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Exploring the Impact of Digital and Energy-Efficient Technology Adoption: A Case Study of Northport Malaysia

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Abstract:
This study aims to examine the impact of digital and energy-efficient technology adoption on operational efficiency and environmental sustainability in seaport operations, focusing on the Northport case study. Global seaports undergo rapid transformation due to revolutionary developments in digital technologies, such as big data analytics, artificial intelligence, and the internet of things. Despite the increasing prevalence of these technologies, there remains a gap in understanding their holistic impact, particularly in terms of operational efficiency and environmental sustainability. To address this gap, this study employs a case study methodology, examining the adoption of digital and energy-efficient technologies at Northport, one of the busiest ports in the region. This research investigates how Northport's implementation of digital and energy-efficient technologies affects the allocation of resources, environmental practices, and operational procedures, utilizing qualitative data analysis based on observations, interviews, and documents. The findings indicate that the implementation of digital and energy-

Keywords:
Digital technology,
Energy-efficient technology,
Seaport,
Sustainability,
Operational efficiency

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efficient technologies has resulted in significant improvements in operational efficiency, such as increased output, streamlined operations, and optimal resource allocation. This study also highlights the positive environmental impact of digitization, including reduced carbon emissions and enhanced environmental monitoring. This research contributes to the understanding of the multifaceted impacts of digital technology adoption in seaport operations and provides insights for policymakers, port authorities, and industry stakeholders seeking to leverage digitalization for sustainable port development.

探索數位和節能技術採用的影響：馬來西亞北港案例研究

摘要:

本研究旨在研究数字化和节能技术的采用对海港运营效率和环境可持续性的影响，重点关注北港案例研究。由于大数据分析、人工智能和物联网等数字技术的革命性发展，全球海港经历了快速转型。尽管这些技术越来越普及，但在理解它们的整体影响方面仍然存在差距，特别是在运营效率和环境可持续性方面。为了填补这一空白，本研究采用了案例研究方法，研究了该地区最繁忙的港口之一北港采用数字化和节能技术的情况。本研究利用基于观察、访谈和文件的定性数据分析，调查了北港实施数字化和节能技术如何影响资源分配、环境实践和运营程序。研究结果表明，实施数字化和节能技术已显著提高运营效率，例如增加产量、简化运营和优化资源分配。本研究还强调了数字化对环境的积极影响，包括减少碳排放和加强环境监测。这项研究有助于理解数字技术在海港运营中的应用的多方面影响，并为寻求利用数字化实现港口可持续发展的政策制定者、港口当局和行业利益相关者提供见解。

关键词：數位科技、節能技術、海港、永續性、營運效率

1. Introduction

Seaports are essential hubs in supply chains that serve as catalysts for the global economy. The advent of novel technologies aimed at maximizing operational efficiency and promoting environmental sustainability has caused seaports worldwide to undergo a paradigm change in response to the revolutionary potential of digital technology (Arunachalam et al., 2018). The UN's 2030 Agenda for Sustainable Development and the IMO's aim of reducing maritime emissions by 15% by 2018 are two international directives fueling this trend (Lim et al., 2019).

Incorporating digitalization and energy-efficient technologies in seaports can augment operational efficiency, promote automation, enhance management processes, and substantially contribute to environmental sustainability objectives (European Sea Ports Association, 2018). However, academic and practical research on this subject remains scarce despite the acknowledged benefits. Researchers have examined the diverse effects of digital technologies in seaports, focusing on the ship-port interface, as these technologies improve operational efficiency and environmental sustainability (Di Vaio & Varriale, 2019; Tseng et al., 2020).

Malaysia, with strategic ports such as Port Klang and Tanjung Pelepas, is a leader in the transformation to improve efficiency and meet international standards (Ignatius, 2023). Initiatives such as the Green Port and National Transport Policy demonstrate Malaysia's commitment to technical advancement and environmental responsibility (Port Klang Malaysia, 2023). Studying the outcomes of Malaysian seaports can provide essential insights into global maritime sustainability (Port Klang Malaysia, 2023).

One of the leading companies in the national port operations market is Northport Malaysia Bhd, included in its broad portfolio. Northport Malaysia Bhd has been a cornerstone of Malaysia’s maritime industry and has been operating as a vital subsidiary of the MMC Corporation Bhd since its establishment in 1965. Northport Malaysia Bhd is strategically located in Port Klang, Malaysia's largest and busiest port, and has grown into a leading port operator known for its quality. Northport Malaysia Bhd was the first Malaysian port to receive the International Association of Ports and Harbors (IAPH) 2022 Sustainability Award on May 18, 2022 (Mardhiah, 2022). This prestigious award acknowledges the company's commitment to global standards and innovative contributions to fostering an ethical, sustainable, and safe maritime environment through outstanding digital strategies. By focusing on Northport, researchers can gain valuable insights into how digital and energy-efficient technologies can transform the seaport industry.

In summary, smart port technologies are expected to be used in most ports by 2027. Port authorities support this trend with considerable blockchain investments, indicating their growing embrace of digital technology. For example, RM20 million was allocated to the Malaysian Maritime Single Window (MMSW) in January 2024 to revolutionize port trade (Ignatius, 2023). However, despite the increasing adoption of digital and energy-efficient technologies globally, there is a lack of research on the effectiveness of digitalization strategies. This study addresses this gap by meticulously exploring the impacts of digital and energy-efficient technology adoption at seaports to bolster operational efficiency and foster environmental sustainability. By studying this gap, other relevant industries can adopt similar strategies for implementing digitalization.

Hence, the research questions that serve as guidelines for reaching the main aims are as follows:

RQ1: What is the current state of digital and energy-efficient technology applications used in Northport Bhd?

RQ2: What is the impact of Northport's digital technologies on operational efficiency and sustainability?

RQ3: What is the impact of Northport’s energy-efficient technologies on improving operational efficiency and promoting sustainability?

2. Literature Review

2.1. Digital Technologies

Digital technology, which includes software, Internet networks, and electronic devices, is revolutionizing modern society, exerting a profound influence on several elements such as communication, professional interactions, and daily life. Digital technologies are transforming seaports and causing seismic upheavals in the maritime industry. Digital transformation at seaports optimizes supply chains, streamlines procedures, and strengthens maritime sector links via electronic devices, software, and the Internet (Parola et al., 2020). Big data, artificial intelligence (AI), blockchain, and the Internet of Things (IoT) are required to measure and improve port sustainability (Kuo et al., 2022; Haleem et al., 2021). Digitization is a prerequisite for long-term success; however, community stakeholders' lack of cooperation hinders port operators' efforts.

Accordingly, the integration of digital technologies into seaports plays an essential role in enhancing operational efficiency and promoting environmental sustainability (Almeida, 2023). Ports optimize operations by implementing automation and smart systems, such as automated gate systems and real-time cargo tracking using IoT sensors. These technologies improve efficiency, minimize human errors, and increase transparency in the supply chain (Heikkilä et al., 2022). Automated stacking cranes and yard vehicles enhance freight handling efficiency by integrating renewable energy sources and minimizing energy consumption and emissions. This facilitates an uninterrupted operation and rapid vessel turnaround (Budiyanto et al., 2021). In addition, digital technologies enable the use of data to make informed decisions, thereby allowing for preventative maintenance, optimized routes, and efficient allocation of resources. Collectively, the incorporation of digital technologies within seaports enhances operational effectiveness and environmental sustainability.

2.2. Energy Efficient Technologies

In addition, the implementation of energy-efficient technologies in seaports is significant in achieving operational efficiency and fostering environmental sustainability. Seaports can achieve monetary advantages and alleviate the carbon footprint by incorporating renewable energy sources, such as solar and wind power, thus decreasing reliance on traditional fossil fuels. Energy-efficient lighting systems and equipment bolster energy use, resulting in lower operational expenses and the establishment of a more secure work environment (Zadeh et al., 2023). Smart grid systems and energy management inventions facilitate the effective allocation of energy, reduce waste, and enhance the consumption of resources (Loschi et al., 2015). In addition, the use of hybrid and electric vehicles for handling cargo and transit within the port not only decreases emissions, but also improves air quality (Densberger & Bachkar, 2022). Overall, the adoption of energy-efficient technologies at seaports improves operational efficiency by lowering expenses and increasing dependability while simultaneously promoting environmental sustainability by decreasing the ecological consequences of port operations (Philipp et al., 2021).

2.3. Operational Efficiency

Operational efficiency involves producing goods and services with minimal time, labor, and money, while maintaining or improving quality. This shows how well an organization uses its resources to achieve its goals (Wong et al., 2019). Global trade relies on the’ capacity of seaports to handle freight and passengers efficiently, cost-effectively, and securely. Vessel turnaround time, cargo throughput, and labor productivity are efficiency indicators (Karnoji & Dwarakish, 2018). Digital technologies have transformed seaport operations and increased efficiency (Parola et al., 2020).

This transformation culminates in freight handling, logistics optimization, and digital technology streamline processes. Real-time cargo tracking and automatic cargo identification using IoT sensors and RFID tags can improve resource allocation and clearing times (Tan & Sidhu, 2022). The incorporation of digital tools grants seaports the ability to make informed decisions about vessel arrivals, cargo movements, and resource utilization by employing real-time data analytics (Almeida, 2023). These technologies utilize IoT sensors and machine-learning algorithms to track the health of equipment, detect probable malfunctions, and enhance overall asset utilization.

Digital advancements such as access control systems and video surveillance aid in the prevention and resolution of incidents, thereby enhancing the safety and security of seaport operations (Almeida, 2023). Furthermore, digital technologies elevate customer service and communication by enabling transparency and real-time information exchange through platforms and applications (Evans et al., 2017). The increasing integration of digital technologies into seaport operations qualifies these maritime institutions not only for operational efficiency but also for survival in a competitive global environment.

2.4. Environmental Sustainability

Environmental sustainability refers to the capacity to uphold a standard of living that fulfils the requirements of the current generation while safeguarding the potential of future generations to meet their own demands (Rafiq et al., 2023). This entails utilizing resources in a manner that avoids depletion or irreversible damage to the environment. In the context of seaports, environmental sustainability involves understanding the multidimensional influence of port activities on the environment, and establishing strategies to mitigate harmful external consequences. Seaports serve as both facilitators and contributors to economic activity, offering jobs, tax income, and investments, resulting in environmental issues, such as congestion, pollution, and accidents (Agatić & Kolanović, 2020).

Environmental sustainability in seaports requires a systematic approach to overcome these difficulties through innovation and the incorporation of green practices. The management and organization of the logistics chain, which is a critical component of a company's strategy, must examine and internalize the external expenses connected with port activities, while also fostering eco-awareness and effective resource use. Seaport environmental sustainability involves a holistic approach that balances economic activity with ecological responsibility, acknowledging the interdependence between port operations and environmental well-being.

3. Research Methodology

This study analyzes Northport, which is one of the largest multi-purpose ports in Malaysia that offers different facilities and services to handle a wide variety of cargo. Starting with a short literature review on the application of digital technologies in port operations, the aim of this study is to explore the impact of digital technologies at seaports.

The primary source of data will be interviews with managers from relevant departments within seaports. The interviewees are chosen for their expertise, qualifications, and direct involvement in seaport digital technology adaptation. This data-gathering procedure seeks to provide insights into seaport digital technology use, advancing the maritime industry's sustainability and efficiency. Overall, this study invited ten senior staffs from relevant departments within Northport. Semi-structured interviews with open-ended questions were arranged to allow interviewees to express their views freely, without being limited to a set of responses (Wong et al., 2022). Quantitative market data, reports, and discussions with experts in the field served as a source of triangulation for ideas that emerged from the qualitative data.

This study adopted an interpretive research approach, which, in the interpretation of concepts in a first-order analysis, gives voice to employees involved in managing digital and energy efficiency technologies (Wiesner, 2022). The insider's perspective was the foundation of our inductive analysis. Following this, we took on the task of formulating deeper, more theoretical, and conceptual second-order interpretations, as shown in Figure 1 (Hübner et al., 2016).

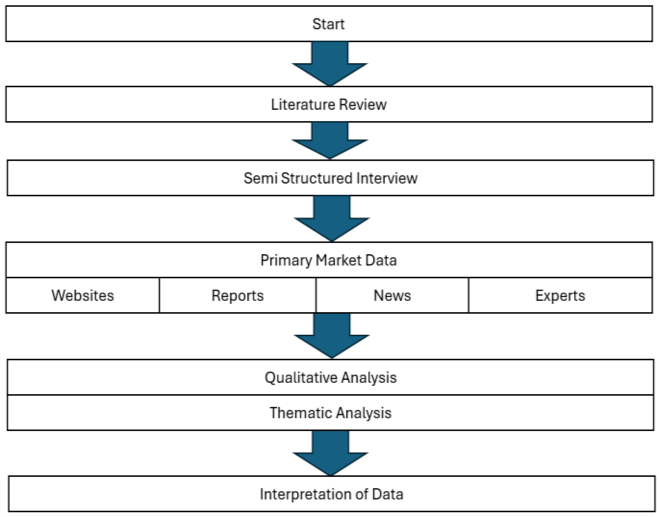

Figure 1. Research flowchart (developed by the authors)

Accordingly, this study employed semi-structured interview with ten respondents and these interviews were conducted physically or remotely using the Zoom platform, as shown in Table 1.

Table 1. Features of interviewees (developed by the authors)

Item	Features	Number
Working experience	2- 4 years	5
	5-10 years	3
	More than 10 years	2
Position	Executive	6
	Manager	4

4. Discussion

4.1. Current Stage of Digital Technologies

Northport Bhd embarked on a transformative journey by incorporating digital technologies in collaboration with Mitsui E&S Machinery Co. and SITC. As a result of their collaboration with SITC, state-of-the-art smart electric container stackers have been acquired, fundamentally transforming the way in which containers are handled (SITC International Holdings Company Bhd, 2023). These stackers maximize container movement within the port environment and improve operating efficiency and safety. These are outfitted by cutting-edge sensors, cameras, and automated control systems.

Moreover, collaboration between Northport Bhd and Mitsui Machinery and Co. has led to the acquisition of electric rubber tire gantry (ERTG) cranes, which have substantially enhanced port operations. These specialized cranes make it easier to handle containers in container yards, including stacking, retrieving, and placing them. ERTGs maximize space utilization and expedite yard management through strategic stacking of containers lifted from trucks or railcars in designated storage areas.

Additionally, the integration of digital technology in Northport Bhd incorporates the Navis N4 Terminal Operating System developed by Kaleris (Mair, 2024). This system is a solution provided by Kaleris, a supply chain execution software expert. The Navis N4 system was designed to boost production, efficiency, and green initiatives at the ports. This technology facilitates smarter decision-making for expedited transportation, reduces the need for container rehandling to promote sustainable operations, and accelerates turnaround time for shippers. Furthermore, Northport will use the Navis N4 system as part of a turnkey solution from Kaleris that comes with all the hardware and workforce management software needed for installation (Mair, 2024).

In addition, as per the interviewee, the Navis 4 Terminal Operating System is seamlessly integrated with another system, called the Contrak Tool System. Northport in Malaysia uses the Contrak Tool System, which is an advanced container tracking system designed to streamline container handling processes while enhancing operational efficiency. The Contrak Tool System utilizes a blend of technologies, including RFID, GPS, and barcodes, to monitor the movement and condition of containers near the port. Each container is assigned a unique identifier, allowing for accurate data collection upon entry, exit, and movement within the port. Scanners and readers extract data from container tags, which are subsequently sent to a central database or software platform for processing and storage. The Contrak Tool System interface provides port operators, customers, and stakeholders real-time access to container locations, statuses, and handling history. This robust monitoring and reporting capacity enables more effective inventory management and operational decision making. Furthermore, the Contrak Tool System integrates seamlessly with Northport's other operational systems, including the Navis N4 Terminal Operating System, Navis Ship Editor, Navis Operational, and Navis Stock to guarantee seamless and effective container handling processes throughout the port facility.

According to the interviewee, despite the Contrak tool system, the Vehicle Mount Terminals (VMTs) system was employed during the operating process. VMTs are widely recognized for their significant contribution to improving operational efficiency inside port facilities. Each vehicle utilized in port operations is equipped with these gadgets, which bear a resemblance to iPad. VMTs are useful instruments for directing truck operators to the optimal positioning of cargo for the next transshipment, considering the heavy machinery used in handling containers and cargo in port sectors. VMTs optimize operational processes and reduce reliance on manual intervention by providing guidance and instructions in real time to vehicle operators. The integration of VMTs with the Contrak Tool System increases efficiency by eliminating the need for employees to rely entirely on computers or software to enter the data. Conversely, operators are granted direct access to relevant information and instructions via the VMT interface, which empowers them to perform tasks with optimal efficiency and devoid of any disruptions or setbacks. The utilization of a hands-free method for data input and guidance was found to have a substantial positive impact on the entire workflow at the port. This technique enables staff members to concentrate on operational responsibilities, while simultaneously guaranteeing accuracy and punctuality in cargo handling procedures.

The digital technology integration initiative, spearheaded by the MMC Corporation Bhd in partnership with Ramco Systems, seeks to digitally revolutionize five ports in Malaysia, including Northport (Malaysia) Bhd (Ramco, 2021). The implementation of this effort has resulted in a substantial improvement in the connectivity between the Northport Klang and its stakeholders. The implementation of an integrated Enterprise Resource Planning (ERP) system throughout MMC ports, including Northport Klang, standardizes processes and consolidates diverse business support services. The integration of operations between Northport Klang and other ports within the MMC group guarantees operational consistency and facilitates smooth communications. In addition, the Enterprise Resource Planning (ERP) system offers the most recent business data, facilitating stakeholders at Northport Klang in making prompt and well-informed decisions. Over 8,000 MMC employees across ports, including those at Northport Klang, will have access to the integrated platform on their computers and mobile devices, promoting better communication and collaboration among employees. Furthermore, an Enterprise Resource Planning (ERP) system integrates intelligent functionalities, including Machine Learning (ML) and AI, which afford stakeholders enhanced visibility and prognostic notifications. Ultimately, this digital transformation initiative aims to enhance the business experience of customers and suppliers of MMC ports, including Northport Klang, by leveraging technology to provide best-in-class services and improve operational efficiency.

4.2. Impacts of Digital Technologies

4.2.1. *Operational Efficiency*

The operational efficiency of the Smart Depot Service (Malaysia) Sdn Bhd in Port Klang is greatly improved using the SMART Electric Stacker. The stacker enhances container handling procedures by using its autonomous operational capabilities, resulting in reduced idle time and increased production. For example, the SMART Electric Stacker and electrified rubber red gantry (eRTG) cranes enhance operational efficiency by optimizing container stacking and retrieval processes, resulting in reduced turnaround times for ships and trucks. Consequently, this leads to an overall increase in the operational throughput. Furthermore, the incorporation of sensors and automated control systems into the stacker system boosts the level of accuracy and precision in the handling of containers, thereby making a significant contribution to operational efficiency. Moreover, the integration of advanced safety systems and automation facilities enhances overall safety and mitigates the potential for operational disruptions. These intelligent technologies from Northport are designed to be flexible and scalable, allowing them to quickly adjust to shifting operational requirements and maintain operational efficiency in an ever-changing port environment.

The integration of an Enterprise Resource Planning (ERP) system, such as the RAMCO System, plays an important role in enhancing operational efficiency by consolidating and standardizing diverse business support services throughout the port. The ERP system facilitates smooth communication and collaboration between various departments and stakeholders by streamlining finance, human resources, enterprise asset management, supply chain management, and logistics management into a single platform. The utilization of an integrated dashboard that provides real-time access to business information empowers port operators to make informed decisions. This enables them to optimize resource allocation, improve inventory management practices, and accelerate operational planning processes.

In addition, the implementation of the Digital Port Community System (DPCS) and SmartApp Framework drastically reduces paper usage throughout Northport's operations. Historically, port and shipping transactions have relied heavily on paper-based documentation, resulting in massive paper consumption and associated consequences for the environment. Through digitization, Northport effectively mitigates the necessity for paper-based documentation, resulting in a reduction in deforestation, energy consumption, and greenhouse gas emissions associated with the production and transportation of paper. The transition to paperless operations not only reduces environmental effects but also streamlines administrative processes, leading to enhanced productivity and cost savings. Furthermore, the incorporation of digital technologies optimizes logistics operations at Northport, thereby lowering fuel consumption and emissions from transportation operations. DPCS provides a centralized platform for stakeholders to easily access and communicate information, automating crucial operations such as vessel clearance, document clearance, and cargo tracking. By minimizing supply chain delays and inefficiencies, the system minimizes idle time for vessels and vehicles, resulting in decreased fuel consumption and emissions. This optimization of logistical operations benefits the environment, while further improving port competitiveness and sustainability.

Furthermore, as per the interviewee, the incorporation of VMTs into port operations augments efficiency through the provision of instantaneous instructions and guidance to vehicle operators concerning the optimal placement of cargo for transshipment. By eliminating the need for manual data entry and providing hands-free access to critical information, VMTs can streamline cargo handling processes and reduce operational delays. Integration with systems such as the CONTRAK Tool System ensures seamless data exchange between VMTs and other operational systems, enhancing the overall workflow efficiency and enabling port operators to achieve optimal performance in container handling operations.

Overall, the integration of VMTs, ERP, the Contrak Tool System, and Navis 4 TOS into port operations signifies a holistic approach for maximizing operational efficiency. Through the centralization of data, provision of real-time visibility, facilitation of more intelligent decision-making, and optimization of cargo handling procedures, these digital technologies collaborate to optimize productivity, augment sustainability, and guarantee a competitive advantage for ports in the contemporary global trade landscape.

4.2.2. *Environmental Sustainability*

The adoption of digital technologies, including electric container stackers, vehicles, and e-RTG cranes, plays a crucial role in enhancing the environmental sustainability of port operations. By shifting from traditional diesel-powered machinery to electric alternatives, ports have the potential to substantially mitigate carbon emissions, in harmony with international initiatives to address climate change. The implementation of the SMART Electric Stacker at the Smart Depot Service (Malaysia) Sdn Bhd at Port Klang, for instance, is a prime example of this transition to more environmentally friendly technologies. In addition to mitigating environmental consequences, the SMART Electric Stacker establishes a favorable model for other port operators, thus promoting wider acceptance of sustainable practices within the maritime industry through its emission-free operation.

Moreover, all newly constructed container yards will use e-RTGs, which will progressively replace traditional diesel-powered models and drastically reduce carbon emissions. The integration of digital technology, such as e-RTGs, e-vehicles, and electric container stackers, promotes sustainable port ecology. This is made possible by significant reductions in carbon emissions, development of renewable energy sources, and encouragement of more widespread adoption of environmentally beneficial practices in the maritime sector.

Since the official implementation of green port initiatives commenced in 2021, a noticeable decrease in greenhouse-gas emissions has been observed (Figure 2).

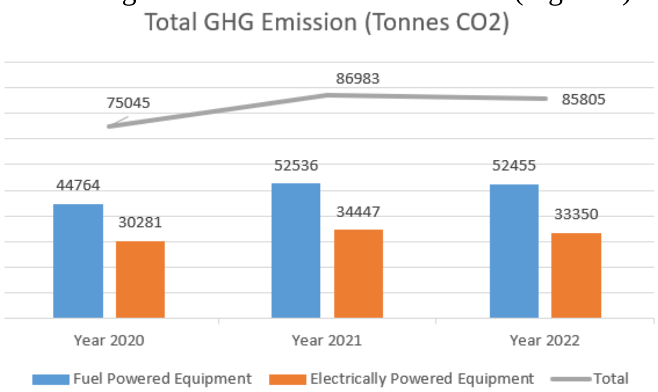

Figure 2. The total GHG emissions at Northport (developed by the authors)

All of these initiatives align closely with the company's objective, which asserts that the adoption of digital technologies in seaports will lead to a significant improvement in operational efficiency and environmental sustainability. Northport Bhd demonstrated the positive effects of adopting digital technologies in the maritime industry by incorporating digital technologies, such as electric container stackers, e-RTG cranes, and smart machinery. This integration improves the operational efficiency and promotes environmental sustainability, resulting in a more efficient and eco-friendly port ecosystem.

4.3. Current Stage of Energy-efficient Technologies

Northport Bhd exhibited praiseworthy dedication to sustainability by implementing a range of energy-efficient technologies throughout its operational activities. The port's proactive approach is reflected in its plan, which includes renewable energy integration, infrastructure enhancements, and energy management projects.

The extensive use of solar photovoltaic (PV) systems is a major component of Northport's energy-efficiency initiatives. By requiring the installation of solar panels on all newly constructed warehouses in the port vicinity, Northport demonstrated its commitment to leverage the potential of renewable energy sources. It is anticipated that solar panels, including those recently installed at the second district park, will generate substantial yearly energy conservation, amounting to 6,490.392 MWh. This program not only decreases reliance on grid electricity, but also reduces carbon emissions, which aligns with the port's sustainability goals.

In addition, Northport embarked on a thorough fleet modernization initiative with the goal of substituting traditional diesel-powered machinery with more energy-efficient alternatives. Furthermore, the increasing replacement of diesel-powered rubber-tyred gantry cranes with electric ones aligns with national transportation goals aimed at lowering air quality and supporting sustainable infrastructure. Northport also added energy-saving features to its buildings. The port's holistic approach to reducing energy consumption is demonstrated by the installation of natural ventilation systems and rainwater harvesting facilities, as well as the use of LED lighting technology. LED lights are more energy efficient and have a longer lifespan, which lowers maintenance costs and enhances operational sustainability.

Furthermore, according to the interviewee, Northport's commitment to environmental sustainability is bolstered by the implementation of hyperconvergence and cloud-computing technologies. Northport's transition from a traditional in-house hosting to a cloud environment lessens the need to manage and operate its own physical servers and networking equipment. Instead, services are hosted in shared data centers, which are frequently placed in ecologically friendly facilities, such as those in Cyberjaya. The entire energy consumption and carbon footprint connected with data center operations are greatly reduced because of the consolidation of infrastructure and sharing of resources with other tenants.

The interviewee highlighted that hyperconvergence technology facilitates Northport to extend its IT infrastructure in an effective and sustainable manner by merging computing, storage, and networking resources into a single integrated platform. This consolidation decreases the physical footprint of the IT infrastructure, preserves energy, and maximizes resource utilization, resulting in higher productivity and sustainability. Furthermore, by using a cloud-based elastic computing model, Northport can dynamically expand its IT resources in response to demand, optimize the usage of resources, and minimize waste. Elasticity promotes environmental sustainability by minimizing wasteful energy usage and emissions from idle infrastructure.

The integration of digital technologies at Northport, which includes initiatives such as DPCS, the Northport SmartApp Paperless Operation Digitalization Framework, and the use of hyperconvergence and cloud computing, is key to strengthening environmental sustainability within the port ecosystem. In conclusion, renewable energy integration, technological upgrades, and strategic planning have achieved the best maritime energy efficiency.

4.4. *Impacts of Energy-efficient Technologies*

4.4.1. *Operational Efficiency*

In Northport, the implementation of energy-efficient technologies has yielded notable improvements in operational efficiency across multiple aspects of port operations. The reliability and performance of the equipment are important areas of improvement. Northport has witnessed enhanced efficiency and effectiveness in its container handling procedures via electric-generated infrastructure, resulting in heightened productivity and diminished vessel turnaround durations. The attached diagram, which demonstrates a reduction in the carbon emission intensity ratio (in tones CO_2/RM million revenue) in 2022 compared to 2021, further supports this improvement in efficiency. This reduction validates the viability of energy-efficient projects and highlights the port's operations' environmental sustainability, while also translating into large cost savings, as shown in Figure 3.

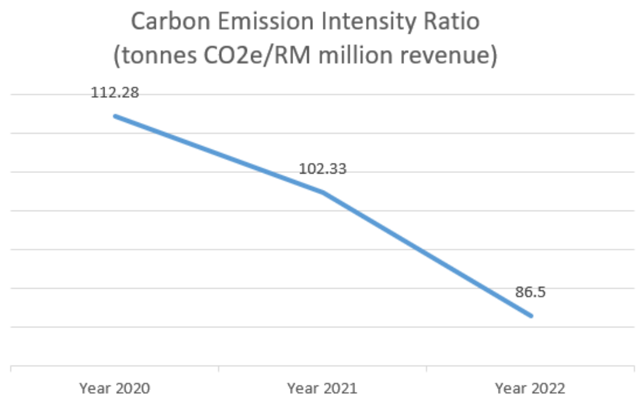

Figure 3. Carbon emission intensity ratio in tones CO_2/RM million revenue (developed by the authors)

In addition, the integration of LED lighting technology and natural ventilation systems in port buildings has contributed to improving the working conditions of port personnel. Compared to traditional lighting fixtures, LED lights provide better brightness and uniformity, thereby enhancing visibility and safety in cargo handling areas and warehouses. Moreover, natural ventilation systems can enhance the quality of air and boost the levels of comfort in enclosed spaces, thereby decreasing the need for mechanical ventilation systems and optimizing energy usage. The integration of enhanced lighting and ventilation not only boosts employee productivity and morale, but also decreases operational expenses related to building upkeep and energy usage.

In addition, the integration of renewable energy sources such as solar photovoltaic (PV) systems has strengthened Northport's energy autonomy and financial viability. Northport has effectively decreased its dependence on grid electricity and minimized its vulnerability to volatile energy prices by implementing solar energy as an energy source for power warehouse operations and related facilities. Solar power is reliable and long-lasting; therefore, there is always sufficient energy to keep the port running. This lowers the chance that activities will be interrupted by grid outages or supply shortage. As a result of this improved energy security, Northport can sustain uninterrupted operations and satisfy customer requirements more efficiently, thereby enhancing its competitiveness and overall operational efficiency in the maritime sector.

The data in Figure 4 illustrate how the electricity consumption intensity (in MWh/RM million income) decreased in 2022 compared with 2021, which presents additional evidence. This decrease emphasizes the value of incorporating renewable energy sources and the financial advantages of reducing the dependency on the grid for electricity. Northport improves its financial resilience and maintains its competitiveness in maritime business by utilizing solar power and reducing the intensity of its electricity use.

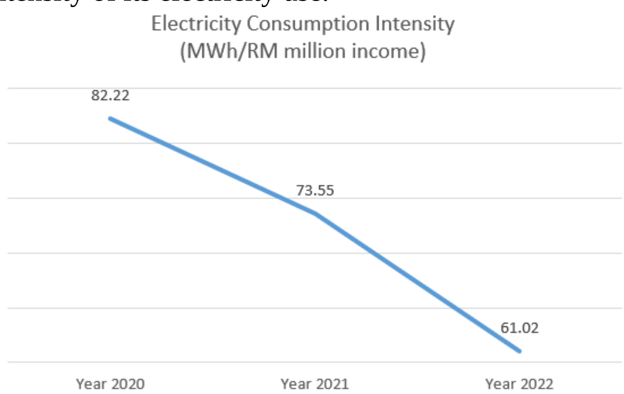

Figure 4. Electricity consumption intensity in MWh/RM million income (developed by the authors)

Moreover, the implementation of energy-efficient technologies has enabled Northport to enhance resource utilization and asset management methods. One example of reducing the dependence on potable water supplies for non-potable activities, such as general cleaning and landscaping, is the adoption of rainwater collection systems. Northport practices on-site rainwater collection and utilization, which functions to preserve scarce freshwater resources and mitigate operational expenses linked to water procurement and treatment. Similarly, the implementation of energy-efficient machinery and infrastructure enhances energy usage and reduces inefficiency, resulting in long-term cost savings and improved operating efficiency. This is further supported by the decline in water consumption intensity (in m^3/RM million revenue) in 2022 compared with 2021, as shown in Figure 5.

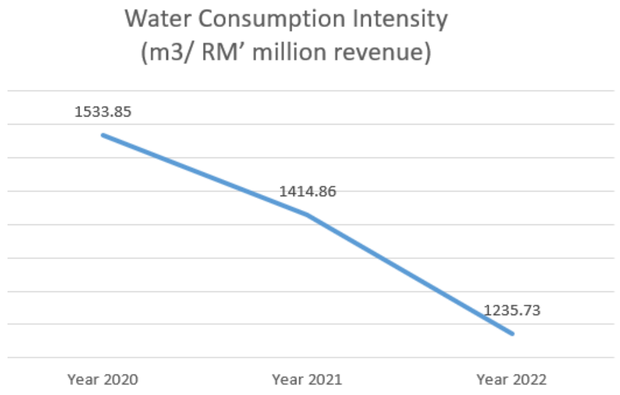

Figure 5. Water consumption intensity in m^3/RM million revenue (developed by the authors)

Northport's reduction not only emphasizes their dedication to sustainable resource management, but also showcases the financial benefits of implementing energy-efficient technologies. Northport achieves substantial cost savings and enhances its overall operational efficiency and financial sustainability by deploying measures, such as rainwater collection systems and optimizing machinery and infrastructure.

In conclusion, Northport has seen a noticeable improvement in operational efficiency across a range of port operations because of the implementation of energy-efficient technologies. These technologies have produced favorable outcomes that translate into increased productivity, cost savings, and competitiveness for Northport in the international marine industry. These outcomes range from improved equipment performance and reliability to improved workplace environments and resource-utilization techniques. Northport prioritizes operational efficiency and environmental sustainability to bring value to stakeholders and to foster a better future.

4.4.2. *Environmental Sustainability*

The implementation of energy-efficient technologies by Northport has resulted in notable enhancements in environmental sustainability throughout various business operations. One significant consequence pertains to the mitigation of carbon emissions associated with port operations. Northport has been able to produce clean and renewable electricity on-site through the integration of renewable energy sources such as solar photovoltaic (PV) systems on warehouse rooftops. This has reduced the company's reliance on fossil fuels and has contributed to reducing greenhouse gas emissions. By employing solar energy to power its activities, Northport assists in combating climate change locally and globally, and contributes to the decarbonization of the maritime sector.

By switching to electrically powered machinery, the air quality of the port area has greatly improved, and the environmental effect of cargo handling operations has decreased. Additionally, Northport's aim to support sustainable infrastructure and lower air pollution emissions is demonstrated by its decision to replace rubber-tyred gantry cranes running on diesel with electric ones.

The data in Figure 6 demonstrate this, showing a decrease in total carbon emissions (tons CO_2) in 2022 compared with 2021. This decrease demonstrates the real results of Northport's deployment of energy-efficient technologies and reaffirms its dedication to environmental sustainability. Northport decarbonizes the marine sector by reducing carbon emissions and promoting environmental sustainability both locally and worldwide.

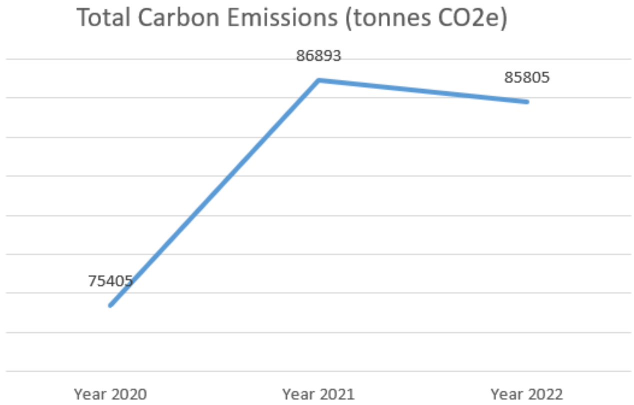

Figure 6. Total carbon emissions in tons CO_2 (developed by the authors)

Figure 7 shows a decrease in the total electricity consumption (MWh) in 2022 compared with 2021. The decrease in energy usage not only emphasizes Northport's commitment to ecological sustainability but also proves that its strategic initiatives were successful in curbing usage. Northport leads marine port sustainability by prioritizing energy-efficient products, equipment, and sustainable governance.

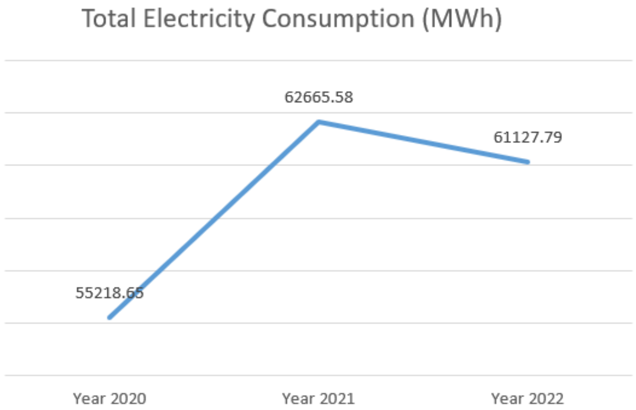

Figure 7. Total electricity consumption (MWh) (developed by the authors)

Accordingly, Northport Bhd demonstrated how the integration of energy-efficient technologies can drive positive change, improve operational performance, and promote environmental stewardship in the maritime industry by embracing renewable energy sources, implementing energy-saving equipment, and encouraging strategic planning and governance. These measures not only boost Northport's competitiveness but also pave the way for a greener, more sustainable future for the port industry worldwide.

5. Conclusion

Based on the first research question, the objective was to assess the current state of digital technologies and the adoption of energy-efficient technologies in Northport Bhd. The findings demonstrate how Northport Bhd effectively incorporated modern digital technologies such as electrified rubber tire gantry (eRTG) cranes and smart electric container stackers, leading to enhanced container handling processes, reduced turnaround times, and lower carbon emissions. Simultaneously, Smart Depot Service (Malaysia) Sdn Bhd collaborated and employed the SMART Electric Stacker to enhance the container stacking and retrieval procedures. In addition, Northport has enhanced its operational efficiency and sustainability by integrating solar photovoltaic (PV) systems, electric rubber red gantry (E-RTG) cranes, LED lighting technology, natural ventilation systems, and rainwater harvesting facilities. Through improved operation, equipment performance, dependability, and maintenance, these energy-efficient technologies have improved. These programs support global efforts to combat climate change and to advance environmentally friendly practices in the maritime sector. Within the context of seaports, the adoption of digital technologies and energy-efficient technologies, as illustrated by Northport Bhd, represents a significant step towards enhancing operational efficiency and promoting sustainable port ecology, as shown in Figure 8.

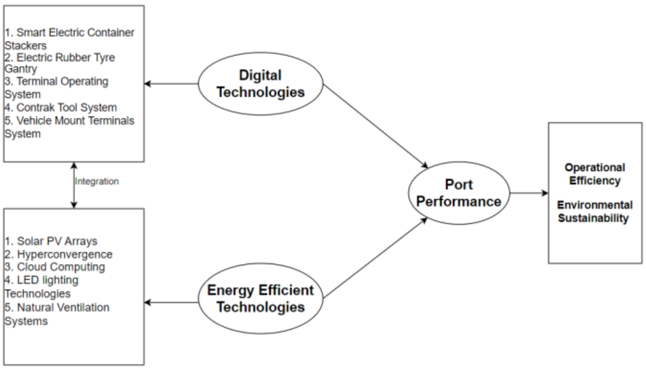

Figure 8 Summary of digital and energy efficiency technologies performance (developed by the authors)

5.1. Digital Technologies and Impacts

To answer the second research question, the integration of these digital technologies has heightened processes, including container handling, inventory management, and logistics operations. Real-time data interchange, aided by systems such as the Contrak Tool System and Navis N4 Terminal Operating System, has improved decision-making, reduced turnaround times, and enhanced overall port efficiency. These approaches have resulted in considerable reductions in paper usage, decreased fuel consumption, and emissions through optimized logistical operations, and have allowed resource-efficient IT infrastructure via cloud computing and hyperconvergence technologies. Northport's integration of digital technology has enhanced operational efficiency, while also contributing to environmental sustainability by streamlining processes, decreasing waste, and minimizing environmental effects.

5.2. Energy-efficient Technologies and Impacts

According to the third research question, the adoption of energy-efficient technologies at Northport Bhd played a pivotal role in enhancing both operational efficiency and environmental sustainability in the maritime sector. The integration of renewable energy sources, such as photovoltaic solar systems, has resulted in greater energy independence, less reliance on the grid, and uninterrupted functioning, ultimately driving productivity and competitiveness. Furthermore, by minimizing carbon emissions, preserving resources, and encouraging sustainable practices, the adoption of these technologies has contributed to environmental sustainability. The implementation of energy-saving procurement strategies and carbon footprint analyses among other strategic planning and governance activities strengthened Northport's dedication to environmental stewardship and sustainability. Northport Bhd achieved greater operating efficiency and environmental sustainability in the maritime industry by using energy-efficient technologies. Northport leads the marine industry toward sustainable port operations by using renewable energy, energy-saving equipment, and sustainable practices.

In summary, this study significantly contributes to the academic understanding of how digital technologies can enhance operational efficiency and promote environmental sustainability in seaports. While the existing literature has recognized the importance of seaports in the global supply chain, few studies have explored the specific impacts of digital technologies on ship-port interaction operations. This study uniquely addresses this critical gap by examining not only technological adoption, but also its nuanced effects on operational efficiency and environmental sustainability. By aligning these findings with global sustainable maritime goals, this study offers a novel perspective on the complex interplay between technological advancements and environmental responsibility. This innovative approach provides a valuable framework for future studies aimed at digitally transforming seaport operations, thereby advancing academic knowledge and practical applications in the maritime industry.

6. Limitations and Further Studies

Comprehensive interviews were conducted to collect extensive qualitative data. The interviews and discussions could have yielded more comprehensive insights, and the purpose of the focused interviews was to obtain valuable information within a given timeframe. However, one limitation of relying on comprehensive interviews for qualitative data collection was the potential for interviewees to provide biased or incomplete information. Interviewees may unintentionally withhold certain details, offer socially desirable responses, or emphasize aspects that align with their perspectives or interests. These biases can limit the depth and accuracy of the insights gathered, potentially leading to an incomplete understanding of digital technology adoption in Malaysian seaports. However, it is crucial to recognize that the study investigates a relatively still developing area of research – the adoption of digital technology in seaports, and thus employs a comprehensive case study methodology. Hence, this methodology enables a thorough analysis of the phenomenon, providing valuable insights that enhance the comprehension of the adoption of digital and energy-efficient technologies in Malaysian seaports.

For future studies, it is recommended to broaden the scope beyond a single seaport in Malaysia to encompass multiple ports. Researchers can identify patterns and evaluate the impacts of digital technology solutions on environmental sustainability and operational efficiency in a variety of port environments by examining a wider range of ports. Additionally, future research may examine various strategies that ports can adopt to deal with the challenge of resistance to technological change and adaptation. Gaining insight into the ways in which these strategies impact the performance of ports, specifically with regard to improving environmental sustainability and operational efficiency, will aid in the realization of the triple bottom-line goals. Port operations must adopt the triple bottom-line approach to remain relevant and create value in today's dynamic business climate, where environmental, social, and governance (ESG) performance is more important.

Author Contributions

Conceptualization, J.F.Y.; methodology, X.L.S.; software, U.K.B.A.B.; validation, S.D.A.P.S.G.; formal analysis, S.D.A.P.S.G.; investigation, X.L.S.; resources, J.F.Y.; data curation, U.K.B.A.B.; writing—original draft preparation, all authors contributed equally; writing—review and editing, S.D.A.P.S.G.; visualization, U.K.B.A.B.; supervision, J.F.Y.; project administration, X.L.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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