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Revolutionizing Maintenance Management In Transportation: The Role Of Digital Twins And Test Site Preparation

Klaudia Winiarska[a], Sylwia Werbinska-Wojciechowska[a], Jan Stoker[b], Robert Giel[a]

[a]*Wroclaw University of Science and Technology, Wroclaw, Poland*
[b]*Rijkswaterstaat, Ultrecht, Netherlands*

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Transportation systems form the backbone of modern societies, enabling the movement of goods and people efficiently. However, ensuring efficient and effective transportation infrastructure operation requires meticulous maintenance management. Traditional approaches often struggle to keep pace with the demands of complex systems and evolving technologies. This work explores the transformative potential of digital twins and advanced test site preparation in revolutionizing maintenance management within transportation sectors (Raposo et al. 2018).

Digital twins (DTs) represent virtual replicas of physical assets, processes, or systems (Liu et al. 2021). They emulate vehicles, infrastructure, and entire networks in transportation (also internal transportation), offering a comprehensive digital representation. DTs provide invaluable insights into asset performance, condition monitoring, and predictive maintenance by integrating real-time data from sensors, IoT devices, and historical records. They facilitate proactive decision-making, optimize resource allocation, and minimize downtime, enhancing operational efficiency and safety (Rossmann and Hertweck 2022; Liu, et al. 2021; Kosacka-Olejnik, et al. 2021).

Following a literature analysis, the use of DT is proposed as a tool to support operations and maintenance management in the materials handling sector. The implementation of DT of the material handling system is based on accurate data on its operation. Within the scope of the dissertation, DT will be used both to monitor the use of technical equipment and also for maintenance management. In addition, due to the extensive period of collecting the necessary data to create the DT, it was decided to use a transport system test site. Therefore, designing and constructing a test site is essential to provide the comprehensive information necessary to develop a DT. Using this test site will enable the accelerated initiation and simulation of faults in system components and the introduction of anomalies, which in a real environment would have to wait several years to observe.

As in a real environment, the test site for the material handling system will be comprehensively equipped with means of transport (conveyor belt, forklifts, mobile robots, overhead crane) and control and monitoring systems. The infrastructure and environmental conditions will also be analyzed to ensure realistic test conditions.

The transport system should be equipped with various devices and sensors to measure and monitor critical parameters accurately. The process of selecting measurement equipment and technologies and DT development involves five key stages (Figure 1).

According to Figure 1, the virtual part of the digital twin framework should include at least user, digital twin, and device communication domains. Effective deployment of digital twins in transportation maintenance management requires rigorous test site preparation. Test sites serve as controlled environments for validating digital twin functionalities, assessing performance under various conditions, and refining algorithms. Key considerations in test site preparation include selecting representative assets or subsystems, instrumenting them with sensors and monitoring equipment, and establishing data collection protocols. Moreover, test sites should replicate real-world operating conditions, including environmental factors, operational loads, and failure scenarios, to ensure the accuracy and reliability of digital twin models.

In this context, the DT can support users (e.g., maintenance managers and engineers) by processing and providing data to monitor, troubleshoot, diagnose, and predict faults and failures in transportation facilities. In addition, a DT can generate actionable recommendations for the users or deliver commands to control the equipment. The DT framework for maintenance management activities is presented in Figure 2.

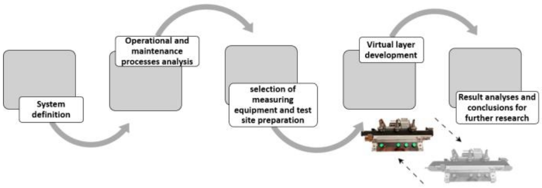

Fig. 1. Process for the selection of measuring devices and DT development in the investigated internal transport system.

In Figure 2, Level I monitors real-world objects using sensors to diagnose their operational state. The focus is on internal transportation systems, ensuring the efficiency of logistic processes and considering material flow and environmental conditions. The next level, the device communication entity, facilitates communication between physical elements and their digital twins or the user entity. It consists of data collection and device control sub-entities, enabling automated or semi-automated operation modes. Level III, the Digital Twin entity, creates digital representations of observed elements based on collected data and includes a data cache. The user entity interprets results, facilitating monitoring, analysis, decision support, and reporting. The Digital Twin framework also contains a cross-system entity for data assurance, translation, and security support, enabling communication with internal informatics systems.

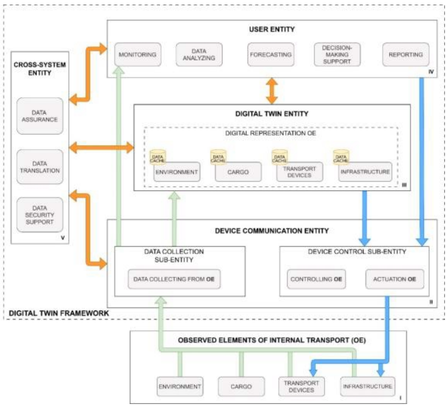

Fig. 2. DT concept for internal transportation system maintenance management.

Implementing DTs in transportation maintenance management poses several challenges despite their promise. Integration with legacy systems, data interoperability issues, and cybersecurity concerns may hinder adoption. Additionally, the complexity of transportation systems and the sheer volume of data generated present scalability challenges. However, overcoming these hurdles offers significant opportunities for innovation and improvement. Collaborative efforts between industry stakeholders, government agencies, and research institutions are crucial to address these challenges and unlock the full potential of digital twins in transportation maintenance management.

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