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The role of the digital twin in solving port-related environmental problems

O papel do digital twin na solução de problemas ambientais relacionados ao porto

El papel del gemelo digital en la resolución de los problemas medioambientales portuarios

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Abstract :

Highlighting the importance of the port industry on the global stage and highlighting the environmental challenges associated with its operations, this article presents the concept of Digital Twin as a crucial tool for promoting port sustainability, enabling detailed monitoring, analysis and simulation in real-time. The implementation of Digital Twin enables improvements in energy efficiency, reduction of carbon emissions and mitigation of environmental impacts, in addition to representing a significant transformation in how port operations are conducted. It also highlights the benefits this technology can offer the port industry regarding environmental sustainability, operational efficiency, and social responsibility. To this end, the methodology applied was an analytical bibliographic review with a qualitative approach and practices observed in the market, which contributes to a better understanding of this study.

Keywords: *Digital Twin; Port Industry ; Environmental Sustainability ; Operational efficiency ; Digital Transformation .*

Resumo:

Destacando a importância da indústria portuária no cenário global e ressaltando os desafios ambientais associados a suas operações, este artigo apresenta o conceito de Digital Twin como uma ferramenta crucial para promover a sustentabilidade portuária, permitindo monitoramento, análise e simulação detalhados em tempo real. A implementação do Digital Twin possibilita melhorias na eficiência energética, redução de emissões de carbono e mitigação de impactos ambientais, além de representar uma transformação significativa na forma como as operações portuárias são conduzidas. Ainda destaca os benefícios em termos de sustentabilidade ambiental, eficiência operacional e responsabilidade social que essa tecnologia pode oferecer à indústria portuária. Para tanto, a metodologia aplicada foi a revisão

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bibliográfica analítica, com abordagem qualitativa e práticas observadas no mercado, as quais contribuem para um melhor entendimento desse estudo.

Palavras-chave: Digital Twin; Indústria Portuária; Sustentabilidade Ambiental; Eficiência Operacional; Transformação Digital

Resumen:

Destacando la importancia de la industria portuaria en el escenario global y destacando los desafíos ambientales asociados con sus operaciones, este artículo presenta el concepto de Gemelo Digital como una herramienta crucial para promover la sostenibilidad portuaria, permitiendo un monitoreo, análisis y simulación detallados en tiempo real. La implementación del Gemelo Digital permite mejoras en la eficiencia energética, reducción de emisiones de carbono y mitigación de impactos ambientales, además de representar una transformación significativa en la forma en que se llevan a cabo las operaciones portuarias. También destaca los beneficios en términos de sostenibilidad ambiental, eficiencia operativa y responsabilidad social que esta tecnología puede ofrecer a la industria portuaria. Para ello, la metodología aplicada fue la revisión analítica de la literatura, con un enfoque cualitativo y prácticas observadas en el mercado, que contribuyen a una mejor comprensión de este estudio.

Palabras clave: *Gemelo Digital; Industria Portuaria; Sostenibilidad Ambiental; Eficiencia Operativa, Transformación Digital.*

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1. INTRODUCTION

The port industry plays a crucial role on the global stage, driving trade and economic development. However, this activity does not come without significant environmental costs. Air pollution is a primary concern, with port operations being a significant source of emissions of pollutants such as nitrogen oxides, sulfur dioxide, particulate matter and volatile organic compounds, negatively impacting local air quality and posing respiratory health risks to surrounding communities. In addition, water pollution is a critical issue, with wastewater discharges, fuel spills and chemicals contaminating adjacent water bodies, harming marine life and compromising water quality, posing risks to human health.

The construction of port infrastructure, such as piers and dikes, can also trigger coastal erosion and alteration of natural habitats, increasing the vulnerability of coastal communities to extreme events. Finally, noise and vibrations resulting from port operations pose another environmental challenge, negatively affecting wildlife, local communities and the health of port workers. Understanding and mitigating these environmental issues is essential to ensuring the sustainability of the port industry and minimizing its adverse impacts on surrounding ecosystems and human health.

Digital technologies play a crucial role in promoting sustainability by offering innovative solutions to address global environmental challenges. The Internet of Things (IoT), big data analytics, artificial intelligence and smart grids enable real-time environmental monitoring, resource optimization, efficient energy and waste management, and sustainable urban planning. These technologies facilitate the transition to renewable energy, promote energy efficiency, reduce carbon emissions and drive more responsible business and industrial practices, and are essential to achieving a sustainable and resilient future.

This article explores the concepts of Digital Twins and their application in port operations. It aims to understand how this technology works in planning environmental issues linked to the Port, such as the emission of polluting gases and resource management.

According to Gil (2002), scientific research aims to organize the facts surrounding a phenomenon to explain it objectively and free from inaccuracies. To this end, one or more methods of logical origin are necessary. The methodology used in this study consisted of a qualitative approach emphasizing purely bibliographical research, a method described by Fonseca (2002) as the process of collecting data and information from technical sources, such as books and academic articles, to obtain prior knowledge about a specific problem.

The data analysis was based on a critical and systematic review of the relevant literature, aiming to achieve an in-depth and contextualized understanding of the phenomena addressed.

Improving energy efficiency and reducing carbon emissions are crucial objectives in the fight against climate change. By monitoring energy performance and identifying areas for optimization, Digital Twin enables precise adjustments to

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reduce energy consumption and minimize emissions associated with industrial operations. Its virtual modeling and simulation capabilities contribute to implementing energy conservation strategies and evaluating alternative scenarios, emerging as a powerful tool in promoting sustainability and energy efficiency, driving innovation and digital transformation in various industries. Its monitoring, analysis and simulation capabilities offer unprecedented opportunities to address global environmental challenges and create a more sustainable and resilient future for the planet.

2. Theoretical Basis

2.1 Industry 4.0 and Digital Twin

Industry 4.0, also known as the fourth industrial revolution, represents a significant transformation in industrial operations. The interconnection of advanced technologies, artificial intelligence and robotics drives it.

This paradigm seeks to integrate autonomous systems through analytical data and operational diagnostics, creating a communication network that connects machines and transmits large volumes of data from different sources. As O'Connell (2019) described, this interconnection forms a digital "copy" of reality.

Digital Twin technology aims to create an accurate digital representation of physical objects, systems and environments based on data collected in real-time and virtual models, replicating and simulating the characteristics of the object, allowing the analysis and processing of activities, revolutionizing the way operations were previously conducted manually, reducing the risk of failures and providing significant benefits for companies (CORREA, 2019).

First introduced in the 2000s by Michael Grieves, a professor at the University of Michigan, and as described by Lv and Xie (2021), the Digital Twin is based on three aspects of data processing used in its operation: acquisition, modeling and application. These are supported by four base technologies: the Internet of Things, Cloud Computing, Artificial Intelligence and Extended Reality (ATTARAN and CELIK, 2023).

The Internet of Things is used as a primary component in any application involving Digital Twin technology. It provides a network of connections between sensors, programs and interfaces (among other components), allowing integration involving everything that makes up the process in which they are found (GILLIS, 2021).

Cloud computing enables storing and processing large amounts of data collected by sensors and other monitoring machinery. Artificial intelligence then processes the information quickly and efficiently without the need for direct intervention by users or moderators on an ongoing basis (RAY, 2018).

Finally, Extended Reality provides a visual presentation of the simulation, according to Steuer (1992), from an interactive experience where each change and consequence can be tested before a final decision.

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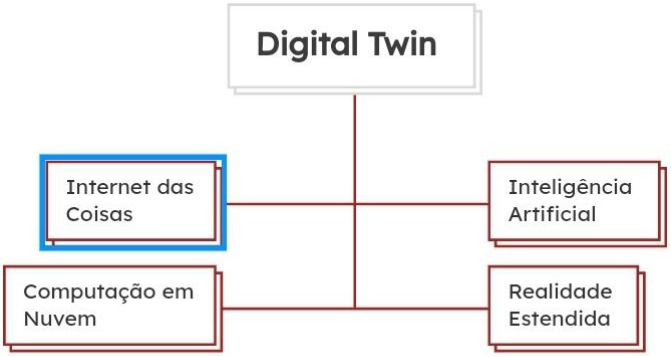
Figure 1 – *Digital Twin Technological Organization Chart*



Source: Produced and Adapted by the author (2024)

This technology's greatest attraction as a tool is simulation. Experimentation in a virtual environment allows for in-depth analysis of any proposed changes to the simulated environment without exposing the location or workforce to potential damage or fatalities.

2.2 General Uses

According to Attaran and Celik (2023), *Digital Twins* are widely used in various sectors, such as manufacturing, construction, transportation, health and energy, to monitor performance, predict failures, perform simulations and optimize processes.

The study conducted by Capgemini (2022) points to a projected increase of 36% in the adoption of *Digital Twins technology* over the next five years. This growth is observed in various sectors, such as automotive, aerospace, life sciences, energy, and utilities. The impetus behind this movement is attributed to companies seeking to advance their digital transformation initiatives, aiming to incorporate intelligence into all stages of the value chain of their operations.

The manufacturing industry uses them to replicate production processes, machines, and finished products digitally. They allow manufacturers to monitor the real-time performance of production lines, identify bottlenecks, optimize resource use, and anticipate potential failures. In addition, *Digital Twins* can be used to simulate different production scenarios, test new product designs, and perform energy efficiency analyses (CAPGEMINI, 2022).

In healthcare, *digital twins* have been used to create virtual models of patients, organs or biological systems. This allows healthcare professionals to monitor health status in real-time, predict trends and develop personalized treatment plans. *Digital twins* are also used to simulate complex surgical procedures, train surgeons and test new therapies or medical devices before their implementation in the real world (CAPGEMINI, 2022).

Digital *twins* play a key role in the energy sector, enabling companies to remotely monitor and control the operation of assets such as wind turbines, solar panels, power grids and power stations. They help with early fault detection, predictive

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maintenance and performance optimization, contributing to operational efficiency and reduced maintenance costs. In addition, *digital twins are* used to simulate energy demand and supply scenarios, supporting strategic planning and decision-making in the energy sector (CAPGEMINI, 2022).

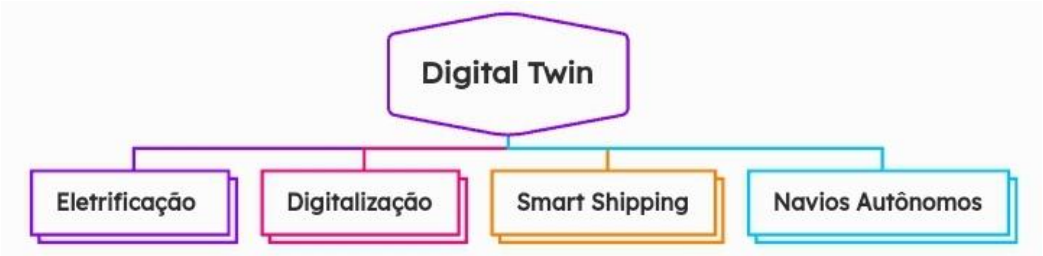
3. METHOD

3.1 The Suitability of Digital Twin in Ports

According to Lind et al. (2020), the digital twin concept is used in the port industry to perform analyses to optimize operations and efficiently monitor the fleet and cargo. The model allows for the accurate simulation and monitoring of port activities, contributing to the continuous improvement of processes and increased operational efficiency.

According to Madusanka et al. (2023), the naval industry has been following a logical process to adapt technology in vessels and ports.

Figure 2. Steps in the vessel adaptation process



Source: Produced and Adapted by the author (2024)

The electrification of most modern vessels focuses on the propulsion system, replacing petroleum-derived fuel (Diesel) with a 100% electric propulsion system to reduce harmful gases emitted into the Earth's atmosphere (Sulligoi et al., 2022).

According to Gasparotti et al. (2023), digitalization is a critical factor in achieving objectives related to competitiveness in the port industry as it is the best solution for optimizing operations. Its main objectives are to increase the effectiveness and efficiency of logistics chains and reduce the environmental impacts of the industry through the transmission of information in real time to all stakeholders and data analysis and processing centers for automation.

Smart shipping basically consists of a digital network interconnected by sensors and data processing centers that use the 5G technology connection architecture (BÁNYAI et al., 2022). Among its applications, according to Ahn et al., there is real-time monitoring of port cargo on sea routes, providing location and readings of the physical conditions of the cargo such as temperature, humidity, oxygen levels or other chemical components inside the container (Sikorski et al., 2017). This technology is not only implemented in containers and cargo; autonomous ships, known as MASS (*Maritime Autonomous Surface Ships*), also use this digital

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infrastructure in conjunction with tools such as GPS (route location and triangulation), radars, sonars and AIS (Automatic Identification System), to provide and collect navigation data for route planning and forecasting departures and arrivals at ports (BLANKE et al., 2020).

The maritime industry's adaptation to using digital tools in its operations focuses on implementing rules related to environmental sustainability and their impacts on port competitiveness concerning competitors, the threat of customer loss if they do not comply with the changes and possible diplomatic incidents in the international market.

3.2 Digital Twin and Environmental Sustainability

The maritime sector, one of the largest emitters of CO2 and GHG (Greenhouse) currently, has one of its main objectives to implement short, medium and long-term solutions to reduce harmful gas emissions since the IMO (International Maritime Organization) has set the target of zero emissions by 2050 (MAVRAKOS et al., 2024).

One such solution is applying Digital Twin technology in ports and ships to avoid waiting times at terminal entrances, thus saving fuel for vessels and energy for terminals, with lower fuel consumption, whether alternative or not, a more dynamic operating routine reduces any emissions resulting from naval activity.

According to Ünal and Albayrak (2023), the Digital Twin is a viable tool for implementing advanced connectivity processes between all those involved in a logistics chain due to its operations optimization feature. This allows resources to be used without being used since orders and manufacturing processes have forecasts based on demand.

This technology's predictive analysis helps prevent potential factors that may lead to abnormalities and waste in any process in which it is implemented. It reduces maintenance costs, stops operations delays, and improves risk management of the procedures analyzed. This results in capital and energy savings and reduced emissions or disposal of non-reusable materials (AGRAWAL, 2023).

According to Garcia Cano (2023), the oil and gas industry has been using Digital Twin in its facilities in recent years to identify points of excessive carbon emissions and optimize processes and operations while collecting and providing details about them in real-time.

The Digital Twin offers the potential for operations carried out in the "Just in time" mode (At the right time – Mode without waiting time, except in the event of unforeseen circumstances). When used in ports, the system detects the arrival and departure of vessels, transmitting the list of times to the port authority to improve operations scheduling at the Port. On ships, once integrated into a network, warnings about delays and possible advances caused by fast operations can help control the use of resources such as fuel, helping to reduce emissions.

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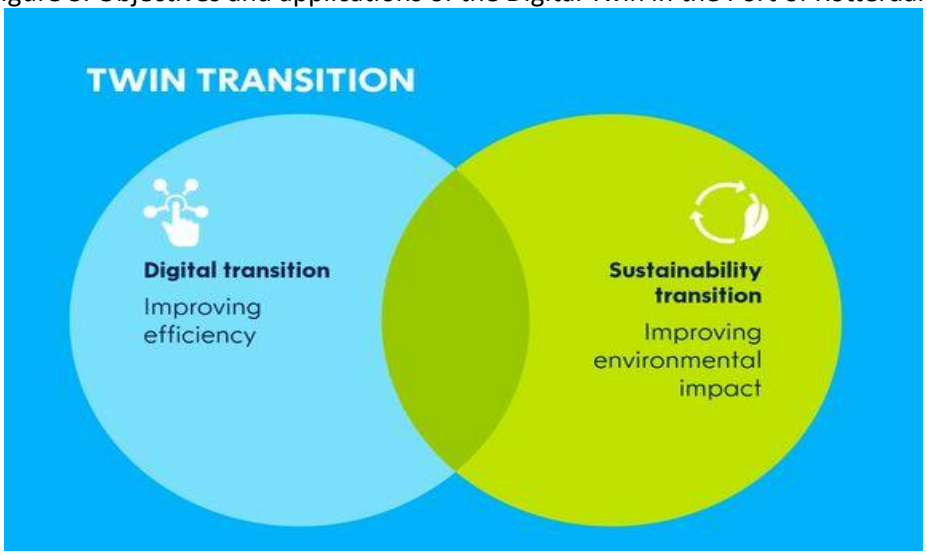
4. Results and Discussion

4.1 Mini Case Study: Rotterdam

The Port of Rotterdam in the Netherlands pioneered using Digital Twins. According to the Port Authority of Rotterdam, the Port invests in digitalization and automation and promotes the transition to alternative fuels to reach the objective established by the IMO (International *Maritime Organization)* of zero carbon emissions within 30 years.

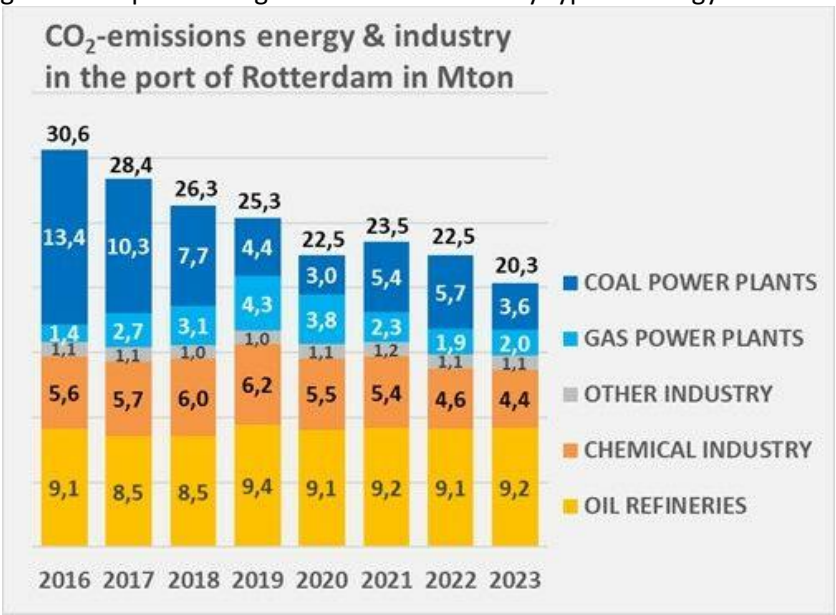
Figure 3. Objectives and applications of the Digital Twin in the Port of Rotterdam



Source: Digital Twin and the sustainable port project, Port of Rotterdam (2023)

In 2023, the Port Authority of Rotterdam reported a 10% decrease in CO^2 emissions compared to the previous year and around 32% decrease compared to 2016.

Figure 4. Graph showing CO^2 emission levels by type of energy installation



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Source: Port of Rotterdam (2023)

Digitization focuses on promoting a fast communication network without physical documentation and monitoring the infrastructure to identify excessive emission points requiring repair and maintenance.

In April 2024, the Port Authority of Rotterdam announced the start of the testing phase of a digital integration between the river ports of the Netherlands operating on the Rhine River and the Port of Rotterdam. This project aims to create a "digital corridor" for the exchange of information between vessels sailing between these ports and their terminals, enabling a real-time data flow in this network, which feeds the digital systems that govern the autonomous points of operations, and can also be used to streamline port calls, reducing vessel stay times and their emissions of harmful gases.

Optimizing the process of entry and exit of vessels (Port *Call Optimization)*, the Port of Rotterdam predicts that the efficiency of the procedure will enable operations to be carried out in the "Just in Time" mode (where the Port is always available for berthing), reducing fuel consumption by up to 14% on container ships. This process will be feasible through data collection and real-time transfer between vessels, terminals and ports for the satisfactory integration of streamlining operations (Port of Rotterdam, 2023).

In Rotterdam, the Digital Twin, still in its early stages, although advanced compared to the rest of the world, has as its main focus being used as a tool for the creation of a single network between ports, where the rapid transmission of data enables a continuous flow of operations carried out without delays, or demurrage, and immediate communication of unforeseen events so that the system self-regulates with the help of the Digital Twin analysis and simulation technology.

5. Conclusion

The port industry promotes trade and economic development as a key player in the global landscape. Nevertheless, this activity does not come without significant environmental costs. Air and water pollution, coastal erosion, habitat disruption and noise are just some of the ecological challenges ports face, negatively impacting the environment and the health of surrounding communities.

Nonetheless, digital technologies are emerging as allies in the search for sustainable solutions to these environmental challenges. By implementing tools like Digital Twin, ports can significantly improve their environmental management and reduce environmental impact. This technology enables real-time monitoring of environmental parameters, simulation of scenarios and identification of opportunities for resource optimization.

This study explored the concepts of Digital Twins and their application in the port industry, highlighting their potential to address complex environmental issues. By analyzing the benefits and challenges associated with implementing Digital Twins

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in ports, it was possible to understand how this technology can contribute to a more sustainable and efficient management of port operations.

Furthermore, the methodology used in this study, based on a qualitative approach and bibliographic research, provided an in-depth and contextualized understanding of the phenomena addressed. The critical analysis of the relevant literature allowed a rigorous evaluation of the theoretical and practical aspects of Digital Twin in the port industry.

Sustainability in ports and terminals is an ethical choice and a strategic necessity. As we face the urgent challenges of climate change, environmental degradation and resource scarcity, it is imperative that we embrace practices that promote economic prosperity, social equity and planetary health. Ports and terminals have a crucial role to play in this collective effort, and it is essential that we work together to build a more sustainable and resilient future for all.

Implementing *digital twins* in ports and maritime terminals offers a range of significant benefits. *Digital twins* enable more efficient and intelligent management of port operations by providing an accurate virtual representation of assets and processes. This has several advantages, such as optimizing cargo flow, avoiding congestion, improving safety and reducing operating costs. Even so, it is important to recognize that implementing *digital twins* in ports and terminals also presents challenges and disadvantages. One of the main challenges is the integration of systems and the collection of data in an often complex and heterogeneous port environment.

In summary, implementing *digital twins* in ports and maritime terminals is a viable and promising strategy to promote sustainability in these vital infrastructures. While it offers many tangible benefits, such as improving operational efficiency and reducing costs, it presents significant challenges, especially regarding systems integration and data collection. Though, given the urgency of environmental issues and the need to promote sustainable practices, it is imperative to overcome these obstacles. Therefore, the adoption of *digital twins* represents an opportunity to optimize operations and a crucial step towards a more resilient and environmentally conscious future for ports and maritime terminals.

In the face of increasingly pressing environmental challenges, implementing Digital Twins is emerging as a promising strategy to promote sustainability and operational efficiency in ports. By harnessing the potential of this innovative technology, ports can move towards a more sustainable and resilient future, benefiting not only the environment but also local communities and the global economy as a whole.

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