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Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

AIIT 3rd International Conference on Transport Infrastructure and Systems (TIS ROMA 2022), 15th-16th September 2022, Rome, Italy

Towards a digital twin-based intelligent decision support for road maintenance

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Abstract

The digitalisation, automation and robotisation of road inspection and maintenance technologies make it possible to collect bigger volumes of data and additional types of information about road infrastructure. Methodologies and tools to support road asset management decision-making are needed to exploit this new information, progressing towards predictive maintenance and improving different aspects of road asset management. This study presents a Digital Twin-based Decision Support Tool to assist road operators in road inspection, maintenance and upgrade. The goal of the paper is twofold. First, the architecture of the Digital Twin-based Decision Support Tool is presented, describing the main components and functionalities. The system is based on a Digital Twin (DT) that mirrors real road assets to integrate different sources of data and support the processing of low-level data into high-level information. The decision support tool (DST) is able to analyse the collected information and compute the road pavement condition to derive optimal intervention plans, addressing road section conditions, human and technical resources and other external constraints. Second, the application of the proposed architecture to road pavement maintenance is described, considering the Italian highway A24 and its connections with Rome´s ring road, managed by Strada dei Parchi SpA. Road pavement data, such as the International Roughness Index (IRI) and the Sideway Force Coefficient (SFC), are integrated into the DT to be analysed through Artificial Intelligence-clustering techniques to perform the sectioning and clustering of road sections according to their status and quality index. The paper shows the benefits derived from the integration of DT technologies with DSTs for improving processes of road maintenance.

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Peer-review under responsibility of the scientific committee of the Transport Infrastructure and Systems (TIS ROMA 2022)

Keywords: Road Asset Management; Digital Twin; Intelligent Decision Support System; AI-based Maintenance Planning; Predictive Maintenance

1. Introduction

In recent years, the Digital Twin (DT) is applied in different sectors to achieve more intelligent maintenance strategies (Errandonea et al. 2020). Indeed, the concept of DT has evolved since its first appearance in 2002 (Grieves 2002) from a simple virtual mirror of real objects to becoming the core element of decision support systems.

Vatn (2018) defined a DT as the replica of a physical asset, process or system used for control and decision making. A DT shall thus be able to provide some services, such as simulation, decision making, monitoring and control of the physical object.

In condition-based and predictive maintenance strategies, the DT model automatically obtains information on the state of the physical asset. Moreover, the highest level of integration, which is an automatic and bidirectional interaction between the physical and digital objects, is used in prescriptive maintenance strategies, where the final step of proposing a maintenance action is provided.

In recent decades, technological progress in several areas like the Internet of Things (IoT), Artificial Intelligence (AI) or Cloud computing have enabled the digitalization of the different assets, systems, and processes also in the road infrastructure sector. In particular, DTs for operation and maintenance in the road sector have been introduced for example dealing with the maintenance of tunnels (Yu et al. 2021), bridges (Lu et al. 2019, Kaewunruen et al. 2020), or road pavement (Bosurgi et al. 2020). The proposed models comprised 3D geometry of the infrastructure components as well as a comprehensive set of semantic information, including materials, functions, and relationships between the components. Existing models are usually based on Building Information Modeling (BIM) and Geographic Information Systems (GIS).

When focusing on DTs for road pavement, Bosurgi et al. (2020) identified the following functionalities: the possibility to acquire and manage the results of pavement condition surveys, graphically and in an interactive way, by means of the commonly adopted indices of geometrical, structural, and functional quality; and the possibility to represent the type and gravity of the distress detected in each section, graphically and in a way easy to be modified in real-time. Oreto et al. (2022) add an additional step by introducing Life cycle assessment (LCA) and the bidirectional exchange of information between the BIM platform and the LCA tool. Yu et al. (2020) combined a DT technology based on BIM, with machine learning techniques, for the accurate and timely prediction of pavement performance.

Therefore, in the literature, it is agreed that DT data and information may represent the input of a decisional process aiming to optimize the final maintenance activities. In particular, DTs can provide a range of functionalities for maintenance decision support in the road sector.

In most traditional planning procedures, however, DT technology is not yet exploited to improve multi-objective optimisation techniques, which consider aspects such as road conditions, maintenance costs, ride quality conditions, environmental impact, etc. (Torres-Machi et al. 2018, Augeri et al.2019, Donev et al. 2020, Leilei Chen et al. 2021, Chen et al. 2021).

Therefore, DT-based decision support frameworks for prioritising maintenance interventions and optimizing maintenance planning, deserve a deeper analysis, especially studying the link between the DT mirroring function and the decision support functionality to strengthen and optimize traditional planning procedures.

The present study aims at progressing the integration of DT and Decision Support Systems techniques, presenting a framework for linking the DT architecture and the DST.

The main contributions are:

- Present an architecture for the integration of DT and Decision Support functionalities.
- Combine data from legacy systems for road inspection with additional data from new inspection technologies.
- Exploiting AI to extract knowledge from the available data.
- Improve traditional asset management systems with infrastructure condition analysis and asset management optimization functionalities.
- Simplify the operator´s decision-making process, thanks to the automation of the analysis and elaboration of the available data and the evaluation of key performance indicators (KPIs).

2. Digital twin-based DST architecture

Fig.1 shows the proposed general architecture of the DT-based DST. This architecture is organized according to four different layers: the physical layer, the database layer, the server layer and the application layer.

The physical layer aims to collect data during the whole lifecycle of the road, from design, and construction, to operation and maintenance. Data along the roads are collected using Lidar Scanner, Red Green Blue (RGB) camera, Near Infrared (NIR) camera, Unmanned Aerial Vehicle (UAV), GPS devices, etc. Road assets include traffic signs, traffic lighting, control and communication systems (CCTV, speed camera, traffic signal and electronic sign), fences and sound barriers and road restraint systems, road markings, road surface structures, etc.

In the database layer, design documents, construction records, periodical survey reports, maintenance records, and legacy data are stored in the asset management database. Meanwhile, 3D models created based on point cloud data and RGB images, which are collected using the Lidar scanner and RGB camera respectively, are stored in the Internet of Things (IoT) database or Cloud Platform (e.g. Microsoft Azure or Amazon AWS). Moreover, these data are visualized thanks to Machine Learning (ML) algorithms and computer vision algorithms which are applied to segment the point cloud to identify the elements/ objects of roads for 3D reconstruction.

In the server layer, the webserver extracts historical data from the asset management database and geometric data and semantic data from BIM models. These extracted data are analyzed by the decision support tools to find patterns using ML and AI algorithms, providing the decision-making functions for road maintenance.
In particular, the intelligent decision support tools include infrastructure condition analysis and asset management plan optimization for road infrastructure maintenance.

Meanwhile, the webserver layer can visualize BIM models and keep these models updated.

The workflow for the DST includes (a) processing data from the DT, (b) assessing infrastructure degradation (and failure) risk, (c) analysing and predicting infrastructure conditions, and (d) suggesting maintenance plans. The DST takes into account different sources of uncertainty, such as asset status prediction and other real operational environment factors. The DST performs using the captured data (e.g. legacy data, geometric data, semantic data, historical maintenance records, condition data, etc.) from the DT and processes it with AI techniques to predict the future condition and set the predictive maintenance planning.
More in detail, the DST processes data from miscellaneous sources, including (i) data from already existing systems, (ii) data from digital inspection systems, e.g. UAV and terrestrial inspection vehicles and (iii) information coming from maintenance activities and the execution of asset management tasks.

The *infrastructure condition analysis* module represents a methodology to define and predict road asset states. The methodology is based on AI techniques and segmentation methods focusing on three main stages:

- Analysis and prediction of infrastructure condition.
- Road sectioning according to condition state.
- Evaluation of asset degradation risk, based on severity levels and criticality.

This module assigns to road sections a related degradation risk in order to be used in the optimisation of the asset management plan.

The *asset management plan optimisation* module has the objective of developing a maintenance planning functionality to improve the availability and reliability of the infrastructure while maintaining the levels of service and the safety of the road infrastructure. It also enables a higher level of automation in decision-making through advanced optimisation techniques. The maintenance plans adapt to short, medium and long-term planning procedures, considering emergency, routine and extraordinary intervention levels and different road assets. This module computes (a) a prioritisation of interventions, considering the previous results from the infrastructure condition analysis, as well as (b) the road sections in terms of safety and impact on traffic. Based on this information, the DST uses advanced optimisation techniques, maintenance plan simulations and comparison via what-if scenarios to optimise asset conditions given monetary and resource constraints.

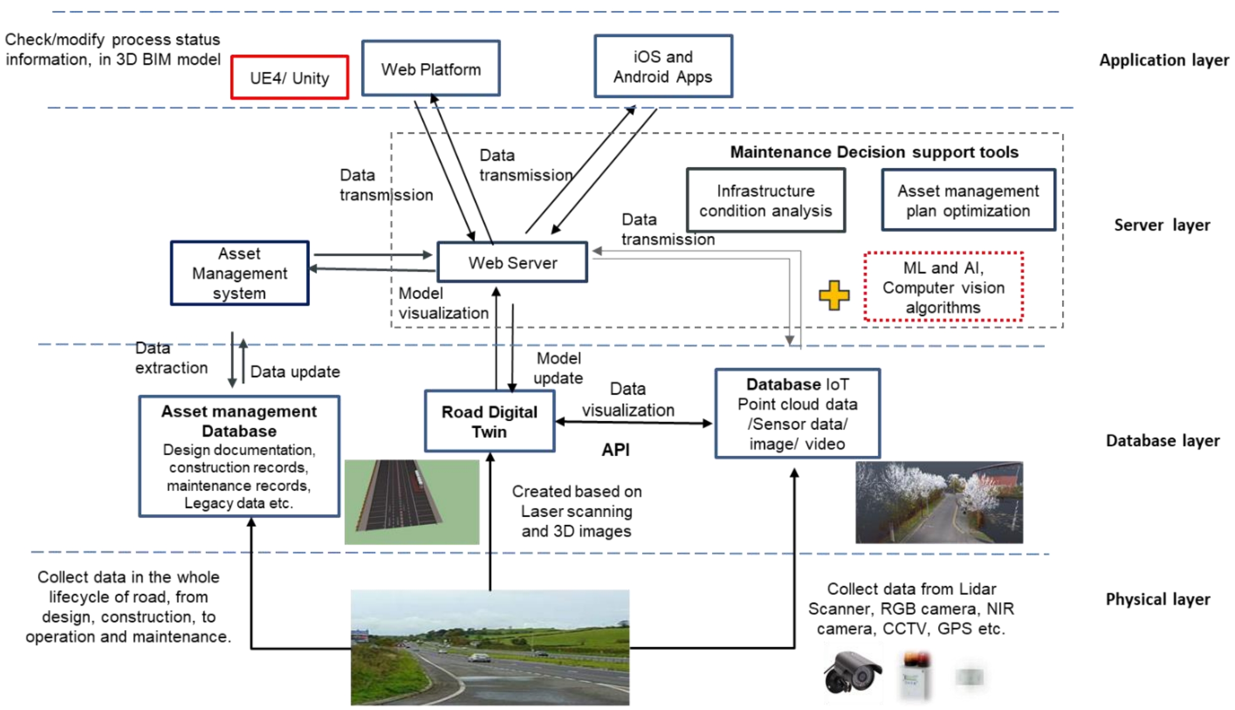

Figure 1: Architecture of the Digital twin-based Decision Support system

Finally, in the application layer, The Unreal Engine 4 (UE4) and Unity platforms can be utilized for 3D model visualization and information interoperability. To ensure user-friendly and convenient remote control, iOS and Android apps are developed.

This paper considers the application of the proposed architecture to road pavement, focusing on the pavement condition analysis. The next section describes the application of the proposed architecture to a specific case study.

3. Case study: Road pavement maintenance on the A24 Italian motorway

The case study considers the A24 motorway and the connection to Rome's ring road, part of the Scandinavian-Mediterranean Connecting Europe Facility (CEF) corridor in Italy, managed by Strada dei Parchi SpA (SDP).
As depicted in Fig. 2, A24 is a highway connecting the East and West sides of the Italian peninsula, from Rome to the Adriatic Sea with a length of more than 500 km. It includes 116 km of viaducts (21% of total highway length) and 70 km of tunnels (13% of total length).
The case study is focused on the application of the proposed architecture to road pavement maintenance.
Fig. 3 reports the Business Process Modeling Notation (BPMN) diagram related to the process for applying the architecture to the evaluation of road pavement conditions.
Regarding the inspection and the data collection, the following type of surveys are performed:

- A *"High Performance" survey* is executed once a year along with the entire network, using diagnostic vehicles to evaluate road pavement parameters (SFC and IRI) on the whole infrastructure and road marking reflectivity.
- A *test of mechanical properties* is executed on selected road sections, with a variable frequency. SDP evaluates mechanical properties through the falling weight deflectometer (FWD) test to measure the deflection of the road pavement under the application of a known load from a predetermined height.

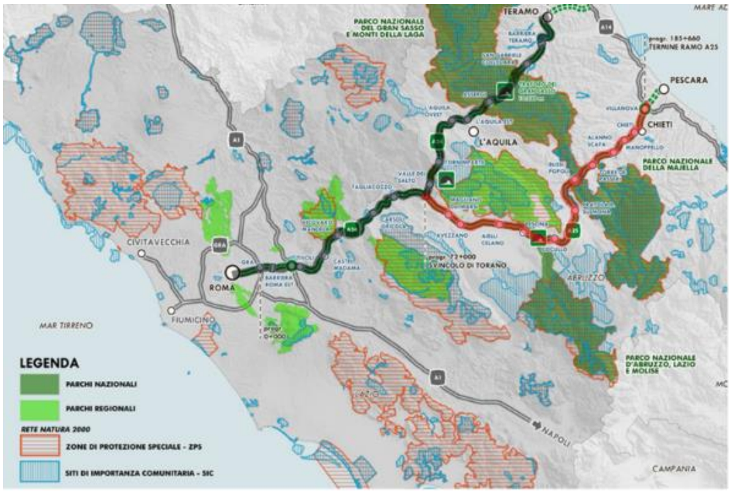

Figure 2: Italian A24 motorway

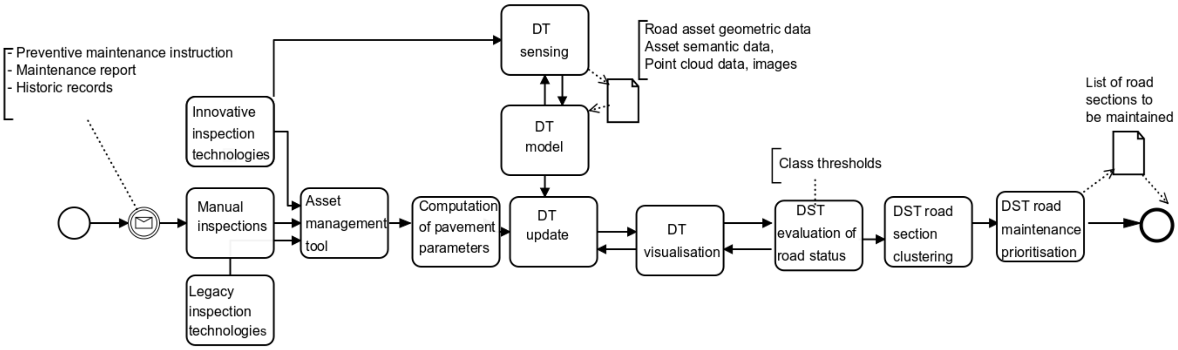

Figure 3: Process to apply the architecture to the road pavement

- *Daily inspections and periodical reports* are performed according to the internal procedures "Zero Defect Manual" by the staff of CSA (Centro Sicurezza Autostradale) to detect pavement defects. In particular, the procedure establishes that minor defects are immediately corrected, while significant defects are included in the maintenance plan according to the inspection report.
- *Inspection using new technologies* is performed in which an innovative sensor combination, integrating with a Lidar scanner (KAARTA Stencil 2), RGB Camera, NIR Camera and Husky A200 is developed. The designed inspection sensors are mounted on an inspection vehicle (a car) with a very large point density and relatively data collection.

The main types of data and parameters, obtained from these surveys and considered in the case study, are reported in Table 1. These data and parameters can be described as follows:

- The *Sideway Force Coefficient* (SFC) characterizes the skid resistance of the surface in the transversal direction of a road, expressed as the ratio between the force (N) perpendicular to the rotation of a wheel and the normal reaction (R) of the road surface under the wheel load.
- The *International Roughness Index* (IRI*)* parameter indicates the road roughness defined as the variation in altitude related to a flat surface. This roughness induces vibrations in vehicles affecting driving comfort, operating costs and user safety. The measurements are made with a laser profilometer using the American standard ASTM E1926-08 as a reference.

Table 1. Description of road pavement data considered in the case study

Data type	Data structure	Data collection
SFC	Kilometric points, SFC value percent. Speed, External temperature and pavement temperature. Data and time	SCRIM machine
IRI	Kilometric point. IRI values on the left and right sides in percentage. Data and time	laser profilometer
Defects images/report	Kilometric point. Data and time.	Manual daily inspections
FWD data	Kilometric point. Data and time. deflection measurements (μm) and elastic modules.	dynamic deflectometer
RGB images	Index of R, G and B, timestamp and geo-location reference	RGB camera
Point cloud data	x, y, and z coordinates. GPS timestamps	Lider Scanner

- *FWD data* consist of deflection measurements (μm) and elastic modules.
- *Defects images/reports* which are collected from daily inspections performed manually by maintenance operators.
- *Data from innovative terrestrial inspection vehicles* which include lidar *point cloud data* from KAARTA Stencil 2 and *RGB images*. Images and Lidar scanning data are pre-processed to be consistent in space and time. In other words, these data are synchronized and calibrated for processing.
  RGB images include the index of R, G and B, as well as the time stamp and geo-location reference.
  The initial point clouds are large collections of 3D elevation points, which include x, y, and z, along with additional attributes such as GPS timestamps.

The DT is developed based on the architecture described in Fig. 1 and the process depicted in Fig.3. The digital data is collected from the roads (physical world), including images, and sensing data. All of the road pavement assets are identified and classified into different categories. Their attributes and relationship are represented in Unified Modeling Language (UML) data models. The geometric information is converted to a digital model. The semantic information is mapped into the corresponding 2-3D objects to enrich the DTs. As information increases and continuous data is being collected, the DT is updated as well. After that, computer vision-based algorithms process captured data for semantic segmentation and classification. The rich information from the DT is then visualised to support road operators in decision making.
In order to assess road pavement status and prioritise maintenance interventions, an AI clustering technique (K-means) is applied to group road sections in classes according to their condition. An example of the results is shown in Fig.4.

The expected results and considered KPIs are reported in Table 2.

The volume of major intervention will be reduced by 10% due to better maintenance planning, while maintenance costs will be reduced by 12%, using the advanced system for the evaluation of road pavement conditions and avoiding corrective interventions. The availability of road infrastructures will increase by 15% due to a reduced number of traffic disruptions caused by interventions.
A reduction of 20% of the Road Hazard Index is expected which is expressed according to the following equation:

$$RHI = \frac{N\,(10^8)}{365\,(MDT)\,L} \tag{1}$$

where:

- N is the number of accidents with fatalities.
- MDT is the mean daily traffic travelling in the considered road section.
- L is the length of the considered road section.

Figure 4: Road sections status

Table 2. KPIs values

KPI ID	Description	Value
KPI 1	The volume of major intervention actions.	-10%
KPI 2	Road infrastructure maintenance costs.	-12%
KPI 3	Road Hazard Index.	-20%
KPI 4	Availability of the network. Impact of a reduced number of traffic disruptions due to interventions.	15%

4. Conclusion

This paper presents the architecture of a Digital Twin-based Decision Support System for road maintenance, showing its application to the evaluation of road pavement conditions. The study shows the expected benefits derived from the integration of DT technologies with decision support tools, providing not just the virtual replica of the physical asset but also additional functionalities that make the system valuable support to the decision-making process in road maintenance. A reduction of 10% in the volume of major interventions and 12% in maintenance costs is expected. Moreover, benefits can be achieved in terms of reduction of the Road Hazard Index and an increase in road network availability, which leads to advantages also for the final users.

The proposed system is to be integrated into an intelligent platform under development within the EU-funded OMICRON project along with other technologies, including terrestrial and aerial inspection technologies, robotic technologies and a V2X communication system. The presented architecture represents the core of OMICRON's Intelligent Road Asset Management Platform, which will be implemented within the final demonstrator of the OMICRON project. Currently, the architecture reaches the Technology Readiness Level 3 but it will be developed and enriched to reach the Technology Readiness Level (TRL) 7 and implemented in practical project use cases. In addition, the platform feasibility will be evaluated to prove its robustness. So, the present research limitations, that is, the current low TRL and the lack of evaluation of platform feasibility will be overcome.

Finally, further developments will consist of developing the optimisation and planning functionalities and testing the proposed decision support system considering different road assets.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 955269.

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