Digital Twins as Enablers of Predictive Maintenance in Rail Transport Services

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***Abstract*—Rail transport services are emerging as a major sustainable transportation option. However, these services are significantly dependent on high investments and complex logistics, which creates the need to identify opportunities to minimize the waste of resources to remain affordable and competitive. The digital twin, one of the core concepts of the Industry 4.0 paradigm, represents an important support in ensuring sound decision making, as it enables detailed real-time monitoring of the state of a piece of equipment during its operation. This work seeks to explore the potential of the digital twin to support predictive maintenance processes in railway vehicles and infrastructure. Two digital twin prototypes – a digital twin of a railway vehicle model, and another for a section of a railroad - were developed. Both prototypes are composed of a relational database for storing the data on the operational conditions of the equipment and a mobile application that works as a dashboard of the digital twin. The developed prototypes provide deeper knowledge of the working conditions of a vehicle, which enables predictive maintenance through the analysis of the historical evolution of the data. The results of the study also allow the identification of possible improvements and research opportunities for future work.**

Keywords- rail transport; digital twin; monitoring; predictive maintenance; Industry 4.0.

I. Introduction

Accelerated technological and scientific progress over the last few centuries has enabled the worldwide growth of industrialization [2]. This phenomenon began with the First Industrial Revolution at the end of the 18th century, which introduced mechanical manufacturing facilities powered by water and steam, as well as equipment such as the mechanical loom. A century later, the Second Industrial Revolution was marked by the spread of mass-production factories powered by electricity, along with the introduction of division of labor. The Third Industrial Revolution, which took place in the early 1970s, was characterized by the employment of electronics and information technology (IT) to achieve an even greater level of automation in manufacturing processes [3]. The emergence of Internet of Things (IoT) technologies has led to a new industrial paradigm shift, which has been dubbed Industry 4.0 [4]. The transition from centralized industrial control systems to decentralized intelligent systems can be considered the central principle behind the Industry 4.0 paradigm. The Industrial Internet of Things (IIoT) – which refers to the real time collection and sharing of data between products, components and industrial machines – allows industrial systems to adapt their behavior to different operating conditions [4].

One of the key technologies in the Industry 4.0 paradigm is the digital twin concept. The digital twin makes it possible to integrate the physical world with the virtual world by creating a virtual representation of a piece of equipment or object. For this reason, a digital twin facilitates the building of information systems that offer a solid basis for decision-making [5]. Consequently, this concept has been adopted not only in the context of industrial production, but also in sectors such as urban planning and health [6]. The digital twin is also a promising technology for improving and modernizing rail transport processes. As these operations are significantly dependent on high investments and complex logistics, it is desirable to optimize costs related to equipment maintenance and modernization, as well as minimize downtime. The digital twin concept can be employed to tackle these challenges, as it enables the monitoring of the operational conditions of rail transport systems and its resources [7].

Rail transport represents a crucial service for a country's logistic and economy, as it allows the transportation of a large number of passengers and heavy loads over long distances. In addition, it is an important means of transportation for maintaining a sustainable economy [8]. Considering the worsening climate crisis - to which the saturation of the road system contributes significantly - it is necessary to increase the competitiveness and attractiveness of rail transport services. For this reason, the European Commission has strongly recommended an increase in the share of rail transport compared to road transport [8].

The present paper seeks to explore the potential of the digital twin concept for rail transport support, especially regarding the monitoring of the conditions of railway vehicles and railroads, and the implementation of predictive maintenance. To this end, two digital twin prototypes were developed: a digital twin of a train model, as well as a digital twin of a section of railroad. Both prototypes consist of a database, a web server and a mobile application for data visualization. This work was carried out as part of the Ferrovia 4.0 research project and was accompanied by project partners throughout the development process. The present paper is based on a previous article presented at the

Ninth International Conference on Fundamentals and Advances in Software Systems Integration (FASSI 2023) [1].

The remainder of this work is structured as follows. Section II details related work in digital twins. Section III describes the methods and tools used in the development of the present work. Section IV details the conceptual models which were built in the early stages of the project. Section V delineates the process of implementation of the digital twin prototypes. The employed evaluation method is explained in Section VI, and its results are presented and discussed in Section VII. Lastly, Section VIII presents the conclusions and opportunities for future work.

II. Related Work

The concept, as well as the term "digital twin" itself, were introduced in 2003 by Grieves in the Product Lifecycle Management course at the University of Michigan. At the time, the notion of virtual representations of physical products was in its infancy, and the technological limitations meant that data on the real product had to be collected manually through paper [9]. These same limitations were the main cause behind the lack of practical studies related to digital twins in the years following its introduction [10].

Although not very specific, a preliminary digital twin model was proposed by Grieves at the time. This model had three main components: the real product, the virtual product and the data connections responsible for linking the real and virtual products [8][9]. Accelerated advances in communication, sensor, simulation and big data technologies over the course of the 2000s have contributed to the rise in the number of digital twin studies over the last decade, as these advances enabled the automated collection of product data [10]. Since the publication of the first study on digital twins in 2011, work on this topic has been growing exponentially [5][9].

According to Canedo [11], the digital twin concept represents a new way of managing IoT equipment and systems throughout their life cycle. The product design process can be improved through the feedback provided by digital twins of instances of a particular product in use by the public. This would allow the manufacturer to analyze how users make use of the product and how different environments promote its deterioration [11]. Digital twins also constitute an important tool for optimizing equipment configurations, the definition of maintenance schedules, and the design of new generations of products [6]. Likewise, the manufacturing [12], distribution and retirement [6] phases of a product’s life cycle can also be improved with the use of digital twins.

Based on previous studies, the first scientific journal article on the concept of the digital twin was published in 2011 [10]. In this article, Tuegel et al. [13] presented a conceptual model of a digital twin to improve the prediction of the useful life of aircrafts, which at the time consisted of using individual physical models of the different categories of stress exerted on the airframe. To this end, the authors proposed the use of high-fidelity models for each unit of a specific variety of aircraft in an inventory. By using data on the estimated flight path and expected maneuvers for a given mission assigned to the aircraft, these models could perform a simulation and calculate the level of stress that would be exerted on the machine's structure as a result of the flight [13]. In an article published in the following year by NASA, the authors proposed the use of digital twins to address the shortcomings of conventional vehicle certification and fleet management methods employed at NASA and the United States Air Force. The authors also presented a formal definition of a digital twin as a multi-physics, multi-scale, probabilistic, high-fidelity simulation that uses historical data, sensor data and physical models to reflect the state of a real product [14].

A proof of concept of the digital twin was presented Haag and Anderl [15]. The authors designed a test bench in which two actuators are used to apply force to both sides of the beam in order to make it bend. Integrated sensors are responsible for measuring the resulting force and calculating the displacement of the beam by using the difference in the position of the actuators. This data is sent to a digital twin of the test bench, which consists of a three-dimensional model of the built structure and a dashboard. Using this dashboard, users can monitor data about the force applied to the beam and the degree of displacement, as well as control the test bench's actuators [15].

The following items introduce some of the main related studies on digital twins according to their respective product life cycle phases. A summary of the related studies is presented by Table I.

A. *Process and Product Design Phase*

Guo et al. [16] proposed a modular approach to assist in the development of a flexible digital twin for evaluating factory designs. The authors make use of parameterized and reusable modules that correspond to real physical entities to make the process of developing the digital twin more flexible, dynamic and faster. This approach results in a simulation model made up of modules that are independent of each other, which speeds up any changes to the model and enables collaboration between multiple designers [16].

Tao et al. [17] proposed a digital twin-based product design framework with the aim of connecting the virtual representation of the product and the collected data. This virtual representation consists of both the reproduction of the functionalities, behaviors and specifications envisaged by the designers, and the reproduction of the state of the physical product in real time. The authors presented a use case for this framework in the process of redesigning bicycles used by a bikesharing service. The virtual representation of the bicycle would receive data related to acceleration, speed, tire pressure level, and maintenance and production process throughout its useful life cycle, and would change in sync with the state of the physical bicycle. This enables designers to perform a more thorough analysis of the product's condition and make it easier to identify design flaws and user needs [17].

B. Manufacturing Phase

In order to enable the design of digital twins that are more geometrically faithful to reality, Schleich et al. [18] proposed a comprehensive model based on the concept of Skin Model Shapes, which takes into account divergences in the geometry of a product resulting from real manufacturing processes [19]. By incorporating simulations of possible geometric divergences, this model allows the consideration of the different variations that can occur in the geometry of a product throughout its life cycle. Thus, it ensures that the required geometric characteristics are met [18].

Dias-Ferreira et al. [20] introduced an architecture for production systems inspired by the functioning of biological systems, called BIOSOARM. In this architecture, both the shop-floor equipment and the product components function as individual elements and are represented in the virtual environment as autonomous entities which are totally dissociated from each other. These elements interact and cooperate with each other, which promotes the emergence of self-organized behavior and consequently results in the necessary production flows [20]. Digital twins can be employed in this architecture as a way of supporting the visualization and analysis of the effectiveness of the different interaction patterns in the system [6].

Vachalek et al. [21] presented a digital twin-based approach for production line optimization. The authors used a simulated pneumatic cylinder production line paired with a detailed digital twin of the actual physical process. In addition to enabling the simulation of alternative manufacturing scenarios by modifying production parameters, the digital twin was also able to monitor the process in real time and identify opportunities for minimizing resource consumption [21].

Tao and Zhang [22] proposed the concept of the digital twin shop-floor, which consists of a virtual reproduction of the geometry, behavior and rules of a given shop-floor. This digital twin is updated in real time according to data related to the operations carried out on the physical shop floor. This enables the digital twin to carry out simulation, evaluation and optimization tasks, as well as regulating physical operations automatically as required [22].

Ameri and Sabbagh [23] introduced the concept of the Digital Factory to help with the sourcing process, which involves the search and evaluation of suppliers of goods and services. Sourcing decisions have a major impact on the agility and responsiveness of companies in charge of manufacturing products, but they are also a time-consuming process since it is often necessary to visit suppliers' facilities and carry out production tests to analyze their capabilities and qualifications. This time expenditure is still present even when evaluating suppliers through online profiles, due to the huge number of results returned by web searches. With these limitations in mind, the Digital Factory concept proposed by the authors represents the digital twin of a real physical factory. It provides a virtual representation of the production facilities, including all installed machinery, material handling equipment and the factory layout. With this, a Digital Factory provides a formal ontology used to represent the production capacities of the facilities. By consulting and analyzing this information, companies are able to gain a deeper understanding of the technological capabilities of suppliers, which consequently results in a more assertive decision-making process [23].

Seeking to overcome the limitations of conventional processes for structural correction of metal components manufactured through additive manufacturing, Knapp et al. [24] developed a digital twin-based framework for making predictions about the most critical factors affecting the metallurgical structure and properties of manufactured components, such as temporal and spatial variations in cooling rates and solidification parameters. The employment of the framework minimizes the empirical tests used in conventional approaches to analyze the effects of process variables on the component's structure, which are costly and time-consuming [24].

In order to reduce the costs related to late changes resulting from faults in the geometry of complex assembly products, Söderberg et al. [25] proposed the use of a digital twin for geometric quality assurance. This digital twin would be applied at the design stage, where it would provide geometric representations of the individual parts of the final product and representations of kinematic relationships, as well as perform simulations of variations in geometry to identify component tolerances. Afterwards, at the manufacturing stage, the digital twin would use the variation simulation models, jointly with data collected through physical inspection of the product, as a way to control the manufacturing process and identify and correct faults [25].

Howard et al. [26] introduced the digital twin concept to the commercial greenhouse production process. In this case, the digital twin was able to estimate the future states of a greenhouse that is being manufactured, based both on previous data stored in a database and on data collected in real time through sensors. This optimizes the production process as a whole and increases the energy efficiency of the system [26].

In addition to improving product manufacturing processes, the digital twin concept also enables the transition to the individualized production paradigm [6]. This paradigm is characterized by the manufacturing of products with the customer as the central focus, in which individual needs and preferences are transformed into personalized products and services at an affordable cost [27]. Zhang et al. [28] proposed a new approach to support glass production line design and optimization with the individualized manufacturing paradigm in mind. This approach uses a digital twin to provide a set of three-dimensional models representing the various pieces of equipment required for the manufacturing process, along with a visualization of the configuration variables, in order to offer assistance on the task of designing the production line. The digital twin is also used to carry out simulations of the system layout and the product manufacturing process to identify possible improvements to the process design [28].

The use of industrial robots for warehouse operations poses a significant risk to the safety of human operators, as robots are extremely heavy pieces of equipment and are in constant motion. For this reason, if a human operator needs to intervene in warehouse processes, the entire fleet of robots is stopped and remains in this state until the human operator has left the site. This interruption of operations can result in a huge negative impact on the efficiency of operations, especially in large warehouses. With this problem in mind, Petković et al. [29] presented an algorithm for estimating the intentions of human operators. According to the authors, this algorithm would allow robots and humans to work simultaneously in an integrated warehouse model. The proposed algorithm is based on Theory of Mind, which is an intuitive human conception of the mental state of other human beings. Using a digital twin of a large warehouse in virtual reality to carry out simulations with real human beings, the algorithm developed by the authors was able to accurately estimate the intentions of human operators in relation to multiple predetermined objectives, based on their position and orientation [29].

Bilberg and Malik [30] proposed a digital twin for controlling collaborative assembly processes between humans and robots. The digital twin balances the assembly tasks between the two, based on the order in which the tasks are performed, the degree of suitability of each task for a robot, and the availability of resources (such as the robots themselves and human operators). The digital twin proposed by the authors can identify delays in the process caused by the time variability of human operators. It is also capable of instructing robots to interrupt their current tasks in order to assist with delayed tasks, as well as optimizing robot trajectories in order to prevent collisions with humans [30].

In order to help with the scheduling and routing of AGVs (automated guided vehicles) in the logistics environment of job-shop production systems, Bottani et al. [31] presented a digital twin prototype of an AGV based on the cyber-physical system paradigm. As the AGV is able to communicate with other equipment that are based on this same paradigm, the proposed digital twin uses the data received by the physical AGV to simulate the different possible trajectories and, consequently, identify the best decision to be made in a given situation. This gives the AGV the ability to automatically adapt to different scenarios, resulting in greater optimization of production and logistics processes [31].

C. Operation Phase

Zheng et al. [32] proposed a design approach for innovation in Smart Product-Service Systems based on data gathered by sensors. The authors presented a case study of a breathing mask equipped with sensors, which collects data on variables such as pressure and temperature. From this data, it is possible to calculate, for example, a user's breathing pattern and how well the mask fits the wearer's face. This information can be used in conjunction with a digital twin that represents a user's facial features to simulate the use conditions of different models of breathing masks [32].

Khajavi et al. [33] proposed a digital twin implementation model to monitor the condition of a building's façade. The authors initially built a wireless network formed by sensors, which were installed inside and outside the windows of an office located in the selected building, with the aim of comparing different network configurations and analyzing the impact of distance on communication between the sensors and the network gateway. The installed sensors are responsible for measuring a series of variables, such as the degree of illumination, the temperature, and the level of relative humidity of the environment. Based on the results obtained through this initial phase, the authors then built a wireless network made up of six sensors positioned along a section of the façade of the same building. The data collected by these sensors was used as the basis for creating a digital twin, which made it possible to visualize the lighting levels of the façade in real time. According to the authors, the use of a digital twin based on this approach represents a way of supporting energy efficiency, as it makes it viable to continuously monitor the distribution of natural lighting along the entire façade of a building [33].

Iglesias et al. [34] introduced a set of digital twin-based applications with the aim of improving the engineering analysis workflow in divertor operations at JET (Joint European Torus), an operational plasma physics experiment located at the Culhan Centre for Fusion Energy in the United Kingdom. According to the authors, the developed applications have the potential to increase the reliability and operational limits of the experiment, as well as providing more accurate results [34].

Jeschke and Grassmann [7] proposed a strategy for implementing digital twins in the German rail transport system. The authors presented a use case of an Intercity Express train, a high-speed rail transportation service that connects several cities in Germany and other European countries. According to the authors, by allowing the representation of a real object in a virtual environment, the digital twin concept enables the monitoring of the rolling stock in real time and the identification of unplanned changes in service operations. Through data-based evaluation and simulation, a digital twin can make early predictions of future events, which enables predictive maintenance and preventive measures against possible failures, as well as avoiding the waste of financial resources. The authors also identify some of the biggest obstacles to the implementation of digital twins in the context of the German rail transport service. They point to the absence of technical norms and standards for the interoperable operation of digital twins on a network, as well as legal barriers to obtaining and using data from pre-existing control and monitoring systems on the system's trains [7].

The Alstom and Simplan companies have developed a digital twin – by using the Anylogic simulation tool - with the aim of optimizing transport services on the West Coast Main Line, one of the UK's most important railways. Although there are fixed schedules for train operations, the need for maintenance regimes and the possibility of faults or accidents make it extremely difficult to predict the location of trains a few days in advance. Considering that simulations based on fixed data are inadequate in this case, a digital twin made it possible to explore different scenarios for optimizing rail services more efficiently and accurately [35].

D. End-of-life Phase

The engine remanufacturing process consists of reusing useful components from expired engines in order to manufacture new engines. This process promotes sustainable development by saving raw materials, energy consumption and financial resources. However, the need to carry out operations such as cleaning, decomposing, and evaluating expired engines, as well as the high variability of the logistics chain for these materials, pose challenges to the planning of remanufacturing processes. Looking to address these obstacles, Lu et al. [36] presented a digital twin-based approach for planning automotive engine remanufacturing operations. This approach uses historical data from traditional engine production processes as a basis for simulating operations, which gives planners a better visualization of the remanufacturing process. According to the authors, this approach allows process planning to be done more efficiently when compared to traditional planning methods [36].

Wang and Wang [37] proposed the employment of the digital twin concept to aid the recovery and recycling processes of expired electronic equipment. The approach developed by the authors involves applying digital twins as virtual avatars of the individual pieces of equipment, which reflect the state of the product throughout its entire life cycle. To do this, information from the equipment's design stage - such as geometric features, components, and any hazardous substances - is integrated into the digital twin. End users are also able to update the status of the equipment by including and changing information regarding location, repair and maintenance directly in the digital twin. After the product expires, the data accumulated throughout its life cycle is used by those responsible for recycling as a basis for decisions on the use of the expired equipment [37].

Liu et al. [38] developed a digital twin-based approach to support the planning of diesel engine machining processes by analyzing and reusing knowledge from previous procedures. The digital twin built by the authors consists of geometry information and data on the current state of the equipment. This data was then combined with the accumulated process knowledge and then filtered through a similarity calculation algorithm, which discarded the process knowledge information that did not correspond to the current operation. The result was the set of process knowledge that was a candidate for the optimization procedure. Finally, the diesel engine components were applied to a prototype module in order to verify the effectiveness of the proposed method [38].

III. Materials and Methods

In order to achieve the desired objectives, two digital twin prototypes were built: the first one consists of a digital twin of an ARCO train, based on the vehicles operated by public transport services in Portugal. The second prototype is a digital twin of a 5km section of railroad based on a real section that is part of the Portuguese railway system. Both prototypes include mobile applications which serve as dashboards for the digital twins. These applications offer a visualization of metrics relating to a series of damage indicators, which are associated with the components of the vehicles and the railroad infrastructure.

The Unity game engine [39] was chosen tool for the development of the mobile applications. Although primarily designed for video game development, game engines are extremely versatile tools that offer a wide range of programming libraries and plugins for building interactive software. In addition, many of the main game engines on the market are either free for non-commercial use or are open-source projects. Unity was specifically chosen because for its versatility, its extensive support for 3D graphics and third-party plugins, as well as for being frequently employed in other research work on the topic of digital twins [6].

The data used by the digital twins was stored in relational databases, which are accessed by the mobile applications via requests to PHP files stored on an Apache web server. We decided to use relational databases as they allow for greater organization and structuring of the data. MySQL was selected as the relational database management system as the PHP language offers native support for the software.

We also chose to run both the databases and the web server inside Docker containers. Docker, unlike hypervisors, performs software virtualization at the operating system level, using individual user space instances called containers. Each instance contains an application and its dependencies and is completely isolated from other instances and the rest of the operating system. Fig. 1 illustrates the structure of the developed system.

Partners involved in the research project in which the proposed work is framed accompanied the development of the prototypes through presentations in meetings and workshops. The final validation of the prototypes was carried out through a quality assessment survey, which was sent to the project partners to assess both the degree of suitability of the graphic interface of the mobile applications, and the potential of the prototypes to support railway operations in a real context.

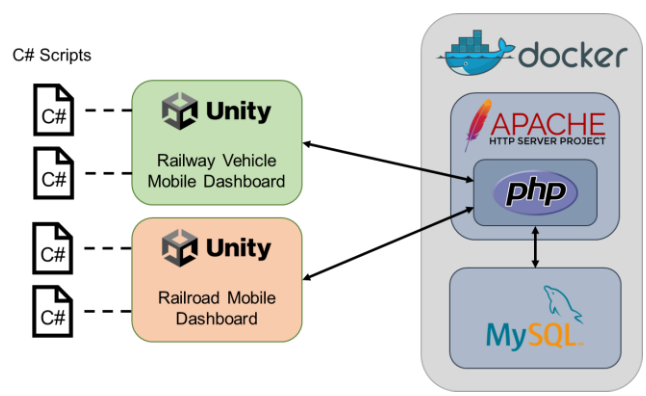

Figure 1. Structure of the developed digital twin system

IV. CONCEPT

The initial conceptual model of the digital twin was based on previous similar work in the area, as well as on meetings with workers and staff of a train maintenance workshop. In the case of the digital twin of the railway vehicle, it is important to define the most relevant components to be considered in order to maximize its benefits to decision-making.

A preliminary group of identified components consisted of the axle boxes, primary suspensions, wheelsets and their respective axis, and the traction system of the vehicle. To narrow down the scope of the study, it was later decided that only the axle boxes and wheelsets would be incorporated into the digital twin. The use case diagram of the digital twin of the vehicle is shown by Fig. 2.

For the digital twin of the railroad, it was decided to display a static image of the selected point in the railroad section alongside the aerial view of the tracks, as to associate the real location with the data in a more intuitive way. Originally, it was planned to display every point in the railroad section as a selectable icon on the aerial image. However, it was determined that showing icons for points in normal operational conditions was redundant. Consequently, only railroad points that presented some degree of damage are shown in the final prototype. The use case diagram of the digital twin of the railroad is shown by Fig. 3.

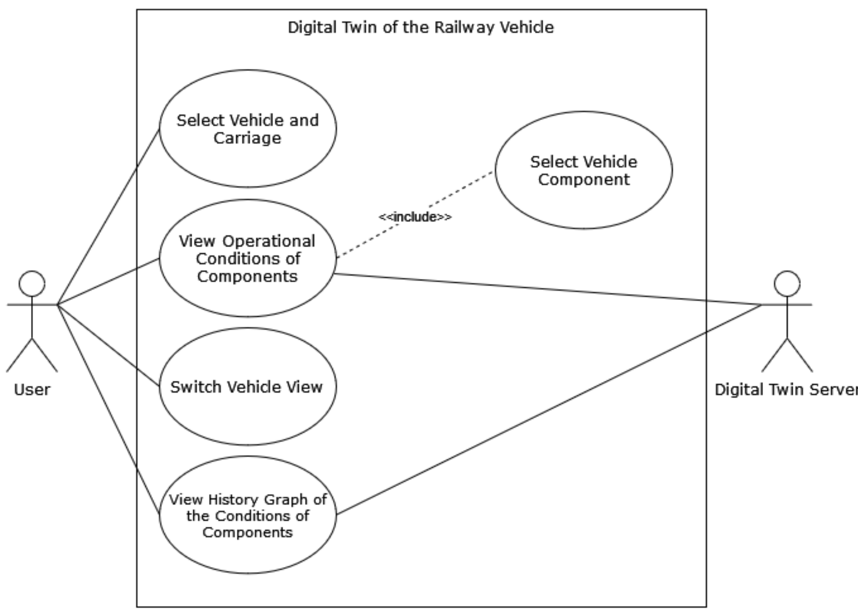

Figure 2. Use case diagram of the digital twin of the vehicle

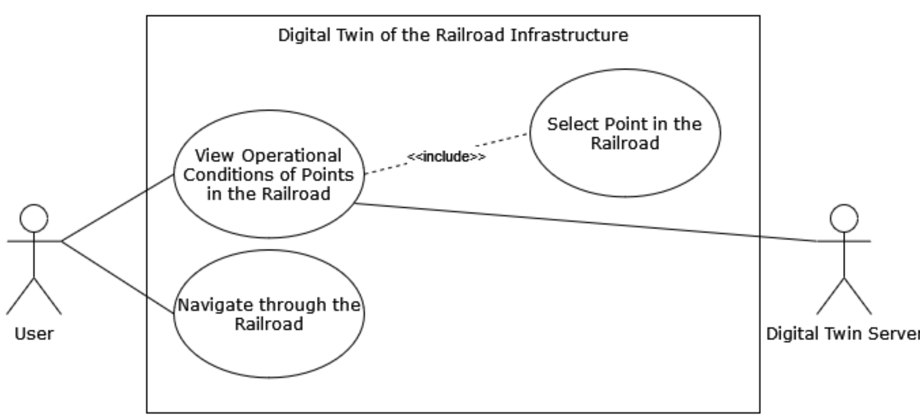

Figure 3. Use case diagram of the digital twin of the railroad

TABLE I. SUMMARY OF RELATED WORK

Related Work	Phase of Product Life Cycle	Main Goal	Findings
Haag and Anderl [15]	—	Prove the concept of the digital twin	The digital twin succesfully reflected the degree of displacement of the beam
Guo et al. [16]	Process and Product Design Phase	Assist in factory design evaluation	The proposed digital twin was able to discover hidden design flaws; the modular approach reduces the time for building a digital twin
Tao et al. [17]	Process and Product Design Phase	Improve the process of product redesigning	The digital twin enbled a more in-depth analysis of design flaws and user needs
Schleich et al. [18]	Manufacturing Phase	Enable the design of digital twins that are more geometrically faithful to reality	The system allowed for the consideration of different geometric variations throughout the life cycle of a product
Dias-Ferreira et al. [20]	Manufacturing Phase	Improve the adaptability of shop-floor operations	The system was able to outperform more tradional scheduling activities
Vachalek et al. [21]	Manufacturing Phase	Optimize production line operations	The digital twin enabled the identificiation of opportunities for optimizing resources
Tao and Zhang [22]	Manufacturing Phase	Build a conceptual model for a digital twin of a shop-floor	The basic operation of a digital twin shop-floor, as well as its components and implementation methods, were identified
Ameri and Sabbagh [23]	Manufacturing Phase	Build conceptual model for a digital twin to improve decision-making in sourcing operations	The architecture basic operation of a “digital factory” system were identified
Knapp et al. [24]	Manufacturing Phase	Improve structural correction operations in additive manufacturing	The presented framework resulted in more accurate predictions when compared to conventional calculation methods
Söderberg et al. [25]	Manufacturing Phase	Minimize costs related to faults in the geometry of complex assembly products	The functionality and methods for building a digital twin for controlling and correctinf faults were identified
Howard et al. [26]	Manufacturing Phase	Optimize production line operations of commercial greenhouses	The digital twin provided estimations of future states of the product during production, improving effiency
Zhang et al. [28]	Manufacturing Phase	Optimize individualized manufacturing operations of hollow glass	The proposed digital twin was able to simulate production line performance dn provide support for optimization
Petković et al. [29]	Manufacturing Phase	Improve safety and efficiency in human-robot cooperation in warehoused	The digital twin developed by the authors was able to provide a realistic simulation of large warehouse, which allowed accurate estimations of the intentions of human operators
Bilberg and Malik [30]	Manufacturing Phase	Optimize human-robot collaboration in assembly tasks	The digital twin was able to optimize robot trajectory and increase efficiency
Bottani et al. [31]	Manufacturing Phase	Optimize scheduling and routing of AGVs	Improved adaptability of AGVs, which, in result, increases effiecy of production processes
Zheng et al. [32]	Operation Phase	Aid innovation in product-service systems	The proposed system facilitates the identification of opportunities for innovation in product-service systems
Khajavi et al. [33]	Operation Phase	Monitor the conditions of the façade of a building	Increased energy effiency by monitoring the distribution of natural light along the building
Iglesias et al. [34]	Operation Phase	Improve JET divertor operations	Several indicators related to the effiency and reliability of the operations were improved

Jeschke and Grassmann [7]	Operation Phase	Develop a strategy to improve the prediction of future events in rail transport systems	The proposed approach provided a better understanding of the requirements and implications of the implementation of digital twins in rail transport systems
The AnyLogic Company [35]	Operation Phase	Optimize rail transport services	The digital twin enabled the simulation of different operational scenarios for optimizing services
Lu et al. [36]	End-of-Life Phase	Improve the planning of engine remanufacturing processes	Increased planning effiency in comparison to conventional methods
Wang and Wang [37]	End-of-Life Phase	Support remanufacturing operations	The approach enables the documentation of a product's life cycle, which in turn facilitates remanufacturing processes
Liu et al. [38]	End-of-Life Phase	Support the planning of engine machining processes	Increased effiency and precision in comparison to conventional methods

V. Implementation

This section details the structure of the proposed prototypes, as well as the functionalities provided by each of digital twin's mobile applications.

A. Railway Vehicle Digital Twin

The mobile dashboard of the railway vehicle digital twin provides the user with a view of the metrics about two damage indicators associated with the components of the hypothetical vehicles: an indicator of the transmissibility of damage to the axle boxes, and an indicator of the length of wheel flats. The data relating to these indicators is synthetic and was obtained through simulations of different damage scenarios.

Through the mobile application, the user is able to select the specific vehicle and railway carriage they wish to analyze. The application interface also features a computer-aided design (CAD) model that represents an abstracted view of the railway carriage, in which only the ends of the carriage (including the bogies) are displayed. This model was built using the Blender 3D modeling tool.

Vehicle and railway carriage selection is carried out through dropdown menus. It is also possible to navigate along the carriages of a vehicle using two navigation buttons. The component of the vehicle is selected directly on the vehicle's CAD model by using touch input. As this prototype only includes damage indicators for axle boxes and wheelsets, these are only component types that can be selected by the user. An indication of the level of damage in each carriage is displayed next to their respective carriage option in the carriage selection dropdown menu. This indication has four different levels, which are dependent on the severity of the damage measured on a given carriage: a green icon, which corresponds to the absence of damage or the presence of superficial irregularities only; a yellow icon, which represents the presence of slight damage; an orange icon, which points to the existence of significant damage; or a red icon, which warns of the presence of serious damage. Similarly, each of the axle boxes and wheelsets in the CAD model are displayed in one of these colors, according to the level of damage shown by the indicators with which they are associated. The user interface also features an "Exploded View" button, which can be used by the user to switch the vehicles' view between the standard view - with the vehicle properly assembled - and the exploded view - in which the carbody, bogies, axleboxes and wheelsets are displayed as if they were disassembled.

An indication of the currently selected component, as well as the most recent measurement of the damage indicator to which the component is associated, are displayed in the left corner of the top menu. In addition, the user can also view a history graph of the indicator through the "View History" option. The user can navigate along the graph by tapping the left and right sides of the screen. Lastly, the user can also activate or deactivate the top menu freely. When it is deactivated, the CAD model of the vehicle takes up the entire screen. Fig. 4 shows the main view of the vehicle's mobile dashboard. Fig. 5 presents the history graph of the damage indicator.

B. Railroad Infrastructure Digital Twin

In a similar way to the railway vehicle's digital twin, the data on the railroad's damage indicators is synthetic and was obtained through simulations of several damage scenarios.

This data refers to vertical and horizontal irregularity indicators on both the left and right rails. Each point on a 5km stretch of a railroad has values associated with these indicators. For visualization purposes on the prototype, we decided to use a 100m interval between each point. Therefore, fifty points along this stretch were taken into account.

A static image obtained using the Google Street View API was associated with each of these points. The Uniform Resource Locator (URL) addresses of the images are stored in a MySQL database, as is the data on the indicators of irregularities in the infrastructure. The railway prototype's mobile application, similarly to how the vehicle prototype works, accesses the database by requesting PHP files and displays the static image associated with the selected point on the railroad. As Unity does not offer native support for displaying web pages, the third-party plugin UniWebView was employed to perform this task.

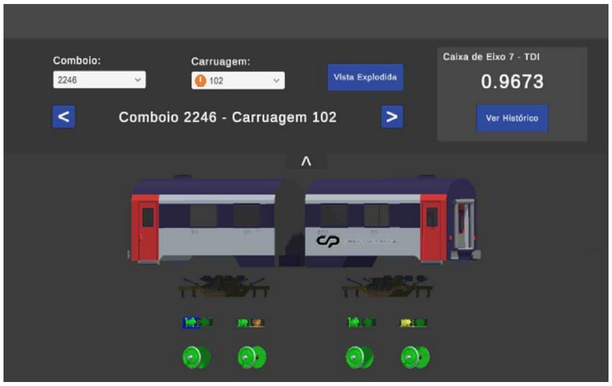

Figure 4. Main view of the railway vehicle's mobile dashboard

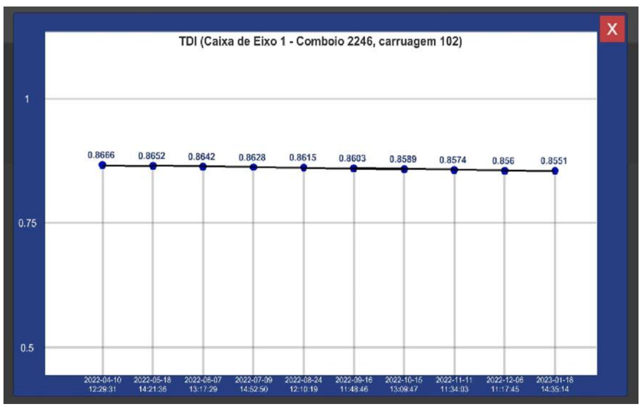

Figure 5. History graph of the damage indicator

Through the mobile dashboard, the user is able to navigate along the fifty points of the railroad and interact with a map of the railroad section. This map was obtained via Google Maps and represents an aerial view of the railroad. Similarly to the approach used in the vehicle's digital twin, alert icons with different colors are displayed on the map according to the severity of the irregularities at each point. These alerts can be yellow, light orange, dark orange or red, which correspond to light, significant, very significant and serious damage respectively. By tapping on one of these alerts, the user can find out what the maximum permitted speed is for the selected point, given the level of irregularity indicated. The user interface of the railroad's mobile dashboard is shown by Fig. 6.

VI. Evaluation

The evaluation of the proposed prototypes was done on meetings throughout the development of the work and through an online quality assessment survey sent to the Ferrovia 4.0 project partners, which served as a complement to the discussions raised at the meetings. The present paper will only discuss the evaluation of the railway vehicle prototype, as the railroad prototype will be assessed at a later date.

We decided to formulate the survey items using the Likert scale, which is a technique for measuring respondents' opinions and attitudes towards a series of statements that represent value judgments. The respondent must indicate their attitude towards each statement on an ascending scale of agreement. This scale usually has five values, which are represented by the numbers 1 to 5 [40]. This method was chosen because it is the most suitable technique for measuring partners' opinions on the quality of the mobile application's graphic interface and the potential of the prototype as a whole. In addition, the Likert scale is widely used for the assessment of software usability evaluation [41].

The survey was developed in an online format through the Google Forms tool and sent to partners via email. We opted for an online survey because it makes communication with partners easier and faster, as it allows participants to respond to the survey at any time. Alongside the survey, we also included a demonstration video of the railway vehicle's digital twin prototype, which respondents had to watch before submitting their answers. This was done to simplify the evaluation process and prevent partners from relying solely on the documentation made during the development of the project to answer the survey. A five-value Likert scale was used for the survey items, which are represented by the numbers 1 to 5 and interpreted in ascending order as "strongly disagree", "partly disagree", "neutral", "partly agree" and "strongly agree". A text field was also included for feedback, where respondents could, if they wished, describe their opinions on the prototype more clearly. It should also be noted that the survey was designed to be answered anonymously. Table II presents the statements included in the survey.

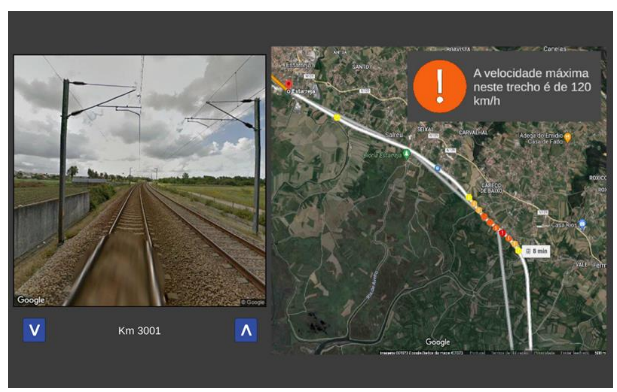

Figure 6. Railroad infrastructure's mobile dashboard. The warning text reads: "The maximum speed in this section is 120 km/h"

TABLE II. EVALUATION SURVEY STATEMENTS

#	Statement
S1	The user interface of the prototype is, in general, intuitive and easy to interact with.
S2	The data on the damage indicators is presented in a clear and understandable way.
S3	The data shown by the history graph of the damage indicators is presented in a clear and comprehensible manner.
S4	If employed in a real-world context, the proposed prototype would be useful for supporting the monitoring of the conditions of rail transport vehicles.
S5	If employed in a real-world context, the proposed prototype would be useful for supporting preventive maintenance.

VII. RESULTS AND DISCUSSION

The survey was sent to 63 partners in total, 3 of whom responded. Although the survey was answered by around 5% of the total number of people to whom it was sent, it should be reiterated that part of the validation of the prototype was carried out in meetings with the partners throughout the development of the project. In addition, it is important to note that the three respondents are experts in the field of rail transport services and played an essential role in the development of the project. The survey results are shown in Table III.

The participants' answers to items S1 to S3 indicate a generally positive opinion about the user interface of the mobile application, although some issues were raised regarding the clarity of the information and navigation, which still need to be improved. The feedback given by one of the respondents mentions that, when the application launches, the user interface displays placeholder texts in the dropdown menus and in the sections where the names of the component and the chosen variable will be displayed. These texts consist of generic words such as "Train", "Component Name" and "Variable". This could make the interface less intuitive, as it creates confusion among users. Changing the placeholder text to explanatory phrases - such as "Select variable" instead of "Variable" - could help make the user interface more intuitive.

TABLE III. EVALUATION SURVEY RESULTS

#	Respondent 1	Respondent 2	Respondent 3
S1	5	4	5
S2	5	4	4
S3	5	4	4
S4	4	5	5
S5	4	4	5

A different participant also mentioned that they would like to be able to "click" on the vehicle component they want to analyze. Although the meaning of the term "click" was not entirely clear in this case, it is understood that the respondent would like to select the vehicle component directly on the CAD model of the vehicle. This functionality already exists and it is essential for the interaction with the application, as it is the only way to select components. This means that the need for direct interaction with the CAD model of the train is not obvious to some users. The inclusion of an explanatory text - such as "Touch the train to select the component you want to analyze" - could eliminate this issue.

Despite receiving a positive evaluation from the respondents, the history graph of the damage indicators also has some points that need to be improved. It was mentioned that the way the graph is presented would not be appropriate, as continuous lines are used to illustrate variations in measurements. These lines, according to feedback from one of the respondents, do not represent real variations and, because of this, broken lines should be used instead. In fact, the value variations illustrated in the graph do not correspond to reality, which could lead to confusion among users and even result in misunderstandings in decision-making if the prototype was employed in a real-world scenario. As stated by the respondent, the use of broken lines would be the most appropriate method.

The participants also mentioned that it would be useful to include a button for viewing measurements prior to those displayed on the graph. The functionality for navigating along the graph is already implemented and is done by tapping the right and left corners of the graph's window. However, due to the lack of buttons or visual indications alerting users to the existence of this functionality, it can go unnoticed. This shortcoming could be remedied by simply adding buttons with arrows pointing to the right and left, positioned in the right and left corners of the graph, respectively.

Finally, the opinions expressed by the respondents in items 4 and 5 indicate that the proposed digital twin prototype shows potential for supporting the monitoring of railway vehicles and the implementation of preventive maintenance in a real-world context. The feedback indicates that, although some corrections are needed in relation to the user interface of the mobile application, the prototype displays the essential characteristics of a digital twin.

VIII. CONCLUSION AND FUTURE WORK

The present work was designed to explore the potential of the digital twin concept in supporting rail transport operations, particularly with regard to monitoring and preventive maintenance. This objective was achieved by developing digital twin prototypes of a railway vehicle and of a section of railroad, which provided a greater understanding of how the digital twin concept can offer a more complete and functional view of the operational conditions of railway equipment during operation. It was also possible to see how this concept supports the implementation of preventive maintenance processes for vehicles, by making it possible to visualize the evolution of damage indicators relating to the vehicle's components.

Although the proposed prototypes allow us to see the potential of the digital twin concept in the context of rail transport, there are several improvements that could be implemented. Among them is the incorporation of functionalities for sending and displaying warnings, through which users would be able to alert others to potential defects or physical irregularities in the vehicles and in the railroad infrastructure. The mobile application would allow users to submit alert notes, which would be stored in a database and associated to the corresponding equipment.

Another improvement that could be implemented is the real-time collection and display of vehicle location data using Global Positioning Systems (GPS) sensors. With this method, it would be possible to identify the exact location of a vehicle along its route, as well as allow the subsequent display of information about the schedule of the vehicles, such as the time taken to complete a given route.

The present work could also encourage interest in exploring the potential of other technologies in the Industry 4.0 paradigm - such as augmented reality and algorithms for analyzing big data and computer vision - in the context of rail transport services. Some of these technologies could be used, for example, to support the maintenance processes of train components: by using a mobile application, operators would be able to view interactive guides - generated by computer vision algorithms - and maintenance instructions in augmented reality.

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