Sustainable Digital Twin Design: The Smart Terminal Use Case

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***Abstract*— This work presents a digital twin for a container-oriented logistics terminal, enabling real-time integration and visualization of operational, environmental, and energy data for equipment such as reach stackers and refrigerated containers. The system provides a holistic view of terminal activities and supports CO_2 emissions monitoring and forecasting, addressing growing sustainability concerns in port operations. Developed within the NEXUS agenda, this work follows a design science research methodology and is structured in two data flows: one capturing equipment states and positions, and another estimating environmental indicators from real data. These flows are integrated into a unified platform using open-source technologies, including Eclipse Ditto, InfluxDB, and Grafana. Results are validated against real and literature data, focusing on CO_2 emissions and fuel consumption. The proposed approach supports near real-time monitoring and improved sustainability in smart terminal operations.**

Keywords—Digital Twin, Logistics Terminal, Sustainability, Carbon Emissions, Data Pipeline, Decision Support

I. Introduction

Logistics terminals are determinant in the transport and distribution chains, as they are responsible for the movement, storage, and routing of goods across different modes of transport [1]. These critical infrastructures integrate multiple processes, equipment, and actors, which results in high operational complexity [2]. Due to their reliance on intensive physical operations, terminal activities generate carbon dioxide (CO_2) emissions, mainly from the use of container-handling equipment, such as reach stackers, and from land-based transport. This equipment plays a central role in terminal operations and contributes significantly to fuel consumption and associated environmental impacts [4].

Growing concerns about environmental sustainability in the transport sector have reinforced the need to understand and evaluate the environmental impacts of logistics operations [3]. In this context, the systematic monitoring and analysis of CO_2 emissions generated by terminal activities represent a challenge, as they require solutions capable of continuously collecting, integrating, and analysing heterogeneous operational data.

Digital twins can help address this challenge by providing a digital representation of physical infrastructures and processes while maintaining a continuous connection between the real system and its digital model [5]. The application of this concept in logistics contexts enables the systematic collection and analysis of operational data, providing a structured view of system operations and supporting decision-making based on up-to-date information.

However, a review of the state of the art reveals some relevant limitations. In particular, many existing approaches rely on fragmented systems with weak integration between components, making it difficult to obtain a holistic view of the system [8], [10]. In addition, most of the work focuses primarily on operational metrics and does not consistently integrate environmental indicators, such as fuel consumption and CO_2 emissions [15], [18]. Finally, several solutions are based on historical data and do not support continuous or near-real-time monitoring [16], [17].

This work presents the development of a Digital Twin prototype for a logistics terminal, aimed at monitoring and analysing both operational and environmental indicators, including distances traveled, fuel consumption, and CO_2 emissions associated with reach stackers. The proposed approach integrates these indicators into a single digital model, providing a unified view of the terminal's operational status and the environmental impact of its activities. The proposed solution is based on a modular architecture that integrates different components responsible for collecting, processing, storing, and visualizing data. In particular, the system allows ingestion of operational data, processing for event detection and metric calculation, historical storage of information, and visualization through an interactive interface.

The main contributions of this work are as follows:

- The definition of an integrated approach to the adoption of sustainability Digital Twins in logistics terminals;
- The implementation of a data pipeline that enables continuous monitoring of operational and environmental indicators;
- The integration of sustainability metrics into the digital model, supporting the analysis of the environmental impact of terminal operations.

The remainder of the paper is organized as follows. Section II presents the state of the art. Section III describes the system architecture. Section IV details the data flow and processing.

Section V presents the model for estimating environmental indicators. Section VI addresses the visualization component and Section VII discusses findings and future work opportunities. Finally, conclusions are presented in Section VIII.

II. State of The Art

Digital Twin technology has been widely explored in the context of cyber-physical systems and industrial environments, with applications in production, simulation, and product life cycle management [6]. However, its application in logistics and transport contexts is more recent and remains at a lower stage of maturity [6]. In the field of supply chains, some works have explored the concept of Digital Supply Chain Twin, with a focus on risk management, resilience, and response to disruptions [7]. These approaches tend to act at a more strategic and tactical level, not addressing in detail the real-time operational monitoring of logistics equipment and processes.

An approach closer to the operational level integrates Internet of Things (IoT) and big data technologies, enabling real-time data collection and processing [8]. In these cases, Digital Twins are used to generate performance indicators and improve operational visibility. Even so, many of these architectures are generic or were originally designed for industrial environments and do not fully address the specific needs of logistics [8].

In the context of ports and terminals, the Digital Twin has been applied as a simulation, planning, and decision support tool [9]-[11]. Some approaches integrate technologies such as BIM, GIS, and IoT to represent infrastructure and operations, thereby improving efficiency and reducing operational costs [9]. However, these solutions face significant challenges, namely in the integration of heterogeneous data, the complexity of modeling real systems, and the use of fragmented systems, which limits the achievement of a holistic view of the terminal [10], [11].

Regarding environmental monitoring, several studies have addressed the estimation of CO_2 emissions in logistics terminals, using both real energy consumption data and bottom-up models [15]-[17]. These studies enable the identification of the main emitting equipment and the evaluation of operational efficiency, but have limitations due to dependence on data quality and the fact that the analysis is often conducted asynchronously, using historical data [15]-[17]. Sustainability-oriented dashboards and environmental decision-support principles have also been proposed in adjacent operational contexts [18].

More recent studies have explored the integration of Digital Twins with sustainability objectives, demonstrating their potential to reduce energy consumption and assess environmental impacts [19], [20]. However, these approaches are primarily applied in industrial contexts, and their practical use in logistics terminals remains limited [20]. To summarize the main contributions, limitations identified in the literature, Table I presents the benefits, limitations, and gaps associated with the different approaches analyzed.

Based on the literature analysis, a clear gap emerges in the development of integrated solutions that combines Digital Twins with operational monitoring and sustainability analysis in near-real-time [8], [10], [15], [19]. In particular, there is a need for architectures that support the continuous integration of operational and environmental data, while also enabling historical analysis and interactive visualization.

TABLE I. Benefits, Limitations, and Gaps of Approaches

Category	**Topics**		
	Benefits	***Limitations***	***Gaps***
Digital Twins in Logistics Contexts	Monitoring, analysis, decision support, risk management	Application limited to complex systems	Lack of integration of environmental indicators
Digital Twins in Ports and Terminals	Optimization, predictive analytics, efficiency improvement	Integration of heterogeneous data, fragmented systems	Lack of continuous integration and a holistic view
Environmental monitoring in terminals	Identification of major emitters, efficiency assessment	Dependence on data quality	Lack of real-time monitoring
Digital Twins integration and sustainability	Reduction of energy consumption, scenario simulation	Application mainly in industry	Lack of application in logistics terminals

III. System Architecture

The architecture proposed for the Digital Twin prototype was designed to integrate, in a modular and scalable way, the components responsible for collecting, processing, storing, and visualizing operational and environmental data from a logistics terminal. The architecture is organized into several functional layers that clearly separate responsibilities and support future system evolution. These layers include: (i) data sources, (ii) processing layer, (iii) Digital Twin platform, (iv) temporal data storage and analysis, and (v) visualization layer.

A. Data Source

At the base of the architecture are the sources of operational data, which provide the information necessary for the system to operate. The data includes records of the activity of reach stackers and forklifts over a month of operation for testing purposes. Each record contains information such as latitude, longitude, container transport status (whether in operation or not), container identifier, associated transport identifier, and its timestamp. These data are processed sequentially, allowing to simulate the behavior of the system over time and approaching a near-real-time data ingestion scenario.

B. Data Ingestion

This layer, implemented in Python, is responsible for reading data from the source and processing and routing it through the system's different workflows. The **Movement Engine** analyzes the evolution of location data to detect relevant events, such as movements, pickups, drops, and container changes. Its operation is based on comparing the previous system state with newly received data. The **Sustainability Engine** computes environmental indicators, such as distance traveled, fuel consumption, and CO_2 emissions, using the processed operational data. The indicators produced are stored in a time-series database (TSDB) along with their timestamps, enabling historical analysis. Simultaneously, these data are forwarded to the Digital Twin platform, where they are aggregated to generate daily sustainbility indicators. Fig. 1 illustrates the flow of information in the system and the organization of the components.

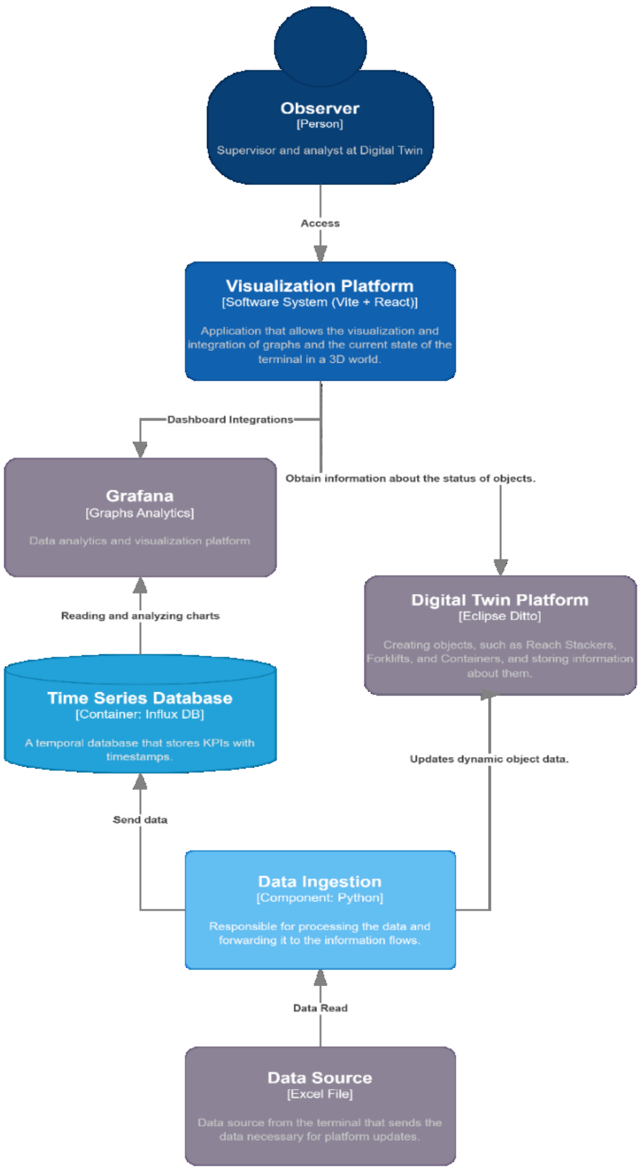

Fig. 1. Flow of information and the organization of the components

C. *Digital Twin Platform*

The Digital Twin platform serves as the system's source of truth, maintaining the current state of the equipment and entities within the terminal. In this work, the Eclipse Ditto platform is used to provide a digital representation of terminal assets and to continuously update their state based on data processed by the backend. Each asset (e.g., a reach stacker, a forklift, or a container) is modeled as a Digital Twin with two categories of attributes. Static attributes, such as the equipment name, identifier (ID), and equipment type, are defined manually and remain unchanged overtime. Dynamic attributes, such as location, operational status, and associated performance and sustainability metrics, are updated continuously. These dynamic attributes are maintained by both the Movement Engine and the Sustainability Engine.

D. *Storage and Visualization of Historical Data*

To support historical analysis and the longitudinal construction of indicators, the processed data are stored in a temporal database. In this work, InfluxDB is used to efficiently storage time series data and to support queries over specific time intervals. To overcome data retention limitations, the database is deployed using a self-hosted configuration. This component is essential for analyzing the evolution of metrics such as distance traveled, fuel consumption, and CO_2 emissions, enabling comparisons across different time periods, equipment types, or individual assets. For data analysis and visualization, Grafana is used to create interactive dashboards. These dashboards support the identification of major emission sources, the most intesively used equipment, and trends in operational and environmental indicators over time.

E. *Visualization Platform*

The visualization layer is responsible for presenting information to the user in a clear, interactive way by combining the terminal's spatial representation with data analysis. The main interface was developed using web technologies, namely React, and integrates interactive maps via Mapbox together with a 3D world populated with dynamic objects. This interface enables users to visualize the terminal layout and its assets and to interact with individual elements in order to access detailed information.

Simultaneously, data analysis is supported by Grafana dashboards, which are embedded in the interface using iframes. These dashboards provide complementary analytical views, including time-series visulizations, cumulative metrics, and performance rankings, thereby enhancing the spatial visualization with quantitative insights.

IV. Data Pipeline and Flow

The system is based on a sequential and incremental data pipeline that transforms raw operational data into structured, up-to-date information consumed by the components of the Digital Twin. This pipeline simulates a realistic data flow, ensuring continuous integration across system layers, from data ingestion to visualization, while mirroring real operational conditions.

A. *Data Reading and Sequencing*

The pipeline starts by reading data from the source. This module loads and preprocesses the data using the pandas library, discarding columns that are irrelevant to the project context, such as operator identifiers and relative positions within the terminal. The dataset is organized chronologically by timestamp to ensure that evets are processed in their correct temporal order. This approach allows simulation of the system's real behavior, in which data is generated continuously over time. Each row in the dataset is treated as an individual event, representing the state of a device at a given instant. The original time intervals between records are maintained, ensuring that the processed events retain the same time spacing as in reality.

B. Incremental Processing

After reading, each record is processed incrementally by the backend. This is carried out line by line, allowing the system status to be updated progressively. During this phase, the data is analyzed by the Movement Engine and the Sustainability Engine. Initially, the current state (as represented by the existing information in Eclipse Ditto) is compared with the new state in the next line of the dataset. Differences between consecutive states trigger the execution of the processing modules. The Movement Engine detects relevant operational events by analyzing changes in location and container-handling status, while the Sustainability Engine calculates derived environmental metrics such as distance traveled, fuel consumption, and CO_2 emissions. This incremental processing enables both near-real-time event detection and the continuous construction of operational and environmental indicators.

C. Digital Twin State Update

After processing, the computed data are used to update the current state of the corresponding entities within the Digital Twin platform. Each new event updates the equipment's dynamic attributes, namely location, operational status, and associated metrics. These metrics are accumulated on a daily basis, reducing the need for runtime aggregation and improving the performance of the visualization layer. This continuous update ensures that the Digital Twin consistently reflects the system's latest operational state, making it the source of truth.

D. Historical Data Storage

In parallel with the Digital Twin update, all processed records are stored in a temporal database, together with their timestamps. This historical storage enables the reconstruction of the indicators' evolution over time, and support subsequent analyses, such as equipment performance evaluation, identification of operational patterns, and comparisons across different time periods.

E. Availability for viewing

The stored historical data and the current Digital Twin state are made available to the visualization layer. The temporal database feeds analytical dashboards using Grafana, that represent time-series, cumulative indicators, and performance rankings. At the same time, the Digital Twin platform provides real-time data to the interactive interface, enabling an up-to-date spatial representation of terminal equipment. This representation is achieved using three-dimensional objects positioned according to the latest state stored in Eclipse Ditto, ensuring a consistent and synchronized view of operations across both analytical and spatial visualization components.

V. SUSTAINABILITY MODEL

The sustainability model adopted in this work draws on approaches from the literature for estimating CO_2 emissions in port and logistics terminals. In particular, models that relate fuel consumption to equipment activity, typically expressed as a function of the number of rides and the average distance traveled, were considered.

In this work, the original approach is adapted to better exploit the granularity of the available data. Instead of using aggregate metrics, such as the number of operations multiplied by the average distance, an incremental approach was chosen, This approach directly calculates the distance between consecutive geographic coordinates recorded for each piece of equipment. As a result, equipment activity can be estimated more accurately and continuously, aligning the emissions model with both the incremental data pipeline and the progressive update logic of the Digital Twin. CO_2 emissions are calculated using a direct relationship between distance traveled and fixed conversion factors for fuel consumption and emissions. The adopted model is defined in Equation (1), where emissions are estimated by multiplying the distance traveled by a fuel consumption factor and a CO_2 emission factor:

$$E = d \times f_d \times f_c \,, \tag{1}$$

where the distance travelled is given by:

$$d = dist(p_a, p_n) \tag{2}$$

In this formulation, E represents the amount of CO_2 emissions (in kg), d corresponds to the distance traveled (in km), f_d represents the fuel consumption factor, assumed as 5 liters per kilometer for *reach stackers*, and f_c corresponds to the CO_2 emission factor per liter of diesel, set to 2.65 kg CO_2/L [16].

The distance is calculated based on the variation between consecutive geographical positions using a geodetic formula as shown in Equation (2), where p_a represents the previous position and p_n the new position of the equipment. This incremental calculation provides a fine-grained estimate of distance traveled over time, which is then accumulated for further analysis.

A. System Integration

The indicators calculated by the sustainability model are integrated directly into the system's data pipeline. During incremental processing, distance travelled, fuel consumption, and CO_2 emissions are continuously updated for each piece of equipment. These indicators are used in two complementary ways. Within the Digital Twin platform, they are aggregated at the daily level to provide up-to-date operational and environmental indicators. In parallel, they are stored in the temporal database with full temporal resolution, supporting historical analysis and dashboard generation.

B. Model Limitations

Despite being functional, this version of the sustainability model presents limitations due to its simplicity. First, it does not account for variations in fuel consumption related to the type of operation or the weight of the transported cargo, which would require integration with container-level data. Second, it assumes constant fuel consumption and emission factors. Third, it does not use direct sensor data or real fuel measurements. Nevertheless, these limitations are acceptable within the scope of this work, as the primary objective is to validate the proposed architecture and its operation, as well as to demonstrate the integration of sustainability analysis within a Digital Twin-based monitoring system.

VI. VISUALIZATION

The main objective of the visualization layer is to present operational and environmental information in a clear, intuitive, and interactive manner by combining a spatial representation of the logistics terminal with data analysis. The developed interface supports two complementary perspectives: (i) real-time visualization of equipment status and (ii) historical analysis of indicators through analytical dashboards.

A. Spatial Visualization

The spatial visualization component is based on a three-dimensional representation of the logistics terminal, using the GLTF format. This representation allows users to observe the position and current status of terminal equipment according to their most recently reported state. This interface was developed using web technologies, namely React, and integrates interactive maps through Mapbox to enhance spatial context.

B. User Interaction and Analytical Visualization

The interface supports direct interaction with the elements displayed in the terminal. Users can select individual pieces of equipment to access detailed information about their operational state and associated indicators. The presented data include both operational and environmental metrics, such as distance traveled, estimated fuel consumption, and CO_2 emissions. See Fig. 2.

Fig. 2. Equipment Selection

To complement the spatial visualization, the system also provides access to historical data through Grafana dashboards, as illustrated in See Fig. 3.

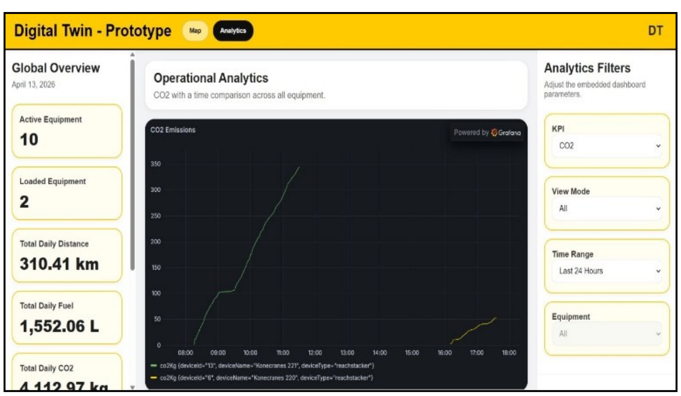

Fig. 3. CO2 Emissions Dashboard Page

VII. Discussion and Outlook

The development of the proposed prototype enable the validation of the architecture through engagement with practitioners, supporting reflection on the role of Digital Twins in logistical contexts. Beyond its technical implementation, it is important to analyze how the solution positions itself relative to existing approaches and to examine its potential for real-world applications. This section discusses the system's main contributions, its ability to cover different dimensions of the problem, and opportunities for future evolution.

A. Scope Coverage

One of the main advantages of the proposed system lies in its ability to integrate multiple analytical *scopes* [21] into a single Digital Twin. Currently, the system focuses on Scope 1 emissions, with planned extencions to cover additional *scopes*, namely Scope 2, which includes indirect emissions from electricity consumption (e.g., equipment operation and terminal lighting), and Scope 3, which emcompasses indirect emissions related to container transport, including rail operations.

In the current implementation, Scope 1 is addressed through the estimation of CO_2 emissions generated by equipment movements within the terminal. Although its modeling is less complex than that of other scopes, it is particularly relevant in this context because it is based on real operational data. This allows the direct environmental impact of terminal activities to be captured and aligns with data-driven, equipment-level approaches reported in the literature [15]. Additionally, the incremental nature of the model highlights how small individual movements, when accumulated over time, can result in significant environmental impacts, reinforcing the importance of continuous operational monitoring [16], [17].

B. Comparison with Existing Works

The proposed solution differs from existing approaches by integrating multiple dimensions into a unified architecture. While existing approaches often focus on isolated aspects, such as simulation [9], decision support [11], or performance analysis [8], the developed prototype continuously combines operational monitoring, temporal analysis, and environmental impact assessment. In addition, many Digital Twin implementations in logistics and port contexts suffer from fragmented data integration and a lack of holistic system visibility [10]. These limitations are addressed through the integration of end-to-end components, spanning data ingestion and processing, storage, and visualization, resulting in a more comprehensive and coherent representation of terminal operations.

C. Operational and Decision Support Applications

The system provides information that can support a range of operational and managerial use cases. First, it can be applied in training contexts, enabling the analysis of equipment usage patterns and the identification of best practices. The combined visualization of movements and performance indicators facilitates a clearer understanding of the operational impact of different decisions. Second, the system supports operational managers by enabling continuous monitoring of terminal activities. Finally, the inclusion of environmental metrics makes the solution relevant for audits and sustainability assessments, responding to the increasing demand for systematic monitoring and reporting of environmental impacts [18].

D. Outlook and Future Work

Future development will focus on extending the system's analytical capabilities and scope. A key direction is integrating forecasting mechanisms to anticipate operational behaviour and estimate future environmental impacts. In addition, the system is planned to expand to include additional equipment types, such as refrigerated containers (reefers), along with indicators related to their energy consumption and CO_2 emissions. This evolution will support broader coverage of emission scopes. Another direction is extending the model to railway operations, enabling analysis of alternative loading and unloading strategies and their operational and environmental implications. This enhancement will contribute to a more comprehensive view of the logistics chain and further support the inclusion of Scope 3 emissions.

VIII. Conclusion

This paper presented the development of a Digital Twin prototype for a logistics terminal, focusing on integrating operational monitoring, sustainability analysis, and interactive visualization into a unified architecture. The system demonstrates the feasibility of combining data ingestion, processing, storage, and visualization into a coherent pipeline, enabling the continuous analysis of operational and environmental indicators, such as distance traveled, fuel, and CO_2 emissions. This work contributes to a broader vision of sustainability-oriented Digital Twins, in line with recent research highlighting their relevance in supply chain contexts [22]. The system addresses a critical segment of the logistics chain where transitions between transport modes, such as road, rail, and maritime, are mediated by handling equipment whose optimization is essential for reducing environmental impacts. By integrating operational and environmental data into a unified Digital Twin, the proposed solution supports a more holistic understanding of system performance, enabling more informed, sustainability-oriented decision-making.

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References

[1] B. Belmoukari, J. F. Audy, and P. Forget, "Smart port: A systematic literature review," *European Transport Research Review*, vol. 15, 2023, doi: 10.1186/s12544-023-00581-6.

[2] R. G. Pereira, R. B. Lopes, A. Martins, B. Macedo, and L. Teixeira, "A simulation tool to forecast the behaviour of a new smart pre-gate at the Sines container terminal," *Sustainability*, vol. 17, no. 1, 2025, doi: 10.3390/su17010153.

[3] C. Y. Lin, G. L. Dai, S. Wang, and X. M. Fu, "The evolution of green port research: A knowledge mapping analysis," *Sustainability*, vol. 14, 2022, doi: 10.3390/su141911857.

[4] M. Kostrzewski and A. Kostrzewski, "Analysis of operations upon entry into intermodal freight terminals," *Applied Sciences*, vol. 9, 2019, doi:

[5] 10.3390/app9122558.F. Tao, B. Xiao, Q. Qi, J. Cheng, and P. Ji, "Digital twin modelling," *Journal of Manufacturing Systems*, vol. 64, pp. 372–389, 2022, doi: 10.1016/J.JMSY.2022.06.015.

[6] E. Negri, L. Fumagalli, and M. Macchi, "A review of the roles of digital twin in CPS-based production systems," *Procedia Manufacturing*, vol. 11, pp. 939–948, 2017, doi: 10.1016/j.promfg.2017.07.198.

[7] D. Ivanov and A. Dolgui, "A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0," *Production Planning and Control*, vol. 32, pp. 775–788, 2021, doi: 10.1080/09537287.2020.1768450.

[8] H. Haße, B. Li, N. Weißenberg, J. Cirullies, and B. Otto, "Digital twin for real-time data processing in logistics," in *Artificial Intelligence and Digital Transformation in Supply Chain Management: Innovative Approaches for Supply Chains*, vol. 27, pp. 4–28, 2019, doi: 10.15480/882.2462.

[9] H. Yao, D. Wang, M. Su, and Y. Qi, "Application of digital twins in port system," *Journal of Physics: Conference Series*, vol. 1846, 2021, doi: 10.1088/1742-6596/1846/1/012008.

[10] J. Neugebauer, L. Heilig, and S. Voß, "Digital twins in the context of seaports and terminal facilities," *Flexible Services and Manufacturing Journal*, vol. 36, pp. 821–917, 2024, doi: 10.1007/s10696-023-09515-9.

[11] W. Hofmann and F. Branding, "Implementation of an IoT- and cloud-based digital twin for real-time decision support in port operations," *IFAC-PapersOnLine*, vol. 52, pp. 2104–2109, 2019, doi: 10.1016/j.ifacol.2019.11.516.

[12] S. Krüger, M. Grafelmann, and C. Jahn, "Digital transformation of inland terminals," in *Advances in Transdisciplinary Engineering*, vol. 34, pp. 93–103, 2023, doi: 10.3233/ATDE230013.

[13] H. Z. Kine, *Assessment of Digital Technology Application in Intermodal Freight Transport: A Low-Income Country Perspective*. Uppsala, Sweden: Swedish University of Agricultural Sciences, 2024.

[14] R. van Duin and B. Wiegmans, "The greening of hinterland corridors: Towards a research agenda," in *Keeping the Focus on Sustainability: A Challenge for Governance*, pp. 110–125, 2022.

[15] J. Martínez-Moya, B. Vazquez-Paja, and J. A. G. Maldonado, "Energy efficiency and CO2 emissions of port container terminal equipment: Evidence from the Port of Valencia," *Energy Policy*, vol. 131, pp. 312–319, 2019, doi: 10.1016/j.enpol.2019.04.044.

[16] M. A. Budiyanto, M. H. Huzaifi, and S. J. Sirait, "Estimating of CO2 emissions in a container port based on modality movement in the terminal area," *International Journal of Technology*, vol. 10, pp. 1618–1625, 2019, doi: 10.14716/ijtech.v10i8.3508.

[17] Y. Zhang, Y. Q. Peng, W. Wang, J. Gu, X. J. Wu, and X. J. Feng, "Air emission inventory of container ports' cargo handling equipment with activity-based bottom-up method," *Advances in Mechanical Engineering*, vol. 9, 2017, doi: 10.1177/1687814017711389.

[18] A. Bernardo, J. Antunes, and J. Barata, "Design principles for sustainable field service management," in *Proc. 2024 26th Int. Conf. on Business Informatics (CBI)*, pp. 247–255, 2024, doi: 10.1109/CBI62504.2024.00036.

[19] Y. Gao, D. Chang, and C. H. Chen, "A digital twin-based approach for optimizing operation energy consumption at automated container terminals," *Journal of Cleaner Production*, vol. 385, 2023, doi: 10.1016/j.jclepro.2022.135782.

[20] L. Li, T. Qu, Y. Liu, R. Y. Zhong, G. Xu, H. Sun, Y. Gao, B. Lei, C. Mao, Y. Pan, F. Wang, and C. Ma, "Sustainability assessment of intelligent manufacturing supported by digital twin," *IEEE Access*, vol. 8, pp. 174988–175008, 2020, doi: 10.1109/ACCESS.2020.3026541.

[21] Greenhouse Gas Protocol, *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*. World Resources Institute and World Business Council for Sustainable Development.

[22] S. S. Kamble, A. Gunasekaran, H. Parekh, V. Mani, A. Belhadi, and R. Sharma, "Digital twin for sustainable manufacturing supply chains: Current trends, future perspectives, and an implementation framework," Technological Forecasting and Social Change, vol. 176, Art. no. 121448, 2022, doi: 10.1016/j.techfore.2021.121448