Architecting Digital Twin-Driven Transformation in the Refrigeration and Air Conditioning Sector

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Abstract Digital twins are a key pillar of the ongoing industrial revolution requiring a strategy tailored for each sector of the economy. However, contributions addressing the sectoral level of analysis are still nascent in the digital twin literature. This paper has a dual research objective of (1) identifying the digital twin potential at a sectoral level of analysis and (2) investigating whether the existent Enterprise Architectures (EA) approaches and languages meet the requirements for the creation of digital twin architectures. A design science research project was conducted in a leading business association representing the Refrigeration and Air Conditioning Sector (RACS). Our findings reveal that RACS digital twins will need to address the grand challenges of climate change and sustainability. Moreover, the digital twin-driven transformation of RACS will be more effective in cooperation between different supply chain segments, increasing the importance of business associations' role in the definition of reference architectures for their sector. Our results also extend recent research suggesting the use of ArchiMate language for digital twin developments. This contribution is relevant to sectoral digital transformations supported by digital twin technology, providing the foundations for future sectoral enterprise architecture frameworks.

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1 Introduction

The Digital Twin (DT) concept is evolving side by side with the disruptive digital transformation in industry. These digital representations of physical objects "*that support not only a prognostic assessment at design stage (static perspective), but also a continuous update of the virtual representation of the object by a real time synchronization with sensed data*" [1] are still emerging in different sectors of the economy. For example, in the refrigeration and air conditioning industry addressed in our research, DTs can leverage the digital transformation, helping digitalize energy systems aligned with efficient and sustainability strategies [2]. However, sectoral architectures that support DT developments are still lacking, for example, exploring the possibilities for Heating, Ventilating, and Air Conditioning (HVAC) systems throughout the lifecycle [3], at both design time and run time.

Enterprise architecture (EA) is a discipline attempts to capture the business and technology logic using models accessible to different organizational experts [4]. Through those models, enterprises can understand the "as-is" situation and establish a vision for the "to-be" architecture that will develop the business increasingly supported by information technologies [5]. There are influential EA frameworks to assist in the steps of architectural analysis and development (e.g., TOGAF [6]), but also languages like ArchiMate [7], suggesting a service-oriented and layered approach to EA. The most critical layers in ArchiMate are: strategy (courses of action, capabilities, and resources which can be used to model the strategy of an organization), business (e.g., processes), application (e.g., software), technology (e.g., hardware, networks), physical (e.g., equipment), and the implementation and migration (programs, portfolios, project management, and plateaus that can be used in gap analysis) that will guide digital transformation. Moreover, it is possible to model the motivation behind organizational change [8].

Enterprise architecture benefits are becoming more visible in Smart Manufacturing Systems (SMS), updating the business models and assisting companies in keeping up with innovative technology [9]. A SMS is defined as a "*highly connected, knowledge-enabled industrial enterprise where all business and operating actions are optimized to achieve substantially enhanced productivity, sustainability, and economic performance*" [10]. Industry 4.0 [11] and digital twins [12] give the first steps to incorporate EA models. However, there is a shortcoming of guidelines to adopt ArchiMate in the sectoral-level or product-level of DT developments. The gap found in the literature and contacts with industry experts gave a solid motivation to set up our research project. It started in cooperation with a national association for the refrigeration and air conditioning. The overall research objectives addressed in this paper are:

- *RO1: Identify the potential of digital twins in the refrigeration and air conditioning sector;*
- *RO2: Propose initial models for sectoral digital twin-driven transformation.*

The remainder of this paper is structured as follows. Section 2 presents background literature. Subsequently, the design research approach is presented, followed by the work conducted in cooperation with an important business association in Portugal. Section 5 discusses the findings and highlights design principles for sectoral digital twin architectures. The paper closes in Section 6, presenting the main limitations of our study and the opportunities for future research.

2 Literature Review

This section presents a bibliometric analysis of digital twin literature and the main trends in this vibrant field of research. Next, the link between enterprise architecture and digital twins is discussed.

2.1 Digital Twins

Several definitions for DT can be found in the literature, namely as being "*a digital representation of a physical element or assembly using integrated simulations and service data*" [13] and "*that mimics the real-world behaviour due to the data analytical and decision-making capability of DT*" [14]. Through the alignment between data integration and the application of data algorithms, the DT "*can perceive, monitor, synchronize mirroring, simulate, calculate, and test the behaviour*" [15] of the correspondent physical device. The different contributions in DT highlight (1) the crucial role of data obtained in the physical realm and providing the basis for digital processing and optimization, (2) the real-time communication between the physical and digital parts, and (3) the extension of product-service system value with new interactive layers available to their users.

Fig. 1. reveals three relevant clusters of digital twin literature in Web of Science and meaningful keywords found in the sample of 2587 papers (search using "digital twin", all fields, no time restriction).

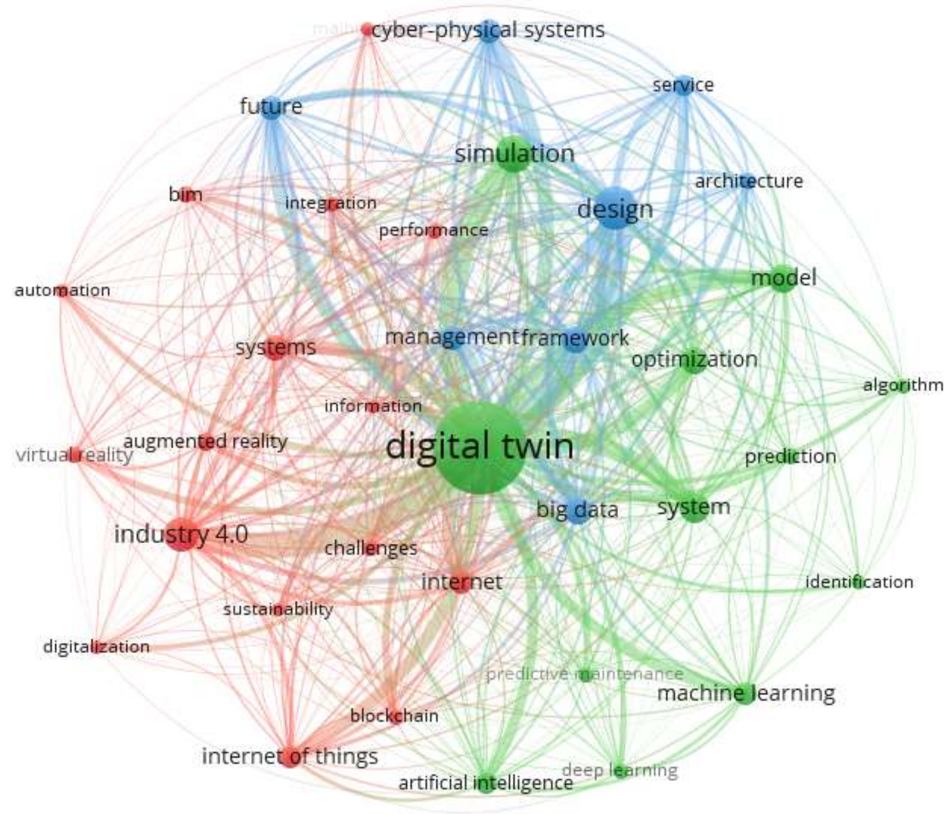

Fig. 1. Bibliometric analysis of digital twin literature in Web of Science.

The analysis presented in Fig. 1, created with VOS Viewer [16], shows the co-occurrence of significant keywords (30+ occurrences; minimum cluster size of 8). Each node of the network shows a significant keyword in digital twin literature, and the lines illustrate the most relevant connections between them. The size and thickness of the elements are proportional to their relevance. The red cluster of papers (on the left) includes important industry 4.0 technologies (e.g., blockchain, BIM) and priorities for digitalization (sustainability, automation, integration). Sustainability is unquestionably one of the most critical strategies for digital twins [17] and also a priority to the refrigeration and air conditioning sector. On the top, the blue cluster includes papers from the system structure and architecture of digital twin advances. Finally, the green cluster emphasizes digital twins' predictive and intelligent perspective, namely, with the adoption of artificial intelligence and new models and algorithms to optimize systems and predict critical events in the physical realm (e.g., in maintenance).

2.2 The Role of Enterprise Architecture in Digital Twin Design

The EA can be referred to as "*a coherent whole of principles, methods, and models that are used in the design and realization of an enterprise's organizational structure, business process, information systems, and infrastructure*" [5]. EA helps find the alignment between business and IT goals to "*bridge communication gap between stakeholder, as well as manage control and evaluate the complexity of enterprises, processes, applications, and infrastructure*" [9]. Therefore, EA seems suitable to model the different layers and elements of the digital twin. For example, the sensors (technology), the functions or processes supported, the application components, or even the strategy of the digital twin development.

Many EA frameworks have been developed. For example, TOGAF, DoDAF, FEAF, or the Zachman framework. In general, the mentioned frameworks cover four correlated domains: Business architecture (business processes of an organization), Data architecture (structure of the logical and physical data resources), Application architecture (landscape of applications, their interactions, and relationships to processes), and Technology architecture (software and hardware capabilities required to support the business processes, data, and application services of the organization) [8]. Moreover, frameworks provide guidance and the key steps necessary to create an architecture and manage strategic change [18].

ArchiMate is a popular EA modeling language [7] EA models serve two important proposes: the first is to build a structure to align the enterprise strategy with the IT goals while providing ways of communication of the different involved stakeholders, considering the different perspectives; the second is to provide to the companies an overview of Industry 4.0 components to derive potentials for further improvements [11].

There are also some limitations in adopting these frameworks for our study. For example, it is possible to get inspiration from TOGAF and ArchiMate [7] to model digital twins in specific sectors of the economy. However, these essential tools do not fit precisely in the scope of digital transformation of an entire economic sector. Other examples, like FEAF [19], DoDAF [20], or the Zachman framework [21] were not built for creating the implementation (an instantiation) of specific artifacts like digital twins. Therefore, we could not find EA frameworks specifically created for manufacturing sectors like the refrigeration and air conditioning addressed in this research. Our requirements will include to (1) model the digital twin architecture with a language accessible to different experts, (2) propose a digital transformation methodology, (3) address data analysis requirements in the supply chain, (4) follow the strategic priorities of sustainability and climate change that are so crucial in the selected sector of the economy.

The authors of [22] propose a new methodology based on IT value, workgroup ideation, and Enterprise Architecture Management (EAM), as an approach for organizations to structure the introduction of Big Data. The methodology consists of the following steps: (1) developing ideas for Big Data usage, (2) assessing these ideas regarding their potential value, as well as the required changes to the organization architecture, and (3) implementing them coherently in the business. With this, EA can assist in developing emerging technologies like Big Data, an important part of the DTs of the future, and help the industry manage the digital transformation. In the scope of data analysis of the DT, there must be resourceful data sources that can be leveraged to optimize the performance of the DT.

As each sector has its own business scope, competencies, processes, skills, and administrative infrastructure, the IT operations must be targeted to its business strategy. Aligning the IT strategy with the business services potentiates the technology transformation of the business and serves the needs of the stakeholders [23]. Moreover, inspired by studies like [22] for the context of Big Data, our literature analysis confirmed the necessity to create EA modeling approaches to align business and IT with increasing volumes of data and leverage industry transformation supported by digital twins.

3 Research Approach

Design science research (DSR) is a popular research approach in studying information systems, aiming to produce knowledge with the design of artifacts [24], [25]. These artifacts can be "*constructs, models, methods, and instantiations*" [24] and generate new design knowledge to real-world problems [25], [26]. Therefore, DSR was considered suitable for our purpose to build a digital twin architecture in the sector of refrigeration and air conditioning.

Our work is depicted in Fig. 2, according to the DSR grid proposed by [26].

Problem Digital twin architectures for specific sectors of the economy are still scarce	***Research Process*** Delimitation to the refrigeration and air conditioning industry; Modeling of a digital twin; Evaluation	***Solution*** The architecture of sector-specific digital twins modeled in ArchiMate
Input Knowledge Digital twin concepts; Sector-specific information; ArchiMate specification	***Concepts*** Digital twin; Enterprise architecture	***Output Knowledge*** Design principles to model digital twins with ArchiMate; Identification of key structural and behavioral elements of air-conditioned digital twins

Fig. 2. A summary of the selected design science research (adapted from [26]).

DSR starts with the problem formulation and evolves in building, evaluation, and theoretical development iterations [24]. The first research cycle had a problem-centered initiation [24] with a literature review on digital twins and enterprise architecture and contacts with industry experts of a leading national association representing over 500 companies. The design of digital twin models followed and the demonstration of its utility [17] with an evaluation made by experts in refrigeration and air conditioning.

Our case company is a private non-profit business association whose primary objective is to defend the common interests of its members, providing a wide range of services to member companies, covering all multidisciplinary fields relevant to the sector. Their mission is to promote the development of a favorable legal and regulatory environment and contribute to the development of the refrigeration and air conditioning sector. The activities of the companies represented by our case company are diverse: design, consultancy, energy certification, manufacturing, imports, representation, distribution, retail, installation, maintenance, technical assistance, building automation and control, and indoor air quality. The type of products and services includes ventilation, air conditioning, heat pumps, refrigeration (professional, commercial and industrial), renewable energies, and building automation control.

According to the business association, the building automation and control systems are more advanced in adopting digital twin technology. Their goal is to continuously monitor facilities equipment, ensure proper maintenance and cost reduction. Accordingly, sensing technologies are already adopted. However, the previous segments of the refrigeration and air-conditioning supply chain, namely, equipment manufacturers, distributors, and equipment installers, are not yet exploring the digital twin potential. Moreover, digital twins are not yet widely available to the end-users of this type of equipment (e.g., freezers, air-conditioned) at home.

Interestingly, a search in Google Scholar using the keyword combinations “air conditioning digital twin” and “freezer digital twin” returns 0 results, while “fridge digital twin” appears in one paper that presents it as an example [27], revealing the need for more studies in this area. As stated by [27], “*most research to-date focusses on the monitoring of production equipment or large assets*”, which is insufficient for the needs of the industrial product service systems from the early stages of design and manufacturing to the end of life [27].

ArchiMate [7] was the language selected to model the digital twin-driven transformation of the selected sector. Two reasons justify our choice. First, the potential of ArchiMate to model Industry 4.0 systems [11]. Second, the recent studies emerging in the literature link enterprise architecture techniques in the design of digital twins. For example, the work of [12] proposing an enterprise meta-model that also models a digital twin with ArchiMate and the study presented by [28] that details the application layer of an intelligent transport system. However, there is a lack of studies addressing a sector-level of analysis, and none of the important papers found in our literature review addressed air-conditioning digital twins.

ArchiMate is a visual language offering "*an integrated architectural approach that describes and visualizes different architecture domains and their underlying relations and dependencies*" [7]. This language includes different elements representing behavioral, structural, motivational, and a composite architecture presentation. The ArchiMate framework can be used to develop an architecture of the enterprise strategy, business, application, technology, physical, and implementation and migration. As stated by the foundational work of Zachman "[w]*ith increasing size and complexity of the implementations of information systems, it is necessary to use some logical construct (or architecture) for defining and controlling the interfaces and the integration of all of the components of the system*" [29]. Therefore, an architectural approach to digital twin development can be valuable to industrial sectors of the economy investing in this concept.

The following section details the design and development stage of our DSR.

4 Architecting Digital Twins in the Refrigeration and Air Conditioning Sector

The work of [13] presents three key elements of DT developments, namely, (1) modeling, (2) connection, and (3) advanced data analysis. Under the scope of modeling, it will be necessary to create a 3D visualization of the object, where the user can interact with the virtual system and use the system service through the interface. This element is associated with the ArchiMate business layer, which models the usability processes of the DT for air conditioning. Connection refers to the integration of the data, which can be acquired (e.g., from temperature sensors, air quality sensors, humidity sensors, or pressure sensors) and saved in data clouds. This scope translates the technology layer, representing the conception of the DT and the configuration of the digital infrastructure. The following step is the data analysis, using intelligent applications, artificial intelligence (AI), analytics, and Big Data processing. The application of computer science algorithms allows to convert unrelated data into relevant usage information and decision making, contributing to address the problems of advanced planning and scheduling, product and process quality improvement, fault diagnosis, defect analysis [9], exploring the application layer.

This section describes the main steps of our exploratory research with the business association and the design and development stage evolving in steps of (1) strategic development, (2) holistic evaluation of the sector, and (3) product-level modeling example.

4.1 Digital Twin-Driven Sectoral Architecture – Strategy and Motivation

According to the experts contacted in our study, the vision of digital twin technology for refrigeration and air conditioning needs to contribute to several strategic goals, namely: sustainability, lower carbon footprints, energy performance optimizations, lifecycle planning, equipment durability, maintaining environmental conditions for health and wellbeing, continuous monitoring, and active & preventive maintenance. Moreover, policymakers must balance the environment's needs, economy, and energy reduction [30]. Therefore, the strategy and motivation layer of the architecture proposed will guide the next steps of the modeling process (Fig. 3).

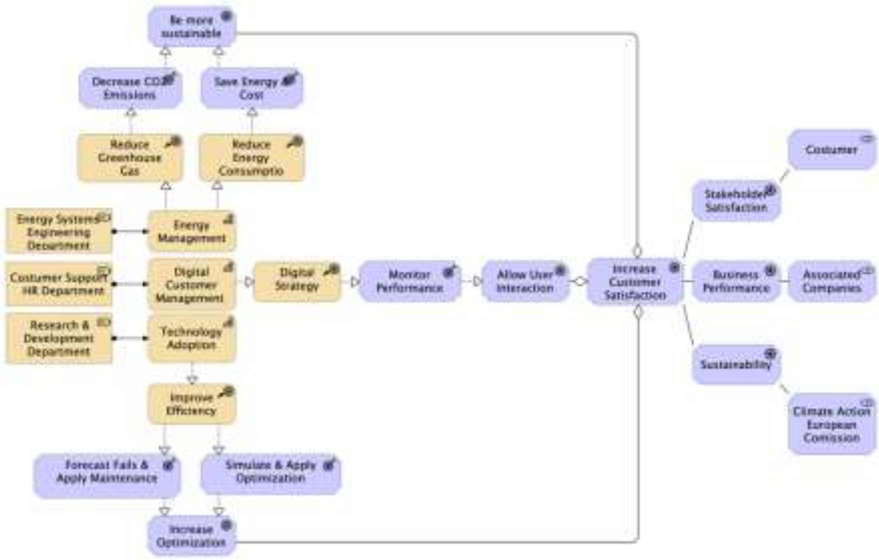

Fig. 3. ArchiMate model for the sectoral strategy and motivation (source: own elaboration).

Fig. 3 presents the strategy and motivation layer. On the right, the elements "Costumer", Associated Companies" and "Climate Action European Commission" present the key stakeholders interested in the sectoral EA and its digital transformation. On the left of these elements are represented the drivers, "Stakeholder Satisfaction", "Business Performance" and "Sustainability", that motivate the organization to implement necessary changes. The main goal is to "Increase Customer Satisfaction". Therefore, this element is connected to other three goals, from different scopes, that converge to the main goal: "Be more sustainable", "Allow User Interaction" and "Increase Optimization". The priorities for this sector are presented as a tangible outcome and connected to each set goal, being respectively: "Decrease CO2 Emissions" and "Save Energy & Cost"; "Monitor Performance"; "Simulate & Apply

Optimization” and “Forecast Fails & Apply Maintenance”. The course of action presents the suggested tactics for the sector.

4.2 Sectoral Landscape for Digital Twin Developments

The strategy and motivation for sector-specific digital transformations will guide the investment priorities. Next, it is necessary to model the sectoral structure and behavior in the entire supply chain. Fig.4. presents the overall architecture.

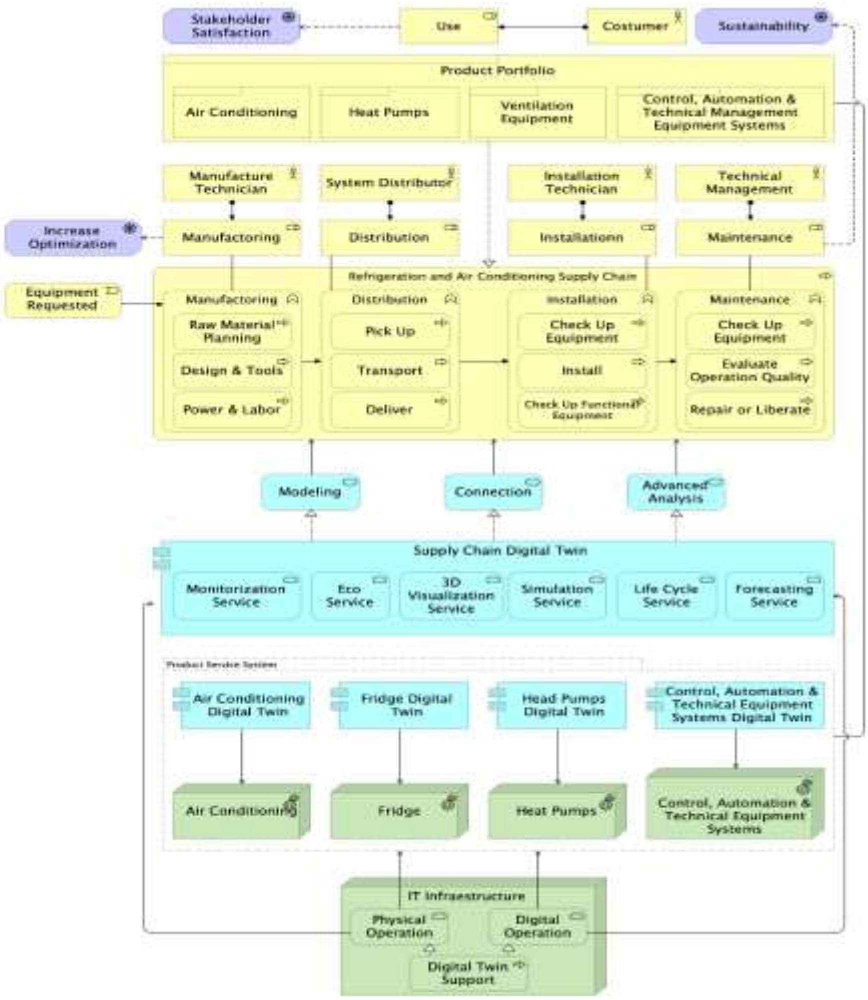

Fig. 4. Sectoral digital twin architecture for RACS (source: own elaboration).

There are four main segments in the refrigeration and air conditioning supply chain: manufacturers, installers, distributors, and technical management (also referred to as building automation and control systems). The supply chain and the product portfolio are represented in the business layer at the top of Fig. 4 (yellow elements). For the sake of simplicity, only a few strategy elements are included in this model – identified in Fig. 3.

Each product requires a detailed analysis of the digital twin configuration, including physical and digital components. Ultimately, the sectoral product offer will be transformed into a product-service system that includes the physical value of the equipment and the digital support to their stakeholders (e.g., advice for energy reduction). The links between the application layer (blue) and the technology and physical layers (green) are bidirectional, as suggested in the work of [12]. On the one hand, the digital twin requires a cloud-based architecture and related software and hardware infrastructure. On the other hand, the digital twin will also serve the physical layer of the architecture (e.g., real-time monitoring and actuation). Both the products digital twins and the supply chain digital twin (addressing aspects like manufacturers equipment, transport, real-time monitoring of the fleet of digital twins of a specific brand) are essential to the sector. This high-level sector model offers the foundation for more detailed modeling of each product.

4.3 Air Conditioning Digital Twin Model

The model shown in Fig. 5 provides an overview of the Technology, Application, and Business layers for an essential product of this sector: air conditioning devices.

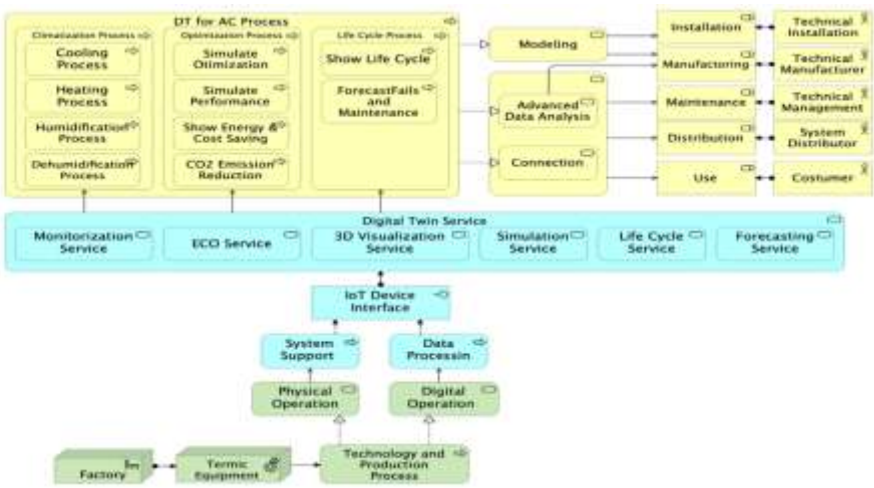

Fig. 5. Digital twin architecture for air conditioning products (source: own elaboration).

Fig. 5 presents an ArchiMate model for the product level of analysis (air conditioning example). The model represents the core physical and digital components of the DT, the services it provides to the processes triggered using the DT, and the different stakeholders. Making a bottom-up interpretation, the Technology layer (green elements) represents the structure and behavior of the technology infrastructure and components of the DT. This layer serves the Application layer (in blue), composed of the software systems that will support the processes represented in the Business layer (yellow). In the Business layer are key stakeholders with direct interaction with the DT, already identified in the sectoral model. For example, the Customer, the Technical Management (also referred to as building automation and control systems Management), or the System Distributor.

Following the services that Air Conditioning can yield and the new services that can be achieved via Industry 4.0, the Business layer of the architecture models the process of using the DT of Air Conditioning. The "DT for AC" process (on the top-left) is triggered when the user powers the equipment and starts. Once the equipment is working, several functionalities are possible to perform in the context of Software as a Service - SaaS – to serve the Consumer. The Digital Twins processes architecture is grouped by equipment processes supported by the DT, namely: "Climatization Process", "Optimization Process" and "Life Cycle Process".

5 Discussion

Enterprise architecture is an exciting approach to identify the current landscape of an economic sector digitalization ("as-is") and identify opportunities for new developments ("to-be") [5]. Our exploratory study with the business association found that it is possible to expand the EA concept to the entire supply chain. The integration of different segments of refrigeration and air conditioning (e.g., manufacturers, installers, distributors, and facility managers) allows a broader perspective of the digital twin features, crossing the borders of a particular company. For example, a digital twin model for air conditioning manufacturers could identify opportunities to create a digital replica of the equipment, helpful to the end-user, and data collection from the fleet – interesting to evaluate or simulate the product performance under different operating conditions. However, it could miss digital twin opportunities for installers (e.g., product instructions) or technical managers interested in real-time warnings for system maintenance. Combining digital technologies with business models can generate significant value for enterprises [31], and business associations are interested in developing the value of data sharing within the entire supply chain. For example, digital twin operation data is valuable for manufacturers and technical managers, and simulation data is interesting for different segments.

Digital twins can be modeled with EA languages like ArchiMate. We decided to use the existing ArchiMate elements (e.g., actors, processes, components) in our test. Although this language was not explicitly developed for the economic sector's needs, it can produce comprehensive digital twin architecture, useful for communication with the experts. Nevertheless, the adoption of ArchiMate for digital twin modeling is still nascent, and new guidelines are necessary to assist enterprise architects. Our work may contribute to strategic enterprise architecture modeling [32] of sector-specific digital twins.

Developing EA models for different sectors of the economy is necessary. First, it is possible to identify similarities in different product types suitable for a digital replica. For example, air conditioning digital twins could inspire the development of digital twin models for smart fridges (e.g., evaluating the use of the equipment to propose energy-saving measures or automatically adjusting energy consumption according to the door opening profile, minimizing food waste suggesting meals). Second, sectoral digital twin models can assist companies with different aims (e.g., manufacturing, services, research), sharing the motivation to improve their economic sector. The models may be used to improve system performance, influenced by both design and control strategy [2]. Modeling digital twins for specific sectors of the economy offers an opportunity to link academics and practitioners in envisioning more impactful digital transformation, producing digital twins that serve the interest of different stakeholders. Sector-specific digital twins may also boost data market initiatives.

The lessons learned in our project allowed us to propose the following design principles useful for future sector-specific digital twin transformations.

- **Design principle 1:** Identify the grand challenges affecting the economic sector. Temperature increase and energy optimization are priorities for refrigeration and air conditioning, but other sectors may have other priorities (e.g., safety, resource conservation). The strategy and motivation layers (Fig. 3) of ArchiMate can be a good starting point.
- **Design principle 2:** Integrate the need of supply chain segments and regulatory compliance requirements. The models can be iteratively improved with more stakeholders' concerns identified and consequently more opportunities for new digital twin features.
- **Design principle 3:** Start with a top-down and upstream approach to improve the EA views, then check the bottom-up and downstream coherence. The first part of this principle suggests that the sector strategy should be followed by the business architecture structure and behavior (e.g., process modeling), then the application, technology, and physical layers. The upstream analysis will start from the needs of the society (e.g., governments) and end-users and then follow each segment of the supply chain until the earlier stages of raw material production. The suggested approach will produce models that give priority to the customers' needs. Then, it is necessary to identify if the sectoral model for the digital twin will have the necessary foundations (bottom-up modeling starting from the physical and technology layer) to produce the necessary data and physical-digital interaction relevant to all the participants in the supply chain.
- **Design principle 4:** Model the strategy, the sector, and the product portfolio. Sectoral models must represent all the sector actors and allow the identification

of digital twins' integrated value. However, each product has particularities that need more specific models. For example, air conditioning has different digital twin features compared to smart fridges (out of the scope of our study).

The suggested principles complement the well-known practices for EA development lifecycles [5] [6], emerging from the design work conducted in this research.

6 Conclusion

This paper presented an architectural approach to evaluate the potential of digital twins in the refrigeration and air conditioning sector. ArchiMate language was used to model relevant views of the industry strategy, business, applications, and technology. Extending previous studies pointing to the applicability of ArchiMate in Industry 4.0 [11], our work reveals its utility for the design and communication of digital twins in critical economic sectors like refrigeration and air conditioning, highly motivated by climate changes and sustainability goals.

There are also limitations in our exploratory study that must be stated. First, this is our first attempt to model digital twins at a sectoral level of analysis. Therefore, the models are not yet complete, requiring an evaluation by different companies. Second, the results are restricted to the refrigeration and air conditioning sector. Third, ArchiMate was considered interesting for our purpose and valuable during our meetings with the practitioners, but other EA languages could be tested. Fourth, our EA approach addressed the main concerns of a sectoral association, but it is possible to include more stakeholders like governments or energy providers. Finally, the models provide a high-level digital twin analysis suitable for business associations, but more specific models and specifications are necessary for digital twin developers.

Future work in this area is promising. Besides the opportunities raised by the study limitations, it would be interesting to create a complete set of ArchiMate viewpoints for sectoral digital twin transformation. These templates could assist enterprise architects in envisioning the multiple implications of digital twin development at different levels of the architecture. Moreover, it will be important to compare the "to-be" architecture presented in this work with the innovation projects conducted by the companies pertaining to refrigeration and air conditioning. The business association participating in our work aims to follow their associates' digital transformation initiatives closely. Another opportunity is the creation of ArchiMate extensions for digital twins. Lastly, sectoral associations need new forms to design and communicate their associates' digital transformation opportunities and challenges. EA approaches can be tested for this purpose, but a sectoral enterprise architecture framework is a priority for future research.

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