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PORT MANAGEMENT DIGITAL TWIN AND CONTROL TOWER INTEGRATION: AN APPROACH TO SUPPORT REAL-TIME DECISION MAKING

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ABSTRACT

Discrete event simulation plays a pivotal role in facilitating decision-making within logistics, necessitating real-time initiation based on the current state of the system. The architecture outlined in this article integrates a real-time Digital Twin with simulation logic and a Control Tower into a cohesive model, thereby reducing offline efforts and runtime. This paper is to presents a groundbreaking project in a Brazilian port. The holistic approach of it offers a comprehensive overview of port operations and enables predictive insights for up to 72 hours in advance. Beyond enhancing operational efficiency, it promotes proactive decision-making and adaptive resource allocation, marking a paradigm shift in port management. The integration of real-time feedback and dynamic optimization algorithms can further enhance the responsiveness and adaptability of the system to changing operational conditions. Future development lies in enhancing the predictive analytics capabilities of the model by leveraging machine learning algorithms and advanced analytics techniques.

1 INTRODUCTION

Global maritime trade continues to expand, posing not only a challenge to terminal capacity but also to the broader infrastructure of port areas (United Nations 2023). Within this framework, port management plays a vital role in facilitating global trade and commerce, serving as central nodes in the logistical networks that underpin the transportation of goods worldwide. In recent years, the maritime industry has undergone a profound transformation driven by rapid technological advancements and evolving market dynamics. Amidst this evolution, the necessity for innovative solutions to enhance port efficiency, optimize resource utilization, and mitigate operational risks has become increasingly apparent.

In response to these challenges, a pioneering initiative was launched to revolutionize port management practices in a Brazilian port. At the core of this initiative lies the integration of digital twin (DT) and control tower (CT) methodologies, representing a significant departure from traditional approaches to port operations. The traditional approach involves management, monitoring and visibility of the operations. The new approach presented in this article combines the traditional approach with prediction and prescription analysis, being able to answer some questions as: a) What is going to happen in the next hours and days? b) What to do in this context? c) Which is the best decision to make?

The DT concept, involving the creation of virtual replicas of physical assets or systems, has gained traction across various industrial operations due to its ability to simulate and analyze real-world scenarios in a risk-free environment. In the context of port operations and management, the DT serves as a powerful tool for visualizing and understanding the complex interdependencies governing port operations, ranging from vessel movements and cargo handling to berth utilization and infrastructure maintenance.

Augmenting the DT is the CT, a centralized command center providing real-time visibility and oversight of various processes, resources, and activities within a complex system, such as supply chain or logistics operations. It integrates data from multiple sources to monitor, analyze, and manage operations efficiently, enabling proactive decision-making and rapid response to disruptions. CTs aim to optimize performance, enhance collaboration, and improve overall agility and responsiveness in dynamic environments.

Effective decision-making in logistics planning and control necessitates decision-makers to (a) identify existing plan deficiencies, (b) devise coherent decision scenarios, and (c) assess these scenarios for efficiency. To meet these requirements, a robust decision support system should possess the following features (Korth et al. 2018):

1. Comprehensive understanding of the current system state, encompassing orders, resources, entities, and processes.
2. Insight into the anticipated future system state, including forthcoming orders, processes, and the availability of resources and entities.
3. Capabilities for identifying both current and impending disruptions.
4. Tools for generating feasible decision scenarios.
5. Mechanisms for evaluating the viability of these decision scenarios.

Decision services include dimensioning, layout design, process planning, and the selection of resources and technologies. Decision support, on the other hand, involves predicting disruptions using online simulation and implementing measures such as real-time resource reallocation and order shifting.

Decision support in logistics represents a significant use case for DTs. While concepts for real-time decision support system architectures already exist, certain aspects, particularly those concerning simulation-based decision support in logistics, are not sufficiently examined and validated (Korth et al. 2018).

Given the increasing complexity and demands of port operations, a DT combined with CT project offers a holistic view of operations and management to facilitate decision-making. By embracing a data-driven approach, the project aimed to optimize resource allocation, minimize turnaround times, and enhance overall port efficiency. Moreover, it fosters greater transparency and collaboration across the entire maritime supply chain, paving the way for improved communication and coordination among stakeholders.

Throughout the remainder of this paper, we will explore the academic literature (Section 2) to present some conceptual definitions. In Section 3, we present a case study illustrating the integration of a DT and CT in a Brazilian port. Through a detailed examination of the project's architecture, features, and capabilities, our aim is to elucidate the transformative potential of this innovative approach to port management. Finally, we conclude with a summary and future outlook (Section 4).

2 STATE OF RESEARCH

Industry 4.0, often dubbed the 4th industrial revolution, harnesses advanced computational technologies to augment the intelligence of various industries. This paradigm shift involves interconnecting sensors, machines, devices, and information technologies across the value chain. By gathering and analyzing data from equipment, Industry 4.0 facilitates quicker, more flexible, and efficient processes, ultimately yielding high-quality products at reduced costs (Rüßmann et al. 2015). Moreover, it enables more effective decision-making strategies. According to Lingdong et al. (2016), nine technologies are revolutionizing industrial production: simulation, augmented reality, autonomous robots, the Industrial Internet of Things (IIoT), cloud computing, cybersecurity, additive manufacturing, horizontal and vertical system integration, and Big Data and analytics.

One of the most important technologies that will contribute to smart manufacturing and operations is the IIoT (Thames et al. 2016). It is based on integration of many standards and technologies, with different sensing, connectivity, communication, storage, computational characteristics and capabilities. This diversity produces challenges in providing connectivity between all the technologies (Čolaković and Hadžialić 2016).

On the other hand, the proliferation of IoT devices and the data they generate facilitates the development of advanced simulation models, enabling real-time and efficient decision-making in manufacturing and operational processes. Simulation, a cornerstone technology in Industry 4.0, allows for the testing and optimization of machine settings within a virtual production environment prior to physical implementation. This approach reduces machine setup times and enhances the quality of products and services (Rüßmann et al. 2015). Consequently, integrating IoT data with simulation offers a promising strategy for industry, enabling swift decision-making, direct access to production resources, and automatic data incorporation into simulation models. Nevertheless, integrating simulation tools with IoT platforms presents challenges. For instance, issues such as acquiring real-time IoT data and converting it for input into simulation models remain unresolved in the literature (Tan et al. 2019).

2.1 Cyber-Physical System

An important element of Industry 4.0 is the integration of the physical and virtual realms (Hermann 2015), made feasible by Cyber-Physical Systems (CPSs). The term "cyber" denotes computation, communication, and control characterized by discrete, switched, and logical operations, while "physical" refers to systems governed by the laws of physics and operating in continuous time (Nadeem 2013). CPSs represent transformative technologies that coordinate interconnected systems by amalgamating computational capabilities with physical assets (Lee et al. 2015). These systems are designed as collaborative IT systems to govern physical objects such as mechanical and electronic devices, communicating through data infrastructure like the Internet. Traditional embedded systems can be viewed as a specific instance of stand-alone CPSs (Schoenthaler et al. 2015).

A CPS typically consists of two primary functional components: (a) advanced connectivity ensuring real-time data acquisition from the physical world and feedback from cyberspace; (b) intelligent data management, computational, and analytics capabilities constructing cyberspace (Lee et al. 2015). Technologies closely associated with CPSs include the Internet of Things (IoT), wireless sensor networks, and cloud computing, with wireless sensor networks recognized as a critical component of CPSs (Kos et al. 2015).

2.2 Simulation

Simulation models have emerged as a prominent technique for analyzing complex industrial systems, particularly at the operational level, offering significant potential for applications. Discrete event simulation has evolved as a popular and cost-effective method for analyzing such systems. This technique involves modeling a system whose state changes at discrete time intervals. Simulation of the material flow is an inherent part of the Digital Twin, allowing prediction of the future of the system (Korth et al. 2018).

Before employing simulation techniques in logistics and manufacturing systems, it is crucial to acknowledge the challenges inherent in providing solutions to real-world problems. Simulation tasks are multifaceted and demanding, often requiring specialized tools to assist novice simulators (O'Kane et al. 2000). Simulation-based techniques play a dual role in both developing and evaluating complex systems, considering factors like physical configuration and operational rules (Sakurada et al. 2009).

Simulation is particularly valuable for analyzing and evaluating contemporary manufacturing and transportation environments due to their complexity and stochastic nature (Lin et al. 2011). It offers an environment to evaluate supply chain network designs and control policies, considering factors such as cost, service, and lead-time (Pirard et al. 2011). These models serve as analytical tools to predict the effects of changes in existing systems and as design tools for new systems under varying conditions (Banks et al. 2001). Figure 1 illustrates the steps of simulation analysis.

Hybrid models, integrating analytical and simulation techniques, provide a comprehensive approach to system evaluation. Multiple replications of simulation models can assess system robustness, offering insights into decision-making consequences (Pirard et al. 2011). In simulations, models represent key characteristics or functions of selected systems, addressing questions regarding system behavior under specific design and operational policies (Banks et al. 2001).

2.3 Digital Twin

The concept of the Digital Twin (DT) originated in 2002 at the University of Michigan (Grieves 2016). Recently, there has been a shift towards incorporating the concept of the DT into data-intensive production systems, particularly cyber-physical production systems, by moving away from the strict product-centric approach (Uhlemann 2017; Zhuang et al. 2018). Consequently, these systems now exhibit typical characteristics of Big Data due to the abundance of real-time data, including large volume, diverse variety, and rapid velocity of data generation (Chen et al. 2014; Zhuang et al. 2018). More recent definition approaches and descriptions also refer to systems and the information associated with them in various life-cycle phases. DT is now described by Borchert and Rosen (2016) as “a comprehensive physical functional description of a component, product or system that contains more or less all the information that could be useful in all current and subsequent life cycle phases”.

DTs can therefore be characterized in the following way (Borchert and Rosen 2016): a) A DT is a linked collection of different types of data, such as operational data, as well as various models; b) A DT evolves alongside the real system throughout its life cycle and c) a DT has the capability to derive solutions that are relevant for the real systems, such as optimizing operations and services.

A significant challenge in implementing a phase-overlapping DT stems from the disparate nature of information generation across various life cycle phases. This complexity arises because different tools produce information in diverse formats, leading to a lack of seamless information flow between the phases (Malakuti and Grner 2018). The DTs aggregate all information from different tools, arranges them phase-specifically and converts them to share them with other phases.

The general technical architecture is shown in Figure 2. Changes in input data are transmitted to an IoT platform, where they are stored in a database. The IoT platform offers streamlined device management, harmonization, and action coordination. It triggers the simulation, utilizing work in progress (WIP) data from the database to establish the current system status. Various dispatching algorithms are then assessed. The outcomes are presented in a web application. The operator oversees the system and the dashboard to make strategic modifications and decisions. Subsequently, the dispatching algorithm autonomously releases the waiting vehicle in the buffer area.

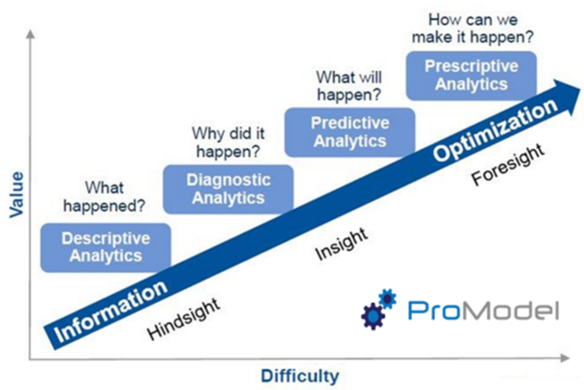

Figure 1: Steps of simulation analysis.

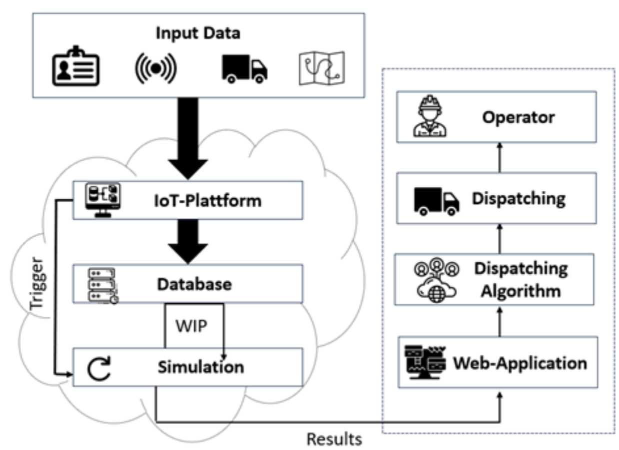

Figure 2: Technical Architecture of a Digital Twin.

The IoT platform processes events from connected devices and initiates simulation runs by triggering a predefined workflow through a web application programming interface (API). This workflow queries the database for simulation input data and activates the simulation service. Deployed as a server-less function, the simulation service receives input parameters, executes the simulation, and stores the results in a database, which powers a web dashboard for operator insights. Automatic scaling enables concurrent simulation runs to capture stochastic behavior and explore different system configurations. Integration testing utilized a simulation model acting as an emulator, connected to the IoT platform, mimicking the physical system. For further details on this approach, see Gutenschwager et al. (2000) and Hofmann et al. (2018). A DT is described to act as a controlling instance and allows forecasting and deciding between a set of actions in order to orchestrate the production system in an optimal manner, resulting in higher efficiency accuracy and economic benefits.

3 USE CASE: PORT OPERATION

The terminal in which the project was implemented is an important port in Brazil that currently operates with an expressive volume of materials. It's growth projection between 2022 and 2026 is around 0,5 millions of tons (ANTAQ 2022). Due to the relevance of this port operation's volume in Brazil's trade and commerce, the integration of the technologies such as DT and CT were chosen to improve its efficiency.

Figure 3 illustrates in a simple way the main operations at the project's terminal. The following subsections present a detailed description of the major aspects of the project.

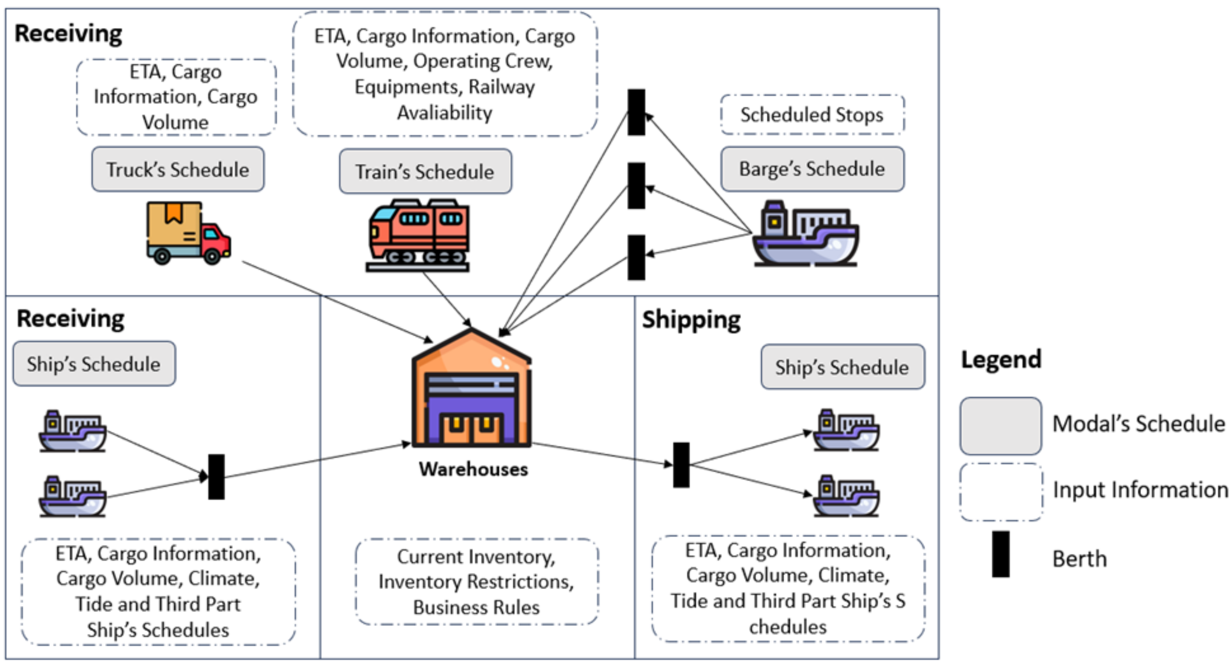

Figure 3: Scheme of data sources and material flow in a terminal.

3.1 Integration of Data Sources

The cornerstone of the DT and CT in this project is the seamless integration of data from diverse sources spanning multiple facets of port operations. Recognizing the inherently complex and interconnected nature of port logistics, the project's success hinges on the ability to aggregate, harmonize, and analyze data from different sources in real-time.

At the core of the data integration process are Enterprise Resource Planning (ERP) systems, which act as repositories for crucial operational data such as cargo manifests, inventory levels, and financial transactions. Through interfaces with these systems, the project can access real-time information on cargo movements, vessel schedules, and port activities, thereby offering stakeholders a comprehensive view of the port's operational landscape.

In addition to enterprise resource planning (ERP) systems, the project leverages data from external sources such as climate monitoring stations, trucking companies, railway operators and shipping agencies to augment its operational insights. Climate data, including meteorological forecasts and tide predictions, enables the project to anticipate weather-related disruptions and optimize berth allocations accordingly. Data from trucking companies and railway operators provides visibility into the movement of material within the port hinterland, facilitating efficient resource allocation and congestion management.

One particular importance is the integration of data from shipping agencies, which provides real-time updates on vessel arrivals, departures, and movements within the port. By interfacing with shipping agency systems, the project is able to track vessel trajectories, monitor berth occupancy, and predict vessel turnaround times with a high degree of accuracy.

To ensure the seamless flow of information across all systems involved, the project employs a combination of standardized data formats, application programming interfaces (APIs), and data integration middleware. By establishing robust data pipelines and governance frameworks, the project ensures the integrity, security, and reliability of the data flowing through the system. Figure 4 below illustrates how the architecture of the DT was designed for the project.

In summary, the integration of data from ERP systems, climate monitoring stations, trucking companies, railway operators, and shipping agencies forms the backbone of the DT and CT project in the Brazilian port. By harnessing the power of data-driven insights, the project aimed to optimize port operations, enhance decision-making processes, and drive sustainable growth in the maritime industry.

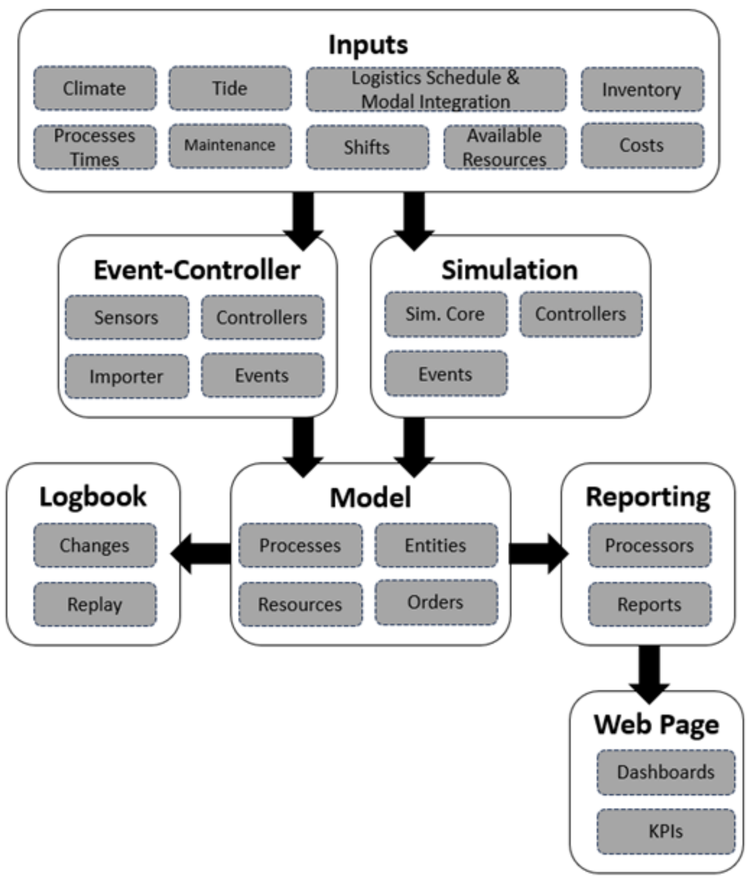

Figure 4: Architecture of the digital twin.

3.2 Features and Capabilities

The project provides stakeholders with a real-time "snapshot" of current port operations, including vessel movements, cargo handling activities, berth utilization, and infrastructure status. Through intuitive dashboards and visualizations, stakeholders can monitor key performance indicators (KPIs) and identify potential bottlenecks or disruptions in real-time.

Leveraging advanced analytics and predictive modeling techniques, the project generates forecasts for the next 72 hours, encompassing vessel arrivals, departures, berth allocations, and tide interactions. By analyzing historical data, weather forecasts, and operational patterns, the project enables stakeholders to anticipate and proactively mitigate potential disruptions, thereby minimizing downtime and optimizing resource allocation.

The project dynamically allocates berths based on real-time operational constraints, vessel schedules, and weather conditions. By optimizing berth assignments and turnaround times, the project enhances port efficiency and reduces congestion, ultimately improving vessel throughput and customer satisfaction.

Recognizing the critical role of environmental factors in port operations, the project integrates tide predictions and weather forecasts into its decision-making processes. By accounting for tidal variations and weather-related disruptions, stakeholders can optimize vessel scheduling, mitigate navigational risks, and ensure safe and efficient port operations.

Through sophisticated algorithms and optimization techniques, the project facilitates efficient resource allocation and congestion management within the port. By dynamically adjusting resource allocation in response to changing operational conditions, stakeholders can minimize wait times, reduce idle capacity, and improve overall port throughput.

The CT serves as a centralized hub for collaborative decision-making, enabling stakeholders from across the maritime supply chain to access real-time data, share insights, and coordinate activities. By fostering greater transparency and communication, the project facilitates alignment of interests and enables stakeholders to collectively address operational challenges and opportunities.

This project offered a comprehensive suite of features and capabilities aimed at optimizing the port's operations, enhancing decision-making processes, and driving sustainable growth in the maritime industry. By harnessing the power of real-time data integration and predictive analytics, the project represents a significant leap forward in port management practices, setting new standards for efficiency, resilience, and agility.

3.3 Simulation Model

The model was developed using ProModel® simulation software. Upon execution, it imports approximately one hundred tables from a database to run the scenario, which simulates a one-month period. These tables provide essential data, including statistical distributions for the durations involved in the handling of cargo – as the time needed to pick up, transport, and release cargo between various locations (e.g., from truck to storage, from storage to ship). Additionally, the tables contain information on ships scheduled in the coming days, as well as details regarding incoming and outgoing cargo, climate information and several other parameters.

With all the relevant parameters imported, the simulation is ready to be run – the data will be used in a entity-based model, with more than 150 subroutines that translate the details and rules of the real operation to a digital twin, generating time-series and aggregated data as results.

After the execution of the simulation model, several KPIs are generated to allow the user to evaluate the scenario – ranging from productivity (ton/h), all the future cargo movements (starting time, ending time, resources utilized, costs), storage decisions (where each incoming cargo with be stored), relevant events (such as berthing, unberthing, stops, hold changes, equipment refueling, cargo securing), labor requirements, berth recommended for each ship, future bottlenecks and conflicts (such as different operations working nearby) and other necessary data to feed the digital twin dashboard.

3.4 Methodology

The project followed a methodology that has been tested and proven effective through previous implementations, encompassing the stages of specification, development and assisted operation, totalizing 18 months.

3.4.1 Specification

The initial phase centered on a comprehensive understanding of the port's operations and the design of the requisite data framework for the project. This process was guided by the principle of reverse engineering, ensuring that the ultimate outputs and objectives dictated the formulation of the simulation model, thereby influencing the selection of inputs and data sources. Commencing with a series of interviews with key stakeholders, the culmination of the specification phase resulted in a blueprint encompassing every aspect, including business rules, data sources, data structures, frequency of data collection, environment, security measures and web interfaces.

3.4.2 Development

During the development phase, the project focused on translating the blueprint requirements into tangible solution components. This employed an agile methodology for scalable software development. Continuous integration practices and testing procedures were implemented to validate system functionality, reliability, and performance. Regular sessions with key users were conducted to refine components and verify outputs in alignment with the reality of the operation. Additionally, documentation was developed to cover system design, functionalities, and operational procedures, facilitating stakeholder and end-user understanding. This disciplined approach ensured the successful realization of project objectives and prepared for the assisted operation phase.

3.4.3 Assisted Operation

In this phase, the project transitioned to real-world application. It involved deploying the system, providing continuous monitoring and support, conducting comprehensive training, gathering feedback for improvement, and performing ongoing maintenance and updates.

3.5 Benefits and Impacts

The implementation of the DT and CT together has yielded a multitude of benefits and catalyzed transformative changes in port management practices. By harnessing the power of advanced technologies and real-time data integration, the project has generated significant value for port stakeholders and the broader maritime ecosystem.

The project has led to substantial improvements in operational efficiency, enabling stakeholders to streamline port operations, optimize resource utilization, and reduce turnaround times. By providing real-time insights into vessel movements, cargo handling activities, and berth utilization, the project has facilitated smoother and more streamlined port operations, ultimately enhancing productivity and reducing operational costs.

The availability of real-time data and predictive forecasts has empowered stakeholders with actionable insights, enabling them to make informed decisions and proactively address operational challenges. By leveraging advanced analytics and predictive modeling techniques, stakeholders can anticipate potential disruptions, optimize resource allocation, and mitigate risks, thereby enhancing decision-making processes and driving more effective outcomes.

The project's dynamic berth allocation capabilities and congestion management algorithms have enabled stakeholders to optimize resource allocation within the port. By dynamically adjusting berth assignments, vessel schedules, and resource utilization in response to changing operational conditions, stakeholders can minimize wait times, reduce idle capacity, and improve overall port throughput, thereby maximizing operational efficiency and resource utilization.

The integration of tide predictions, weather forecasts, and environmental data into the project's decision-making processes has enhanced safety and resilience within the port. By accounting for environmental factors and navigational risks, stakeholders can mitigate the impact of adverse weather conditions, optimize vessel routing, and ensure safe and efficient port operations, thereby enhancing the resilience of the port infrastructure and reducing the risk of accidents or disruptions.

The CT serves as a centralized hub for collaborative decision-making, enabling stakeholders from across the maritime supply chain to access real-time data, share insights, and coordinate activities. By fostering greater transparency, communication, and collaboration among port stakeholders, the project has facilitated alignment of interests, improved coordination, and enabled stakeholders to collectively address operational challenges and opportunities.

This project has delivered a wide range of benefits, ranging from enhanced operational efficiency and improved decision-making to optimized resource allocation and enhanced safety and resilience. By harnessing the power of advanced technologies and real-time data integration, the project has set new standards for port management practices, driving sustainable growth and resilience in the maritime industry.

3.6 Challenges and Lessons Learned

One of the primary challenges encountered during the implementation of the project was the complexity of integrating data from diverse sources. ERP systems, climate monitoring stations, trucking companies, railway operators, and shipping agencies each have their own data formats, protocols, and standards, making data integration a complex and time-consuming process. Lessons learned from this challenge include the importance of establishing clear data governance frameworks, standardized data formats, and robust data integration pipelines to streamline the integration process and ensure the integrity and reliability of the data.

Another challenge faced was ensuring the accuracy and reliability of predictive models. Predicting vessel arrivals, departures, berth allocations, and tide interactions requires sophisticated algorithms and accurate data inputs, but uncertainties and variability in operational conditions can pose challenges to the accuracy of predictive models. Lessons learned from this challenge include the importance of continuously refining and validating predictive models based on real-world data, incorporating feedback from domain experts, and accounting for uncertainty and variability in model inputs.

A key challenge encountered was managing change and engaging stakeholders effectively. The introduction of new technologies and processes can disrupt existing workflows and practices, leading to resistance and skepticism among stakeholders. Lessons learned from this challenge include the importance of proactive communication, stakeholder engagement, and change management strategies to build buy-in, foster collaboration, and ensure the successful adoption of new technologies and processes.

Technical infrastructure and scalability emerged as significant challenges during the implementation of the project. The volume, velocity, and variety of data generated in port operations pose scalability challenges for data storage, processing, and analysis. Lessons learned from this challenge include the importance of designing scalable and resilient technical architectures, leveraging cloud-based technologies, and adopting modular and flexible solutions to accommodate evolving business needs and scale up as the project expands.

Regulatory and compliance considerations posed additional challenges. Privacy regulations, data security requirements, and industry standards impose constraints on data collection, storage, and sharing practices, requiring careful attention to ensure compliance. Lessons learned from this challenge include the importance of conducting thorough risk assessments, implementing robust security measures, and maintaining compliance with regulatory requirements to safeguard sensitive data and protect the interests of stakeholders.

In summary, the challenges encountered during the implementation of the DT and CT project in the Brazilian port have provided valuable lessons and insights that can inform future projects and initiatives in port management. By addressing these challenges proactively and incorporating lessons learned into project planning and execution, stakeholders can mitigate risks, improve outcomes, and drive greater success in port management endeavors.

4 CONCLUSION AND OUTLOOK

The DT and CT combination project in a Brazilian port presented in this article has laid a strong foundation for future advancements in port management practices. Building upon the successes and lessons learned from the initial implementation, there are several promising avenues for further development and innovation in the realm of port operations.

One area of future development lies in enhancing the predictive analytics capabilities of this kind of project. By leveraging machine learning algorithms and advanced analytics techniques, stakeholders can improve the accuracy and reliability of predictive models, enabling more precise forecasting of vessel arrivals, departures, berth allocations, and tide interactions. Additionally, integrating real-time feedback loops and dynamic optimization algorithms can further enhance the responsiveness and adaptability of the system to changing operational conditions.

The rapid evolution of technology presents opportunities for integrating emerging technologies into the DT and CT framework. For example, leveraging Internet of Things (IoT) sensors, drones, and autonomous vehicles can provide real-time visibility into port operations, enabling more granular monitoring and control. Similarly, exploring the potential of blockchain technology for secure and transparent data sharing among port stakeholders can enhance trust, collaboration, and efficiency in the maritime supply chain.

Another future direction is the digitalization of port infrastructure to enable more seamless and automated operations. By integrating digital sensors, smart devices, and automation technologies into port equipment and infrastructure, stakeholders can optimize asset utilization, reduce maintenance costs, and improve safety and reliability. Additionally, exploring the potential of DTs for simulating and optimizing port layout and design can inform infrastructure investments and future expansion projects.

Collaboration and ecosystem integration are critical for realizing the full potential of the DT and CT framework. Future developments should focus on enhancing interoperability and data sharing among port stakeholders, as well as integrating with broader supply chain ecosystems. By fostering greater collaboration and visibility across the entire maritime supply chain, stakeholders can optimize end-to-end logistics, improve resilience, and drive greater value for all participants.

With increasing concerns over environmental sustainability and climate change, future developments in port management should prioritize sustainability and environmental management. Integrating environmental monitoring and reporting capabilities into the DT and CT framework can enable stakeholders to track and mitigate the environmental impact of port operations, such as emissions, noise pollution, and habitat disruption. Additionally, exploring the potential of renewable energy sources and green technologies for powering port operations can contribute to reducing carbon footprint and promoting environmental stewardship.

The future directions for the DT and CT project in ports and terminals are diverse and promising. By embracing emerging technologies, enhancing collaboration, and prioritizing sustainability, stakeholders can continue to drive innovation and transformation in port management practices, ensuring the long-term success and resilience of port operations in an increasingly complex and dynamic global landscape.

REFERENCES

Agência Nacional de Transportes Aquaviários (ANTAQ). 2022. “Plano de Negócio Referencial”. https://www.gov.br/antaq/pt-br, accessed 15th May.

Banks, J., Carson, J.S., Nelson, B.L. and Nicol, D.M. 2001. *Discrete-Event System Simulation*. 3rd ed. Upper Saddle River: Prentice Hall, Inc.

Boschert, S. and Rosen, R. 2016. “Digital twin—the simulation aspect”. *Mechatronic futures*: *Challenges and solutions for mechatronic systems and their designers* 59-74.

Chen, M., Shiwen, M. and Yunhao, L. 2014. “Big data: A survey”. *Mobile networks and applications* 19: 171-209.

Čolaković, A. and Hadžialić, M. 2018. “Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues”. *Computer Networks* 144:17-39.

Grieves, M. and Vickers, J. 2016. *Origins of the digital twin concept.* Vol. 8. Florida Institute of Technology.

Gutenschwager, K., Fauth, K. A., Spieckermann, S. and Voß, S. 2000. “Qualitätssicherung lagerlogistischer Steuerungssoftware durch Simulation”. *Informatik Spektrum* 23(1): 26-37.

Hermann, M., Pentek, T. and Otto, B. 2015. *“Design Principles for Industrie 4.0 Scenarios”.* In *49th Hawaii international conference on system sciences (HICSS)*, IEEE, 5-8 January, 2016, Hawaii, USA.

Kos, A., Tomažič, S., Salom, J. Trifunovic, N., Valero, M. and, Milutinovic, V. 2015. “New benchmarking methodology and programming model for big data processing.” *International Journal of Distributed Sensor Networks* 11(8): 271752.

Korth, B., Christian S. and Zajac, M. 2018. "Simulation-ready digital twin for realtime management of logistics systems". *IEEE International Conference On Big Data (Big Data)*, 10-13 December, Seattle,WA, USA .

Lidong, W. and Guanghui, W. 2016. "Big Data in Cyber-Physical Systems, Digital Manufacturing and Industry 4.0." *International Journal of Engineering and Manufacturing (IJEM)* 6(4):1-8.

Lee, J., Bagheri, B. and Kao, H. A. 2015. "A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems". *Manufacturing Letters* (3):18–23.

Lin, S. W., Vincent, F. Y. and Lu, C. C. 2011. "A simulated annealing heuristic for the truck and trailer routing problem with time windows". *Expert Systems with Applications* 38(12):15244–15252.

Malakuti, S., and Sten, G. 2018. "Architectural aspects of digital twins in IIoT systems." Proceedings of the 12th European Conference on Software Architecture: companion proceedings, 24-28 September, 2018, Madrid, Spain.

Nadeem, T. 2013. "Cyber Physical Systems Seminar", Dept. of Computer Science, Old Dominion University, USA, Spring.

O'Kane, J. F., Spenceley, J. R. and Taylor, R. 2000. "Simulation as an essential tool for advanced manufacturing technology problems". *Journal of Materials Processing Technology* 107(1):412–424.

Pirard, F., Iassinovski, S. and Riane, F. 2011. "A simulation based approach for supply network control". *International Journal of Production Research* 49(24):7205–7226.

Rosen, R. Von Wichert, G. Lo, G. Bettenhausen, K. D. 2015. "About The Importance of Autonomy and Digital Twins for the Future of Manufacturing". *IFAC – PapersOnLine* 48(3):567–572.

Rüßmann, M., Lorenz, M. Gerbert, P. Waldner, M. Justus, J. Engel, P *et al*. 2015. Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. *Boston Consulting Group* 9(1):54-89.

Michael Rüßmann, Markus Lorenz, Philipp Gerbert, Manuela Waldner, Jan Justus, Pascal Engel,

Sakurada, N., and Miyake, D.I. 2009. "Aplicação de simuladores de eventos discretos no processo de modelagem de sistemas de operações de serviços." *Gestão e Produção* 16:25-43.

Schoenthaler, F., Augenstein, D. and Karle, T. 2015. "Design and governance of collaborative business processes in industry 4.0". In *Proceedings of the Workshop on Cross-organizational and Cross-company BPM (XOC-BPM) co-located with the 17th IEEE Conference on Business Informatics (CBI 2015),* July 13th, 2015, Lisbon, Portugal.

Tan, Y., Yang, W., Yoshida, K. and Takakuwa, S. 2019. "Application of IoT-Aided Simulation to Manufacturing Systems in Cyber-Physical System". *Machines* 7(1):2.

Thames, L. and Schaefer, D. 2016. "Software-defined Cloud Manufacturing for Industry 4.0". *Procedia CIRP* 52:12–17.

United Nations. 2023. "Review of Maritime Transport". https://unctad.org/system/files/official-document/rmt2023_en.pdf, accessed 15th May.

Zhuang, C., Jianhua L. and Hui, X. 2018. "Digital twin-based smart production management and control framework for the complex product assembly shop-floor". *The International Journal Of Advanced Manufacturing Technology* (96):1149-1163.

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