 tons per year.

LED lighting and solar energy infrastructure represent the strongest documented sustainability measures in this case because they are supported by investment and environmental performance data. However, their integration with digitalization remains limited unless energy consumption, equipment utilization, and environmental performance

are systematically monitored through digital indicators. This means that sustainability investments alone do not create digital-green integration. Such integration requires that environmental data be connected with operational decision-making and performance monitoring systems.

Table 6. Pollution abatement measures for the marine container terminal.

Tarsha	Pollution Reduction Techniques
Air pollution	Organize 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.

These results demonstrate that sustainability measures provide both environmental and operational benefits. However, not all effects are supported by the same level of empirical evidence. The effects of LED lighting and solar energy infrastructure are documented more clearly, while the contribution of electrified or hybrid equipment, reduced container re-handling and lower equipment idling remains mainly qualitative because detailed fuel-saving, equipment-use and emission-reduction data were not available. Similar findings are reported in the literature, where energy efficiency and renewable energy integration are identified as 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 14001:2026 [57], 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 6 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 [26,30]. Acciaro et al. [26] 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 [30] 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 dependence on conventional energy sources. Similar benefits have been identified in recent studies on port decarbonization and sustainable infrastructure development [22,38].

4.4. Sustainability Integration and Strategic Orientation

The analysis of sustainability objectives (Table 7) indicates that the terminal prioritizes the electrification of handling equipment, increased use of renewable energy, and reduction in energy consumption. Additional measures include pollution monitoring, process optimization, investments in green technologies, and the use of green electricity.

Table 7. 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”.
	Renewable energy	R-C “<...> we will electrify the fleet as far as possible <...>”. 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 organization	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.”

The evidence presented in Table 8 shows that sustainability objectives are increasingly influencing operational and investment decisions within the terminal. The emphasis on electrified and hybrid equipment, renewable electricity, LED lighting, solar energy, pollution monitoring and more efficient process organization demonstrates a clear sustainability orientation. However, these initiatives remain predominantly project-based and operationally focused rather than fully embedded within a comprehensive strategic management framework.

This finding corresponds with previous sustainability research, which has shown that many ports implement environmental initiatives incrementally through individual projects rather than through integrated sustainability strategies [41,44]. 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 systematic performance monitoring.

The findings also demonstrate that sustainability and digitalization are becoming increasingly interconnected. Activities such as environmental monitoring, energy management, process optimization and operational planning depend on digital technologies and data availability. This supports recent studies suggesting that digitalization can function as an enabler of sustainability by improving transparency, resource efficiency and evidence-based decision-making [12,22,40]. However, in the analyzed case, this integration remains incomplete because sustainability measures are not yet fully connected with digital performance indicators and integrated environmental data flows.

Table 8. 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”.

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 8, these risks can be categorized into three main groups: knowledge-related, technological, and financial risks.

Knowledge-related risks include limited experience with new technologies and insufficient understanding of their operational implications. Technological risks are associated with system compatibility, reliability and uncertainty regarding performance in the specific terminal context. Financial risks relate to return on investment, maintenance costs 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, ergonomics and maintenance costs. While this approach reduces uncertainty and protects operational stability, it may also slow the adoption of more advanced digital-green solutions. Similar challenges have been reported in studies examining innovation adoption within maritime logistics and port environments [12,14,33].

The risk mitigation measures identified by respondents, including technology assessment, staff training, contractual safeguards, equipment return options and performance evaluation, are consistent with recommendations found in the literature [14,33]. Nevertheless, balancing innovation and risk management remains one of the most significant challenges for medium-sized container terminals pursuing digital and sustainable transformation.

To deepen the interpretation of these barriers, Table 9 provides a root-cause analysis linking the observed implementation problems with their possible underlying causes and consequences for digital-green integration.

Table 9. Root-cause analysis of digital-green integration barriers.

Identified Barrier	Immediate Manifestation in the Case	Possible Root Causes	Effect on Digital-green Integration	Suggested Managerial Response
Limited interoperability between Autostore and KIPIS	Manual data transfer between systems; higher administrative workload; increased risk of human error.	Legacy system architecture; lack of API-based integration; investment constraints; dependence on existing software providers.	Operational data cannot be fully used for real-time coordination, environmental monitoring or performance indicators.	Assess technical integration options; develop data-exchange interfaces; prioritize interoperability in future IT investments.
Uneven access to real-time information	Some users evaluate Autostore positively, while others report limited system visibility.	Role-based access permissions; incomplete user-interface adaptation; managerial decisions on data access; system-design limitations.	Digitalization benefits remain uneven across departments, and sustainability-related decisions are not equally supported by data.	Review access rights; define information needs by user role; improve dashboards and reporting functions.
Staff training weaknesses	Employees report insufficiently targeted training and confusion during automated gate implementation.	Training focused on system functions rather than practical tasks; lack of role-specific scenarios; limited change management.	Digital systems do not achieve their full operational or sustainability potential because users cannot apply them effectively.	Introduce role-based training, practical simulations, refresher sessions and user feedback loops.
Driver errors at automated gates	Drivers enter wrong lanes, causing congestion and traffic disruption.	Insufficient external user guidance; unclear signage; weak interface design; limited communication with transport companies.	Potential reduction in truck waiting time and idling is partly lost.	Improve signage, pre-arrival instructions, driver communication and lane guidance.
Fragmented sustainability data	Sustainability measures exist, but they are not fully connected to systematic digital monitoring.	Absence of an integrated environmental management system; limited performance indicators; fragmented operational and environmental datasets.	Sustainability effects remain partly descriptive rather than measurable.	Develop sustainability KPIs; link energy and emission data with operational systems; consider ISO 14001:2026 or an equivalent EMS.
Cautious investment strategy	Preference for familiar and proven technologies.	Limited financial capacity; uncertainty about ROI; operational risk avoidance; lack of experience with new sustainable technologies.	Reduces investment risk but may slow adoption of advanced digital-green solutions.	Use pilot projects, phased implementation, supplier guarantees and cost-benefit assessment.

The root-cause analysis shows that digital-green transformation is constrained not only by separate technological or financial risks, but also by deeper organizational and system-level conditions. Limited interoperability, uneven access to data, training weaknesses, driver adaptation problems, fragmented sustainability data and cautious investment behaviour jointly reduce the ability of digital systems to generate measurable sustainability outcomes.

The identified investment risks reveal a broader structural constraint typical of medium-sized terminals. New digital and sustainable technologies are evaluated not only according to their environmental or operational potential, but also according to uncertainty about compatibility, reliability, maintenance costs and return on investment. This explains why the terminal tends to prioritize familiar and proven technologies. Such a strategy reduces operational and financial risk, but may also slow the adoption of more advanced digital-green solutions.

4.6. Alignment with ESPO and IMO Decarbonization Priorities

To assess whether the terminal's digital and sustainability measures are aligned with current sectoral policy priorities, Table 10 links the case findings with ESPO environmental priorities and the IMO 2023 GHG Strategy.

Table 10. Alignment of terminal measures with ESPO and IMO decarbonization priorities.

Terminal Measure/Finding	Relevant ESPO/IMO Policy Direction	Policy Alignment Assessment	Implication for Digital-Green Integration
LED lighting and energy-efficient infrastructure	ESPO environmental priorities emphasize energy efficiency, environmental monitoring and improved environmental performance in European ports.	Strong alignment. LED investments directly support lower electricity consumption and energy-efficiency objectives.	LED lighting represents one of the strongest documented sustainability measures in this case because it is supported by investment data and direct energy-efficiency logic.
Solar energy infrastructure and renewable electricity generation	ESPO priorities include climate change mitigation and energy efficiency. The IMO 2023 GHG Strategy sets a broader decarbonization direction for the maritime sector, including the transition toward net-zero GHG emissions by or around 2050.	Strong alignment. Renewable electricity supports port climate and energy-transition priorities. In this case, solar infrastructure covers around 13% of electricity demand and reduces CO ₂ emissions by approximately 250 tons per year.	Solar energy is the strongest documented digital-green-related sustainability result in this case. However, it should be interpreted as a terminal-level contribution to decarbonization rather than as direct fulfilment of IMO targets.
Electrified and hybrid cargo-handling equipment	ESPO priorities include climate change, energy efficiency and air quality. Equipment electrification contributes mainly to local emission reduction and improved port-side environmental performance.	Partial alignment. The measure is directionally consistent with decarbonization and air-quality priorities, but its contribution remains insufficiently quantified.	Electrified and hybrid equipment should be treated as a potentially important sustainability measure, but its actual effect requires additional indicators, such as fuel savings, annual operating hours and CO ₂ reduction.
Vehicle Booking System (VBS)	ESPO environmental management logic supports operational measures that reduce congestion, waiting time and local transport-related externalities.	Indirect alignment. VBS can support sustainability by coordinating truck arrivals and reducing congestion and idling, but the case evidence remains mainly qualitative.	VBS demonstrates a plausible digital-green link, but future monitoring should include average truck waiting time, gate turnaround time and estimated idling-emission reduction.

Table 10. Cont.

Terminal Measure/Finding	Relevant ESPO/IMO Policy Direction	Policy Alignment Assessment	Implication for Digital-Green Integration
Automated gate system	ESPO priorities emphasize environmental monitoring, operational efficiency and performance management. Automated gates may improve vehicle processing and operational data capture.	Indirect but constrained alignment. The system supports smoother traffic flows and better data capture, but staff training gaps and driver lane-selection errors reduce the potential benefit.	The automated gate system can contribute to digital-enabled sustainability only if implementation barriers are addressed through role-based training, clearer signage and better driver guidance.
TOS/Autostore and yard planning	ESPO does not refer to TOS specifically, but environmental management requires operational control, data availability and performance monitoring.	Indirect alignment. Autostore supports container tracking and yard coordination, but sustainability benefits are limited by system age, uneven data access and insufficient integration with KIPIS.	Autostore should not be presented as a direct environmental measure. Its sustainability relevance lies in its potential to reduce unnecessary container movements and improve resource-efficient planning.
Autostore-KIPIS non-integration and manual data transfer	ESPO environmental governance priorities emphasize monitoring, data-based management and performance indicators. Fragmented digital systems weaken such monitoring.	Policy gap. Fragmented data flows limit the terminal's ability to develop systematic environmental indicators and data-based sustainability management.	This is a critical digital-green integration barrier: the terminal has both digital and green measures, but their integration is weakened because operational and environmental data are not fully connected.
Absence of certified environmental management system, such as ISO 14001:2026 or PERS	ESPO/EcoPorts strongly emphasize environmental management systems, monitoring routines, environmental policies and port-specific environmental governance tools.	Important gap. Sustainability practices exist, but they are not fully embedded in a formalized environmental management framework.	Formal environmental management certification or an equivalent internal EMS would strengthen the link between sustainability measures, operational data, KPIs and managerial accountability.
Staff training and organizational adaptation	ESPO environmental governance logic includes environmental awareness, training and organizational capability development as part of effective environmental management.	Partial alignment/implementation gap. Training-related weaknesses limit both digital and sustainability outcomes.	Digital-green transformation requires role-based training, practical simulations and training content linked not only to system use, but also to environmental performance objectives.

The alignment analysis shows that the terminal's LED lighting, solar energy infrastructure, equipment electrification and environmental monitoring are generally consistent with ESPO environmental priorities and the broader IMO decarbonization direction. However, the strength of alignment differs across measures. LED lighting and solar energy infrastructure represent the strongest documented examples because they are supported by investment and environmental performance data. In contrast, the contribution of electrified and hybrid equipment, VBS, automated gates and TOS-based yard planning remains mainly qualitative or indirect because detailed performance indicators are not fully available.

The analysis also reveals an important implementation gap. The terminal has introduced several green and digital measures, but operational data, environmental indicators and digital systems are not yet fully integrated. In particular, the lack of interoperability between Autostore and KIPIS limits systematic environmental monitoring and weakens the use of digital data for sustainability management. Therefore, the next stage of digital-green development should focus on linking digital systems with measurable environmental indicators, rather than only introducing additional technologies.

4.7. Synthesis of Findings

The findings show that digitalization contributes to sustainability in the analyzed terminal through three types of links: direct, indirect and potential. Direct links refer to measures where a sustainability-related effect is clearly identifiable and supported by documented or operational evidence. Indirect links refer to digital systems that improve operational efficiency and may therefore contribute to sustainability through reduced movements, waiting time, congestion or duplicated work. Potential links refer to cases where sustainability benefits are theoretically plausible but remain insufficiently realized because of fragmented systems, limited data integration or the absence of quantitative indicators.

This distinction is important because the case does not demonstrate a uniform or fully measurable relationship between digitalization and sustainability. Instead, the evidence shows different levels of maturity. LED lighting and solar energy infrastructure represent the strongest documented sustainability effects. VBS and automated gates demonstrate a more direct but mainly qualitative link through truck flow coordination and potential reduction in congestion and idling. Autostore contributes more indirectly by supporting container tracking and yard coordination. The Autostore–KIPIS non-integration represents a potential but not fully realized digital-green link, because the absence of automated data exchange limits the use of operational data for environmental monitoring and performance management, as summarized in Table 11.

Overall, the synthesis indicates that digital-green integration in the analyzed terminal is uneven. Energy-related measures are the most clearly documented, while the sustainability effects of digital systems remain mostly qualitative or indirect. Therefore, the next stage of digital-green transformation should focus on linking operational data with measurable sustainability indicators.

Table 11. Evidence of digitalization–sustainability links in the case terminal.

Digital System/Measure	Operational Mechanism	Sustainability-Related Outcome	Evidence in the Case	Strength of Link
Terminal Operating System/Autostore	Container tracking, inventory management and yard coordination.	Potential reduction in unnecessary container movements, duplicated work and inefficient equipment use.	Respondents indicate that Autostore supports container location tracking, inventory updates and container movement reports, but also mention outdated functionality and limited information access.	Indirect/qualitative
Vehicle Booking System (VBS)	Pre-registration and coordination of truck arrivals.	Reduced gate congestion, waiting time and vehicle idling at the terminal entrance.	The case indicates that VBS supports the coordination of vehicle arrivals and helps reduce congestion and waiting times at terminal gates.	Direct/qualitative

Table 11. Cont.

Digital System/Measure	Operational Mechanism	Sustainability-Related Outcome	Evidence in the Case	Strength of Link
Automated gate system	Faster vehicle identification, lane processing and gate data capture.	Fewer queues, smoother traffic flow and potential reduction in idling-related emissions.	Respondents evaluate the system positively, but note driver lane selection errors and insufficiently targeted staff training.	Direct but constrained
Autostore-KIPIS data exchange	Information transfer between the terminal operating system and port community system.	Potential reduction in manual work, data duplication, errors and fragmented information flows.	The absence of integration requires manual data transfer, increasing administrative workload and limiting data-driven decision-making.	Potential/not fully realized
LED lighting	Lower electricity consumption in terminal infrastructure.	Reduced energy use, lower light pollution and lower indirect CO ₂ emissions.	The manuscript reports an investment of approximately EUR 800,000 in energy-efficient LED lighting systems.	Direct/documented
Solar energy infrastructure	Renewable electricity generation for terminal operations.	Around 13% of electricity demand covered, and approximately 250 t CO ₂ reduction per year.	The manuscript reports an investment of approximately EUR 350,000 in solar energy infrastructure.	Direct/documented
Electric/hybrid handling equipment	Lower use of diesel-powered equipment during cargo handling operations.	Potential reduction in fuel consumption, local air pollution and CO ₂ emissions.	Respondents mention electrified and hybrid handling equipment, but detailed procurement cost, annual fuel savings and CO ₂ reduction data are not provided.	Potential/insufficiently quantified

4.8. Discussion

The findings confirm that digitalization and sustainability are increasingly interconnected in container terminal operations, but their relationship is not automatic. Digital technologies support sustainability only when they improve operational planning, data availability, resource use, congestion management or environmental monitoring. In the analyzed case, the strongest documented sustainability effects are related to energy-oriented measures, whereas the effects of TOS, VBS, automated gates and system integration remain mainly qualitative, indirect or potential. This distinction is important because it shows that the digitalization–sustainability relationship in medium-sized terminals should not be treated as a single direct effect, but as a layered process in which operational improvements become sustainability-relevant only when they are connected to measurable environmental indicators.

The study therefore does not claim to identify entirely new relationships between digitalization and sustainability. The importance of interoperability, information sharing, staff training, digital integration and operational coordination has already been emphasized in previous smart port and maritime logistics studies. Rather, this case study shows how these established factors operate together in a medium-sized terminal context and how

they influence whether digital systems generate measurable sustainability value or remain mainly operational tools.

The study refines previous smart port and green port research by showing how digital-green integration is constrained in a medium-sized terminal context. The main barriers are not limited to technology adoption itself, but include system interoperability, fragmented information flows, uneven access to real-time data, insufficiently targeted training and cautious investment behaviour. This supports previous studies emphasizing that digital transformation in maritime logistics is a socio-technical process requiring both technological and organizational adaptation [14,18].

The case also shows that the sustainability value of digitalization depends on whether operational data can be converted into measurable environmental and managerial indicators. In the analyzed terminal, digital systems support container tracking, truck arrival coordination and gate processing, but these operational improvements are not yet fully connected with systematic sustainability monitoring. As a result, the terminal can demonstrate some direct sustainability achievements, such as LED lighting and solar energy infrastructure, but the environmental effects of several digital systems remain insufficiently quantified. This finding is consistent with previous studies emphasizing that data integration, environmental indicators and performance monitoring are essential for linking smart port development with sustainability-oriented port management [12,22,40].

This finding is particularly important for medium-sized terminals because their digital-green transformation often takes place under resource, investment and organizational constraints. Unlike large hub ports, medium-sized terminals may not have fully integrated digital architectures, extensive environmental monitoring systems or sufficient capacity to implement advanced technologies rapidly. Therefore, the case demonstrates that digital-green integration in such terminals is usually gradual, selective and dependent on practical organizational readiness rather than on technological availability alone. This interpretation corresponds with previous studies showing that medium-sized and regional terminals often face more visible barriers related to fragmented systems, limited investment capacity and slower organizational adaptation [12,14,40].

From a theoretical perspective, the study provides a modest but specific contribution. It does not propose a new general theory of smart-green port transformation. Instead, it refines the operational interpretation of digital-green integration by distinguishing between documented, indirect and potential sustainability effects. Documented effects are observed where sustainability outcomes are supported by investment or performance data, such as LED lighting and solar energy infrastructure. Indirect effects are observed where digital systems improve coordination, planning or traffic flow, but environmental benefits are inferred rather than directly measured. Potential effects are observed where digital systems could support sustainability monitoring, but their contribution remains limited by fragmented data flows, manual data transfer or the absence of integrated indicators.

From a practical perspective, the findings suggest that medium-sized terminals should prioritize system integration, role-based staff training, external user guidance, digital sustainability indicators and the connection of operational data with environmental performance monitoring. These steps are necessary to move from separate digital and green initiatives toward a more coherent digital-green transformation pathway. Future improvements should therefore focus not only on acquiring new technologies, but also on ensuring that digital systems generate reliable data for sustainability management, operational decision-making and performance evaluation.

The transferability of the findings should be interpreted cautiously. The results may be relevant to comparable medium-sized or regional container terminals operating under similar conditions, including partial digitalization, legacy information systems, limited

interoperability between terminal and port community systems, incremental sustainability investments and constrained investment capacity. However, transferability should not be assumed for highly automated global hub ports with advanced digital twins, fully integrated environmental dashboards and extensive quantitative monitoring, nor for very small terminals with minimal digital infrastructure.

Overall, the findings suggest that digital-green integration in the analyzed terminal is real but uneven. Digital systems support sustainability-related outcomes mainly when they improve operational coordination, reduce fragmentation, support resource-efficient planning or enable environmental monitoring. However, the strongest documented sustainability effects remain associated with energy-oriented measures, while the sustainability value of several digital systems remains qualitative, indirect or potential. This reinforces the need for medium-sized terminals to link digital systems more systematically with measurable sustainability indicators.

5. Conclusions

This study examined the operational-level integration of digitalization and sustainability in a medium-sized container terminal in the Port of Klaipeda, Lithuania. The findings show that digitalization and sustainability should not be treated as separate development directions. Digital systems may support sustainability-related outcomes when they improve planning, information exchange, gate processes, resource use, environmental monitoring and data-based decision-making.

The main contribution of this study is to provide exploratory, case-based evidence on how digital-green integration is shaped and constrained in a medium-sized terminal context. The study shows that sustainability value does not emerge from technology adoption alone, but from the interaction between digital systems, operational mechanisms, data availability, employee competencies and managerial responses. This operational-level perspective helps explain why digital systems may support sustainability in some areas, while their potential remains only partly realized in others.

The terminal operating system, vehicle booking system, automated gate solutions and port community system contribute to sustainability mainly through operational mechanisms such as container tracking, yard coordination, truck arrival management, faster gate processing and information exchange. Their sustainability relevance is therefore mostly indirect, as these systems may reduce unnecessary container movements, congestion, waiting time, vehicle idling and fragmented information flows. However, these effects remain only partly quantified.

The strongest documented sustainability effects in the case are related to energy-oriented measures, particularly LED lighting and solar energy infrastructure. In contrast, the contribution of electrified and hybrid handling equipment, VBS, automated gates and system integration remains mainly qualitative or potential because detailed quantitative indicators are not fully available.

Several barriers limit digital-green integration: limited interoperability between Autostore and KIPIS, manual data transfer, fragmented data access, uneven availability of real-time information, insufficiently targeted staff training, driver adaptation problems and investment uncertainty. These findings indicate that medium-sized terminals should prioritize system interoperability, role-based training, clearer user guidance for automated gate processes, integration of operational and environmental data, and measurable sustainability indicators.

This study is limited by its single-case design, three key informants and limited quantitative validation. Future research should include multiple terminals and combine qualitative insights with quantitative indicators such as gate waiting time, truck idling

time, equipment fuel consumption, electricity use, CO₂ emissions, container re-handling rates and return on investment. Comparative studies involving medium-sized terminals, large hub ports and small branch terminals would further clarify which digital-green transformation barriers are context-specific and which are transferable across different port environments.

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