Leveraging Digital Twins for Condition Monitoring in Railway Infrastructure

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***Abstract*—Rail transport services are emerging as a major sustainable transportation option, especially in metropolitan areas. 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 so that these services remain affordable and competitive. The digital twin, one of the core concepts of the Industry 4.0 paradigm, enables detailed, real-time monitoring of the state of a piece of equipment during its operation. For this reason, the digital twin represents an important support in ensuring sound decision making. This work seeks to explore the potential of the digital twin to support the monitoring of the conditions of railway vehicles and railroad infrastructure. First, a research was conducted on the implementations and studies of digital twins carried out in recent years. Next, two digital twin prototypes – a digital twin of a railway vehicle model, and another one 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, a mobile application that works as a dashboard of the digital between the application and the database. With the developed prototypes, it was possible to glimpse how the digital twin concept provides a deeper knowledge of the working conditions of the components of a train. Besides, the prototype also supports preventive maintenance through the analysis of the historical evolution of the data collected from these components. The results of this study also allow the identification of possible improvements and research opportunities for future work.**

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

I. INTRODUCTION

Accelerated technological and scientific progress over the last few centuries has enabled the worldwide growth of industrialization [1]. 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 [2]. The emergence of Internet of Things (IoT) technologies has led to a new industrial paradigm shift, which has been dubbed Industry 4.0 [3]. 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 [3].

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 [4]. Consequently, this concept has been adopted not only in the context of industrial production, but also in sectors such as urban planning and health [5]. 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 [6].

Rail transport represents a crucial service for a country's logistical and economic scenario, 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 [7]. 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 [7].

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 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 delineates the process of implementation of the digital twin prototypes. The employed evaluation method is explained in Section V, and its results are presented and discussed in Section VI. Lastly, Section VII 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 [8]. These same limitations were the main cause behind the lack of practical studies related to digital twins in the years following its introduction [9].

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 [9]. Fig. 1 shows the growth in the number of scientific publications related to digital twins since the introduction of this concept.

In 2011, the first scientific journal article on the concept of the digital twin was published [9]. In this article, Tuegel et al., [10] sought to apply the digital twin concept 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 [10].

In an article published in the following year, NASA formalized the 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. In this article, 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 [11].

Guo et al., [12] 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 [12].

Vachalek et al., [13] 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 [13].

Tao and Zhang [14] 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 [14].

Haag and Anderl [15] presented a proof of concept of the digital twin by employing it to a bending beam test procedure. 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].

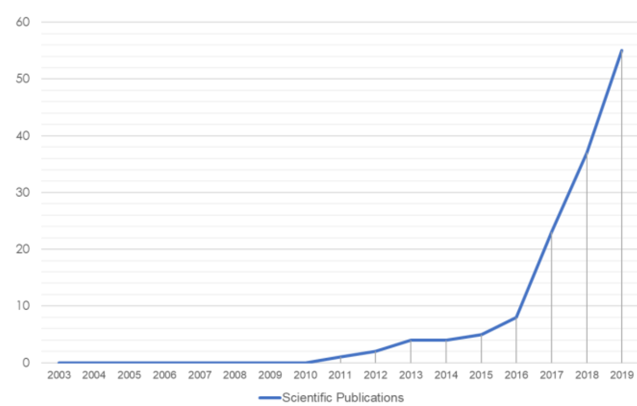

Figure 1. Approximated number of digital twin-related scientific publications per year. Adapted from [5][9]

Liu et al., [16] 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 [16].

Jeschke and Grassmann [6] 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 [6].

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 [17].

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 [18] 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 [5].

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. 2 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.

IV. 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. This model was built using the Blender 3D modeling tool.

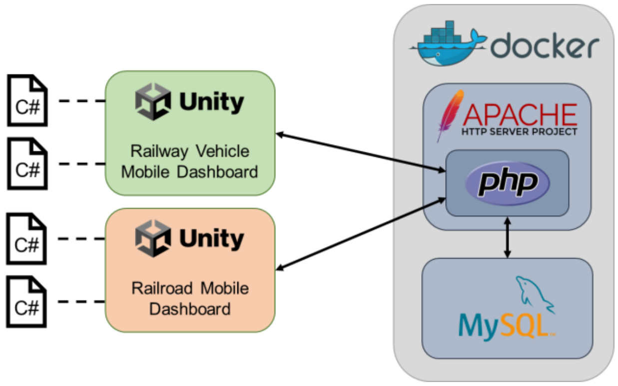

Figure 2. Structure of the developed digital twin system

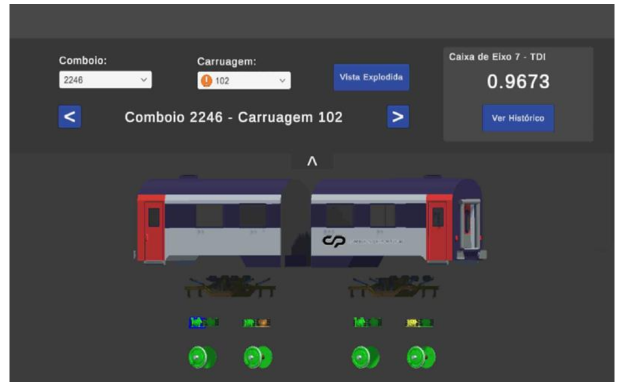

Figure 3. Main view of the railway vehicle's mobile dashboard

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. 3 shows the main view of the vehicle's mobile dashboard. Fig. 4 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.

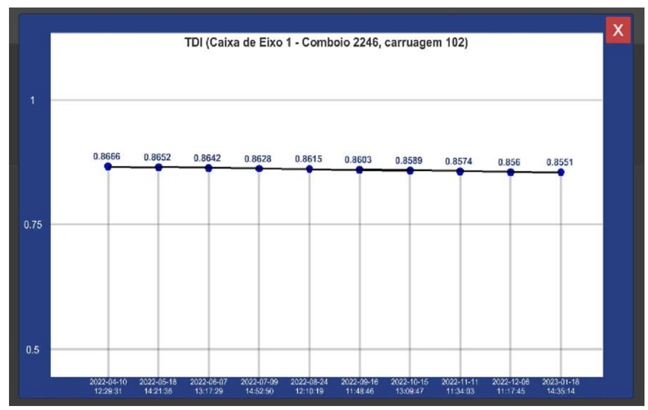

Figure 4. History graph of the damage indicator

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.

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

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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. 5.

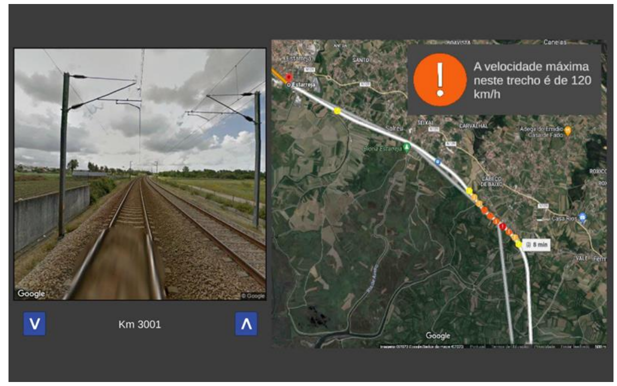

Figure 5. Railroad infrastructure's mobile dashboard

V. 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 [19]. 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 [20].

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 1 presents the statements included in the survey.

TABLE I. 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.

VI. 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.

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 II. 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.

VII. 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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