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A Reference Architecture for Dry Port Digital Twins: Preliminary Assessment Using ArchiMate

Joana Antunes[1[0009-0004-3025-7947]], João Barata[1[0000-0002-7456-594X]], Paulo Rupino da Cunha[1[0000-0003-2701-5248]], Jacinto Estima[1[0000-0001-8837-4637]], José Tavares[2]

[1] University of Coimbra, CISUC, DEI, Coimbra, Portugal
[2] Fordesi, Lisboa, Portugal
{joanantunes@student.dei.uc.pt, barata@dei.uc.pt, rupino@dei.uc.pt, estima@dei.uc.pt, jose.tavares@fordesi.pt}

Abstract. Dry Ports are critical infrastructures in the logistics chain, optimizing seaport operations by providing customs services and container storage on land. Some of their main challenges include traffic congestion, environmental impacts, high dependence on regulations and paper documentation, and the need to provide reliable information to government authorities and road and rail freight industries. More recently, Digital Twins emerged as a promising solution to monitor real-time information and optimize Dry Port operations simultaneously. This paper presents the initial proposal of a reference architecture for developing Dry Port's Digital Twins. It results from a design science research project conducted in cooperation with a major IT company in the logistics sector and a Dry Port operator in Portugal. ArchiMate was the selected language for architecture modeling. Our theoretical contribution is in the form of a high-level reference architecture confirming the suitability of the ArchiMate language. For practitioners, this work is part of the Portuguese NEXUS agenda: Innovation Pact for Green and Digital Transition for Transport, Logistics, and Mobility, assisting in adopting Blockchain, Optical Recognition, and Artificial Intelligence as crucial technological enablers.

Keywords: Dry Port, Digital Twin, Enterprise Architecture, Archimate.

1 Introduction

Seaports are pillars of global supply chains. However, many locations that produce and consume goods lack access to advantageous coastal areas or have limited storage capacity [1] and customs authority services. These problems ultimately led to the creation of Dry Ports. The logistic links between Seaports and Dry Ports enable import and export supply chains at regional, country, and cross-board levels and are usually supported by railway transport, which is far more efficient and greener than trucks.

These logistics infrastructures extend port operations inshore, also called the port's hinterland, by providing customs authority services, managing larger container flows, and expanding storage capacity. The digital transformation of Dry Ports is a priority due to some of their challenges [2]: high dependence on regulations and paper documents, traffic congestion requiring optimization of all movements in the facility, environmental impacts that need to be minimized (e.g., reduce energy resources), and the necessity of providing reliable information to all stakeholders (e.g., government, railroad and truck operators, insurance companies, among others).

Digital Twins are virtual replicas of physical objects or systems, supporting bidirectional communication between both spaces through which data is exchanged [3]. The information, captured in real-time using Internet of Things (IoT) devices, can be used for multiple purposes, from preventing and predicting faults to simulating future behaviors. As Digital Twins architectures increase in complexity, shifting from representing single objects to broader contexts like factories or cities, the need for a reference architecture and standards ultimately justifies this preliminary assessment.

Architectures are crucial not only to better understand the elements that describe the system but also to adapt it more easily to changes. Research showed a few examples of Digital Twin architectures, modeled with ArchiMate, of complex systems such as Smart Cities and Smart Factories. Still, none focus on Dry Ports.

This research is part of NEXUS[1], a project whose stakeholders include Sines' Port and the Portuguese Government, which intends to digitalize and decarbonize ports and value chains through technological solutions. This particular research is part of WP3-Smart Gates And Smart Terminal, and intends to model the architecture of a Dry Port Digital Twin using the modeling language ArchiMate.

This paper is structured as follows: Section 2 explains the methodology used to conduct the research, and Section 0, Literature Review, defines the foundations of Enterprise Architecture (EA), explores the adoption of Digital Twins in Dry Ports, and presents how EA has been used to model Smart Spaces. Section 4 studies the existing AS-IS architecture of the Dry Port, presents the TO-BE architecture, and identifies the new technological additions. Section 5 presents both the conclusion and future work.

2 Methodology

Considering the lack of studies regarding Dry Port's Digital Twins and the insufficient guidance on creating the correspondent architecture, the chosen methodology was Design Science Research (DSR) [4].

DSR aims to create knowledge by designing artifacts (e.g., models, frameworks, or digital solutions) in real settings. It considers six iterative steps, starting with the identification of both the problem and the motivation, followed by the objectives' definition, design and development, demonstration, evaluation, and, lastly, the conclusion. It is not mandatory to realize each step consecutively, as research can start in any of the steps and move outward. To better describe the research steps, Table 1 shows the adapted

[1] https://nexuslab.pt/ [Online] [Accessed in 18th of January 2024]

version of the DSR method, one iteration completed, and relates each step with the specific case of the Dry Port considered.

Table 1. DSR Method (adapted from [4])

Problem	Objectives	Design
Lack of existing architectures of Dry Port's Digital Twin using ArchiMate	Model a Dry Port's Digital Twin Architecture with ArchiMate	Design the envisioned architecture
Development	**Evaluation**	**Conclusion**
Implement the envisioned architecture, with all requirements and technological changes identified	A major IT company in the logistics sector evaluates the proposed architecture	Changes, if needed, are applied to the architecture, and a possible representation of a Dry Port's Digital Twin is made available

Overall, the steps taken to conduct this research were the analysis of existing Digital Twin architectures and the high-level blueprint of a Dry Port. After modeling the AS-IS architecture using ArchiMate and comparing both representations, it was concluded that this modeling language could accurately represent all architectural elements. Then, the TO-BE architecture was made, including all new technologies, and evaluated by an IT company, specialized in developing technological solutions for the logistics sector.

3 Literature Review

3.1 Digital Twins in Ports

The increasing research on Digital Twins [5] and their applications has justified the need for accurate ways to describe the elements involved, the data flow, and the capabilities and interactions with the user. Most of its benefits, like the increase in productivity, efficiency, scalability, and customer experience, are achieved by implementing autonomous systems and IoT devices, mixed with machine learning capabilities. Digital Twins are crucial components in an IoT ecosystem, "*...bringing many vendors and technologies together*" [6] and allowing a flexible way to integrate and configure other applications and devices.

From virtually representing a unit to an entire system, the increase in complexity and flexibility [7] has further complicated maintenance and development operations, justifying the need for methods to describe each component more comprehensively. Creating an adequate architecture is challenging and can have long-lasting impacts on the organization that will consider it [7].

The lack of established design principles to create a fitting architecture complicates the representation of systems that are becoming more complex. In [8], it is explained that the conceptualization and implementation of a Digital Twin involves four phases, essential to consider when modeling its architecture: (1) the collection of data, (2) the addition of sensors to gather information in real-time, (3) the creation of the simulation tools, and (4) the implementation of the platform to be accessed by the user.

Despite the clear benefits of implementing a Digital Twin, there are some challenges [9] regarding modeling, data acquisition, complexity, and adaptability to changes [10]:

- Adapting modeling tools to the context of Digital Twins is challenging due to the lack of solutions that integrate both data from the physical system and from data models [11].
- Each system being represented is unique, therefore, the deployment and integration of real-time data with a Digital Twin are more challenging [12][13].
- The large scale and high volume of data produced by enterprises [10] results in increased complexity and the need for more challenging predicting algorithms to anticipate issues and system's responses to changes.
- The lack of standardization [12] contributes to a lower willingness to invest in their adoption.

While all problems should be considered, the predominant ones are data-related. Some of those include managing and integrating external data efficiently, ensuring the trustworthiness of the information, and protecting it from loss and attacks during transmission [14]. For example, privacy concerns and regulatory compliance can't be ignored when using drones [6] or other devices in Ports to capture data, requiring to ensure trustworthiness in data lifecycle management. Along with these challenges, protecting and managing cargo documentation has increased the interest in adopting Blockchain [11], to minimize the likelihood of data tampering.

Dry Ports has multiple processes where adopting Digital Twins can lead to improvements, ranging from process automation to asset optimization, sustainability, safety, regulatory compliance, and stakeholder engagement [15]. The three core capabilities of this technology that can potentially improve these infrastructures are situational awareness, smarter decisions, and collaboration [10].

A study considering Qingdao Port [9] proposed a Digital Twin that integrated data from different sources and enhanced its visualization, allowing the early warning of risks and the optimization of business processes. Singapore's Port [11], through real-time traffic tracking, increased awareness about the procedures needed by the time the trucks arrived, reducing traffic congestion.

In China, Mawan's Port [11] visually represents the entire Port, facilitating the access to information in different formats and from various sources and creating simulations. Oulu's Port, in Finland [14], uses Digital Twins to formulate better environmental plans. In Livorno's Port [11], in Italy, data from sensors and cameras is used to simulate the best placement for the cargo and the most efficient order tasks.

These examples indicate a rising interest in adopting Digital Twins due to their clear advantages, ranging from the capacity to model the Port's elements to the data collection from multiple sources, which can then be used to simulate potential issues. Therefore, how to create Digital Twin architectures is an essential line of research.

3.2 Foundations of Enterprise Architecture

Architecture is the design of every structure that makes a product, device, system, and enterprise [7], from its properties and interfaces to relationships. A proper architecture enables the early analysis of potential trade-offs related to certain decisions and is easy to update and control over time [16].

Enterprise Architecture (EA) addresses the very specific design concerns related to large Information Technology (IT) systems and the company dependent upon them, documenting the human interactions with the technology used to conduct business operations [7]. A well-defined architecture is crucial for identifying potential changes and integrating new applications, allowing the enterprise to grow and innovate in a controlled way [17]. Several frameworks for Enterprise Architecture [5] define the tasks and artifacts needed for the architectural process and the views that answer different stakeholders' needs and ease discussion among them [17].

Some examples of prominent frameworks include:

- Zachman Framework [7], created in the 1980s is a two-dimensional table with thirty cells, classified by many as the fundamental structure for Enterprise Architecture. Easy to create [18], it is challenging to read and does not allow a strategic analysis of possible new technological solutions to add value to the enterprise.
- The Federal Enterprise Architecture Framework (FEAF) was defined specifically for the U.S. Federal Government in the 1990s to guide the integration of technology, business, and strategic processes across all U.S. Federal Agencies. Heavily influenced by the Zachman Framework, it shares its disadvantages and is challenging to apply to enterprises that do not follow the U.S. Federal Agencies' standards [18].
- The Open Group Architecture Framework (TOGAF), created in the 1990s, is one of the most widely used frameworks nowadays. It provides the steps required to model an Enterprise Architecture [18], helping to identify the business and IT goals and their alignment with the enterprise. This framework intends to define a shared language, understood by everyone involved. Additionally, it is possible to align TOGAF with popular EA languages like ArchiMate, allowing the creation of multiple views and layers, and strategic justifications for changes.

However, when considering the complexity of concepts such as Cities and Ports addressed in our research, most of the EA frameworks have limitations [19], as they were created to operate within an enterprise with a complete overview of its data and information systems [20]. For instance, a larger number of stakeholders guided by different rules, multiple data sources with various restrictions of access, and the service-oriented nature of these enterprises, are some of the challenges yet to be solved when modeling in Smart Spaces that are not restricted to simple components like machinery or production lines [19].

3.3 How EA Shapes the Current Advances of Smart Spaces

We found no studies modeling Dry Port architectures or addressing Digital Twins developments in this context. Therefore, our review explored the adoption of Enterprise Architecture approaches in complex spaces like Cities, Ports, or Rail Stations.

Two of the driving forces for Cities are sustainability and digital transformation [21]. Smart Cities have evolved into systems that now provide citizens with services that fit their needs and improve their quality of life [20][19]. The data captured with IoT devices and from other sources is crucial for creating valuable services [20].

Two of the problems repeatedly identified in some of the EA frameworks were the lack of focus on the user perspective and the unclear description of the data relevant to improving services [20]. To answer that challenge, the authors of [20] established a framework to model a Smart City architecture with two perspectives and seven layers. The two perspectives are those of (1) stakeholders, which focus on all entities involved and their relationships with data (from regulations to policies, privacy, and even access limitations), and (2) data, enhancing the need for its governance and security. Regarding the layers, from top to bottom, *context* describes the drive of each service, *services* meet the needs of the citizens, *business* depicts the flow of the enterprises' procedures, *application* identifies the systems that manage the heterogeneity of data sources, *data* provides storage for the information, and both *technological* and *physical* layers regard the devices that produce the real-time data and the infrastructure to run the applications.

The framework proposed by [20] has been widely adopted by other authors, for instance in the work of [19], where the focus is on designing services according to citizens' needs. Based on the context, service, information, and technology layers, guidelines to model both the context and service layers are shown, from the identification of the requirements to the definition of the scope and goals, as well as the explanation of service functions and the actors' resources. Other examples regarding, for example, the adoption of electric mobility services and focusing on data management and governance are [21] and [22], and to model an evaluation and monitoring platform for Smart Cities [23] was conducted. However, a few limitations [24] have already been identified when adopting ArchiMate to model Smart Cities, leading to extensions of its elements, as presented in [25]. In it, the authors present new elements such as, for example, the *domain* (which describes a critical field of urban development), the *objectives* (which shows the progress towards a city goal), and the *decision* (which presents an option based on data collected to support the decision-making process).

Overall, the research regarding Smart Cities is significant, and their modeling using ArchiMate has led to the creation of specific frameworks that could inspire other complex smart spaces, for example, Smart Ports. Generally referred to as intelligent ports that can operate autonomously, they use real-time information to improve operations and ensure harmonious communication among all devices, actors, and elements of the Port [26][27]. With the need to remain competitive and with processes whose tasks are repetitive and monotonous, their automatization can be achieved with adequate data processing and management [27]. Their key components include [26] (1) the smart infrastructure, which describes the technological solutions to increase productivity; (2) the smart traffic flows, responsible for the seamless flow of moving assets; and (3) the smart logistics, which supports the automatic movement and handling of containers, as well as the communication between stakeholders.

In contrast to Smart Cities, EA adoption in the development of Smart Ports is still fragmented and underexplored [26], especially when considering the impact those have on response time, asset utilization, and the environment. Existing contributions focus on specific operational aspects of a Port. For instance, the authors of [27] used ArchiMate to model a platform that allows all stakeholders to access the various applications and Port information, focusing on the application and business layers. In [28], the processes were identified and split into administrative and operational levels, followed by the description of possible technological services that could improve each one.

Seaports can combine transport options like vessels, trucks, or trains that are particularly relevant in their configurations. The work presented by [29] studied the adoption of a Digital Twin within the Rail Freight, in the Netherlands. Firstly, all operations, actors, applications, and the interfaces between them, were identified. The main problems noted were the lack of transparency, data accuracy, and liability, and, to answer these, a Digital Twin prototype was created, as well as its architecture using ArchiMate. The high-level architecture includes six layers chosen based on modularity, scalability, and considering the Model-View-Controller (MVC) architectural pattern [30]. It splits a system into three main logical components: (1) the model represents all the actions related to data, functioning as the intermediate between the controller's data requests and the database access, handling the data logic; (2) the controller enables the connection between the model and the view, sending requests to the model and rendering the final output through the view; (3) the view is dynamically rendered and generates the user interface, to be accessed by the user.

In the work of [29], the models to be used by the Digital Twin are stored in the database included in layer 5, while the views to be interacted with by the user are described in layer 6. Lastly, layer 4 represents the controller. Considering this modulation, it is possible to understand how easy it will be to add more models and views to the Digital Twin, based on future changes. To effectively connect the existing technology, REST APIs are used to integrate data from different sources, and an event hub ensures the asynchronous data acquisition from the different sensors installed and the easier integration of new event-triggered solutions. Regarding the remaining layers, layer 3 represents the data server, where all data gathered by the IoT devices will be stored and shared with the event hub, layer 2 includes all the device controllers, and Layer 1 represents the devices themselves. This architecture is more generalist and can be adapted to other Rail Freights or industries.

Our literature review confirmed the importance of EA approaches to digital transformation in Smart Spaces, the suitability of the ArchiMate language, and the lack of research in Dry Ports Digital Twins. However, it was also possible to identify frameworks to guide new developments in this field and relevant layers to model a Dry Port architecture. The following section presents the results of our design science research in developing an innovative Reference Architecture for Dry Port Digital Twins.

4 Dry Port Digital Twin Architecture

The main applications already implemented in the Dry Port are identified in Section 4.1, based on a high-level blueprint of this infrastructure. The TO-BE architecture considers the seven layers introduced in [20] and adapted in [25], starting with the context, followed by the services and actors' identification, and finishing with the applications and technological infrastructure needed. In Section 4.2, the new technological solutions are explained, and in Section 4.3, the preliminary modeling of the Dry Port Digital Twin with Archimate is explained. Lastly, in Section 4.4, a brief evaluation of the architecture of the Dry Port Digital Twin is presented.

4.1 AS IS Architecture

To model the architecture of the Dry Port, it is crucial to first describe and identify all applications and APIs accessed. The PHC Enterprise Resource Planning (ERP) is an internal financial management and payroll system. Simultaneously, JUL is an application used to facilitate the communication between entities part of the logistics chain and MSC is an API that helps to obtain route information.

- JUL[2] is an application implemented in 2019 by APP (Portuguese Ports Association). It is installed on all Portuguese ports' administrations with a strong connection with the national tax authority (AT), to improve information exchange between stakeholders and to centralize the access to all information regarding Seaports and hinterland Dry Ports. JUL acts as a hub, as it facilitates message exchange, increases data flow efficiency, and amplifies the Port's capabilities, reducing the need for physical documentation, administration costs, and waiting times.
- MedTOS[3] is a Multimodal Terminal Operating System with a strong and complete API with JUL. It manages information regarding the yard operations and shares real-time data with all freighters and cargo agents through JUL, such as the gate in and gate out of trucks and trains.

Next, the requirements regarding the TO-BE architecture are described, from the new applications to the expansion of existing IoT devices' capabilities with image recognition for trucks and containers, machine learning algorithms for yard movements optimization, and the addition of Blockchain technology to ensure data quality and reliability to external entities.

4.2 Requirements Identification

Table 2 explains the main technological additions to create the Dry Port Digital Twin, which intends to optimize operations, ensure reliable information, reduce the dependency on paper documentation, and decrease environmental impacts.

[2] https://www.projeto-jul.pt/ [Online] [Accessed in 17th of January 2024]
[3] https://www.fordesi.pt/solucoes/gestao-para-terminais-multimodais-de-mercadorias/ / [Online] [Accessed in 19th of January 2024]

Table 2. Requirements for the Dry Port Digital Twin Architecture

Technology/IoT Device	Description
License Plate Recognition (LPR) cameras	Cameras that capture trucks' license plates and confirm if each is allowed to enter (or exit) the Port. These remove the need for someone to control the flow of traffic manually.
Optical Character Recognition (OCR) cameras	Cameras that will capture images of all containers that enter and or exit the yard.
AI to confirm containers' state	Based on the images captured of each container, the model is meant to be able to detect damage.
Public Blockchain	A public Blockchain will be created to store crucial documentation for the Port's operations. For instance, bill landing documentation, CMR documents, dispatch orders and pictures of containers that arrived damaged have to be stored securely.
AI to optimize the interior movements in the port and container organization	Based on previous data regarding the arrival and exit times of containers and their characteristics, the model is meant to predict and present the best route for the container's movement within the Port.
MedTOS ENT	Application to be used by the Dry Port's operators which, based on the vehicle selected, shows the tasks to be done.
Trucker App	Application to be used by the truck drivers which allows a remote check-in. When done, the information is stored and, on arrival, the camera can confirm the operation and allow the entrance into the port. This removes, as well, the need for someone to control the flow of traffic manually.
Digital Twin	To provide reliable information about the Port's operations, the Digital Twin is meant to ensure access to data stored in the Blockchain, show a realistic overview of the Port and each of its elements, the circuit to be done by each container inside the Port, and even an administrative dashboard, listing all crucial information.

4.3 Preliminary TO BE Architecture

Figure 1 presents a preliminary version of the TO-BE architecture, considering the requirements identifying the technological additions to the Dry Port.

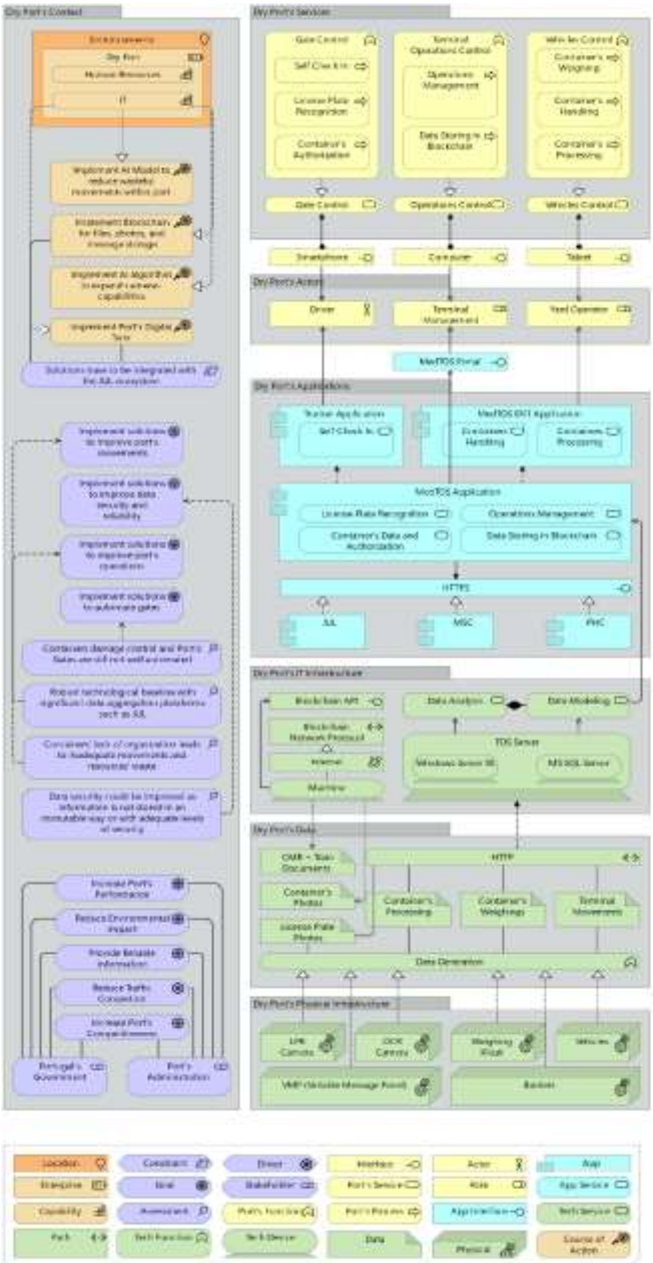

Figure 1. TO-BE Architecture of a Dry Port (ArchiMate legend presented below)

Based on the framework in [20], (1) the context layer (on the left of Figure 1) identifies the main stakeholders of the port (the port's administration and the national government), their drivers, and the assessments done. After the identification of the main problems in the Dry Port, the solutions are defined, and, in (2) the service layer (top-right), the functions of this infrastructure are presented, split into three services (gates, operations, and vehicles control). Between this layer and (3) the actors' layer (which includes yard operators, terminal managers, and drivers), the interfaces are identified.

In (4) the application layer (blue elements), two new applications are identified, which are the Trucker Application and the MedTOS ENT Application (explained in Table 2), and a new service is added to the MedTOS Application, the capability to store data in the Blockchain. (5) The IT infrastructure layer identifies the servers and the Blockchain infrastructure and (6) the data layer describes all the data produced by the IoT devices. Lastly, (7) the physical infrastructure layer describes all devices that capture information, from cameras to vehicles, the weighing kiosk, and the barriers. Blockchain is essential to ensure trust in specific Dry Port data, namely, photos collected during container inspections (e.g., to certify the source of potential damages – before arrival or at the Port facilities) and the data changed in JUL, which is critical to ensure traceability of editing records about container movements.

The MedTOS application uses data from the applications/APIs presented (JUL, MSC, and PHC) to ensure the services needed to the Port and the devices such as cameras, vehicles, and weighing kiosk, generate data that is stored in the TOS server and used to, for instance, allow the entrance of a truck in the Dry Port.

Compared with the existing AS-IS architecture, the interactions of the drivers with the Port's services are now achieved through a mobile application, Trucker Application, which allows self-check-in before arrival at the port. MedTOS ENT Application shows yard operators the route of each container, based on the vehicle selected, and considering the least number of movements. The other noticeable change is the addition of Blockchain, which will be considered to store electronic consignment note documents (eCMR, one of the essential documents in logistic operations) and pictures of the containers (if they are detected to be damaged at arrival) and the data analysis and modeling, considered by the Digital Twin. The data stored in the Blockchain will include the CMR documentation and the photos captured by the OCR cameras.

As previously mentioned, Digital Twins serve as virtual replicas of physical objects or systems, supporting bidirectional communication between both spaces [3], that data captured in real-time using Internet of Things (IoT) devices. In Figure 1, the representation of the Digital Twin is done by identifying the main data sources (cameras, weighing kiosk, vehicles, JUL and Blockchain) and technological functions such as data analysis and data modeling. Artificial Intelligence is responsible for the definition of models that will, based on historical and real-time data, define the best route for the vehicles to organize the containers and detect, based on the images captured, if containers are damaged.

4.4 Summative Evaluation of the Dry Port Digital Twin Architecture

A summative evaluation was conducted using the FEDS framework [31], created explicitly for DSR projects. This evaluation "*…are more often used to measure the results of a completed development or to appraise a situation before development begins*" [31].

According to the project partners responsible for the digital transformation of the Dry Port, the ArchiMate model is an advance compared to the traditional (informal) architectural representations. First, providing a standard representation language for different building blocks of a Digital Twin. The mere adoption of IoT is not enough to create a digital replica of a complex system, requiring the inclusion of (1) the business impact, (2) the applications supporting the key processes at the port, and (3) the elements responsible for Digital Twin intelligence. In the NEXUS vision, artificial intelligence is crucial to ensure resilient, human-centric, and sustainable port operations, aligned with the emerging priority of Industry 5.0 [32].

The proposed architecture for Dry Port Digital Twin will be the leading guide for multiple teams developing specific IT components at the port (e.g., computer vision for container identification and damage analysis and Blockchain-based file management system are implemented by different teams), ensuring alignment between architectural elements, assisting in hardware identification requirements (green elements supporting the application portfolio), and providing a simple blueprint of business – IT alignment (on the top, representing business layer interactions).

5 Conclusion

One of the intentions of this research was to model a Dry Port Digital Twin using ArchiMate, as there is still a considerable lack of guidelines to do so, even though this infrastructure has been recognized as fundamental for logistics chain optimization. Research showed a considerable increase in the modeling, using ArchiMate, of Smart Spaces, the most easily comparable to a Smart Port, Smart Cities. Based on the modeling of these complex smart systems, the TO-BE architecture of a Dry Port Digital Twin was made, identifying the elements mandatory for each of the seven layers. Our work contributes to a systemic approach to Digital Twin design and provides a real example for Dry Port Digital Twins.

There are important limitations that need to be stated. First, the proposed architecture modeled in ArchiMate was considered an advance to the current practice of Digital Twin modeling in ports, but the system has not yet been fully deployed. In the case presented, the TO-BE architecture is classified as preliminary because a lot of the digital elements to be added (the Blockchain, the Artificial Intelligence Model to optimize the movements within the port, among others) are still being conceptualized and developed, which conditions the level of detail possible to model. Second, only the high-level architecture is presented at this stage. The following steps include the detailed modeling of all the necessary views and an extension proposal for ArchiMate. Third, although the experts participating in this project confirmed the applicability of the proposed architecture to other Dry Ports and, with some adaptations, the use in traditional Seaports (an extension would be required for vessel interoperability, including berth planning features to optimize the port) is feasible. However, our summative evaluation conducted in the scope of Work Package 3 of Nexus does not allow us to confirm generalizability. Future work aims to devise design principles for Dry Port Digital Twins, emerging from the results of the instantiation in the selected case.

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