Developing a Lifecycle Infrastructure Digital Twin

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Abstract

The concept of Digital Twins gradually gains much attention in the infrastructure sector, since it is a tool that can enhance several lifecycle activities of a construction project, by mimicking the behaviour of the physical asset. However, there is little consistency in how data is structured throughout lifecycle phases. In particular, it appears that asphalt failure data representation is rather immature. This paper reports ongoing work on a project whose main aim is to systematically link asphalt failure modes with their influential properties and forms of visualisation. The aim is to provide a discussion mirror for Digital Twin experts in how best to visualise asphalt failure modes and in so doing, provide better insights in failure behaviour and prediction, and thus better optimise maintenance planning.

1. Introduction

The concept of Digital Twin (DT) is gradually gaining ground and being adopted by several sectors, including construction. This concept introduces a dynamic modelling practice where the virtual model updates its state to mimic the behaviour of the physical asset via the assistance of sensors and the Internet of Things (IoT). According to a generally adopted definition, DT is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product that uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin [1].

Focusing on the construction sector, and mainly on infrastructure, several use cases and application frameworks have been proposed for the application of DT. Structural Health Monitoring (SHM), equipment, material and worker location tracing, damage detection and emergency response operations are some examples of the DT applications in the construction sector [2], [3], [4], [5]. However, this research argues that little attention has been paid to the development of DT for road assets. To address that, this research aims to improve the modelling potential of roads by offering a framework to classify, incorporate and visualise asphalt defect information in the virtual model.

The remainder of the report is structured as follows. Firstly, a literature review summarizes the existing efforts to apply DT in the infrastructure sector and classifies them in different lifecycle phases. Following, the achieved state-of-art regarding DT applications is assessed based on a typical Technology Readiness Level (TRL) framework [6]. A SWOT analysis in the next part aims to assess the situation and identify critical points to be considered for defining the future directions and next steps. Following, the research proposal is described alongside the way it is expected to contribute to the desired direction. Finally, a discussion addresses the limitations of the study as well as the expected input from the participation in the conference, followed by a summarizing conclusion.

2. DT in the infrastructure sector

There are many ways DT can assist the lifecycle of an infrastructure asset. Several applications of DT in the construction sector have been reviewed in literature [2], [3] & [4]. Those, relevant to infrastructure assets are summarized, classified according to the lifecycle phase in which they are applied, and presented in this section. Firstly, Table I briefly summarizes the applications found in literature, and following, the different cases are further elaborated for each lifecycle phase.

2.1. Design

A DT implies the existence of interrelated physical and virtual counterparts. During the design phase, the physical counterpart is not present yet. However, a DT can be made for the environment, the surroundings and related existing projects to assist conceptual, preliminary and detailed design [3]. Also, it has been proposed that DTs from previous generations of projects can be used during the design phase to retrofit the design of the new generations [4]. It follows that for road construction, this practice is relevant for road widening, reconstruction and expansion projects. Furthermore, the application of DT in the design phase provides designers with a complete digital footprint of the project and assists informed decisions about material selection, energy management, procurement, supplier selection, energy analysis, sustainability and ultimately the feasibility of the project itself [4].

Table I. Summary of DT applications for infrastructure assets

Design	Construction
D1. Conceptual preliminary & detailed DT-driven design **D2.** Retrofit design **D3.** Reconstruction and expansion **D4.** Decision making **D4.a.** Material selection **D4.b.** Energy analysis **D4.c.** Sustainability analysis **D4.d.** Procurement **D4.e.** Supplier selection **D5.f.** Feasibility analysis	**C1.** Progress monitoring **C2.** Tracking changes and updating models **C3.** Quality controls **C4.** Timely realignment actions **C5.** Safety monitoring **C5.a.** Trace proximity between worker and hazards **C5.b.** Machinery monitoring **C5.c**. Ergonomics **C6.** Training environments **C7.** Material monitoring **C7.a.** Dynamic tracing of on-site demand and supply status
O&M	**Demolition**
OM1. Logistics processes and energy simulations **OM2.** Sustainable management of utility tunnels **OM3.** Inspection and defect detection **OM4.** Structural Health Monitoring of bridges **OM5.** Enrichment of Industry Foundation Classes (IFC) for damage components	**DM1.** Exploitation of knowledge from predecessor to next generation

2.2. Construction

DT can be applied in several contexts during the construction phase. Laser scanning and photogrammetry applications offer as-built models which, when compared to the as-designed ones, assist progress and quality controls. Regarding progress monitoring, DT offers a bidirectional communication that allows tracking changes and updating models, exchanging information between the design office and the job site and documenting the as-built status in real-time [7]. As far as quality monitoring is concerned, DT's accuracy plays an important role in comparing the actual quality with target quality and enables timely realignment actions [3]. Also, safety issues can be addressed during the construction phase. Technologies such as GPS and tag identification systems for tracing pedestrian workers and hazardous material are being used to address potentially fatal workplace accidents related to the close proximity between them [3]. An application example in the infrastructure field proposes the use of Ultra-Wideband system movement trajectories combined with 3D laser-scanned point clouds in field trials, to monitor the close proximity between heavy construction equipment and workers [8]. Apart from fatal accidents, working ergonomics are addressed with the use of wearable sensors, machine learning and virtual reality to track body kinematics to develop a cyber-physical postural training environment, where workers can practice performing work with reduced ergonomic risks [9]. Finally, regarding the applications of DT in the construction sector, DT enhances effective stakeholder management by providing stakeholders with ample information about the project [10].

2.3. Operation & Maintenance

In the Operation & Maintenance (O&M) phase, DT is a valuable tool for assessing the condition of an asset. By obtaining geometric information, the DT provides a visual and efficient way for inspection and defect detection by processing forms of data, such as point clouds, digital images, thermal images and sensor data from laser scanners, cameras, thermal imaging devices, sensors and other devices [3]. Regarding the infrastructure sector, DT has mainly been applied for defect detection and Structural Health Monitoring (SHM) of brides. Visualizing Light Detection and Ranging (LiDAR) data in a Virtual

Environment application has been proposed to assist the inspection of bridges [11]. Furthermore, BIM has been employed to organize and visualise large amounts of sensor data for long term SHM of a long-span bridge [10]. The use of BIM has also been suggested for integrating damage components stemming from point cloud-based detection [5]. The step taken forward in this case study concerns the enrichment of the as-built Industry Foundation Classes (IFC) model to incorporate damage information.

Regarding road assets, it has been proposed to employ DT in different levels of detail. More specifically, visualizing the in-situ road geometry in different resolutions has been achieved by implementing macro-twinning and micro-twinning [13], [14]. Macro-twinning refers to utilization of LIDAR and Unmanned Aerial Vehicles (UAVs) to quantify road geometry over large areas, whereas micro-twinning concerns the representation of surface texture by utilizing photogrammetric reconstruction techniques. Even if the proposed application achieved representing information in different levels of abstraction, the visualization of the road condition still occurs through a mesh representation, missing the annotation of a 3D object with properties.

2.4. *Demolition*

It has been acknowledged that during the demolition phase, a DT may assist by offering information about the recovery of secondary raw materials, material storage, recycling, and circularity options, however, no case study was identified to have applied DT technology in the demolition and recovery phase of a construction project [4]. However, several cases have been reviewed where 3D laser scans have been used for retrofitting, reconstruction, and renovation activities [3]. These cases were though focused on the building sector offering no insight into infrastructure assets.

Overall, it can be observed that the applications of DT in the Infrastructure sector vary in different lifecycle phases and are intensely characterized by fragmentation. The proposed applications range from frameworks and proofs of concept to fully implemented solutions. Additionally, different lifecycle phases receive different attention concerning the case studies. Most attention is given to the O&M phase; hence significant DT achievements have been identified in that phase. Furthermore, even if during the design phase there is no physical counterpart yet, it seems that a remarkable amount of information is generated during that phase, therefore effort is being put into creating DT from the early design of the projects already. Finally, the potential of DT's assistance during the demolition phase has not been explored yet.

3. State-of-the-art assessment

3.1. Technology Readiness Level

While the previous chapter explicated the many ways that DT can assist the lifecycle of an infrastructure asset, this chapter explores the functional maturity of DT applications from a user readiness perspective. The maturity of the DT applications in the infrastructure sector is being assessed using a Technology Readiness Level (TRL) scale. The purpose of this tool is to assist management in making decisions concerning the development and transitioning of technologies. The TRL scale consists of 9 levels, the definitions of which can be seen in Figure 1.

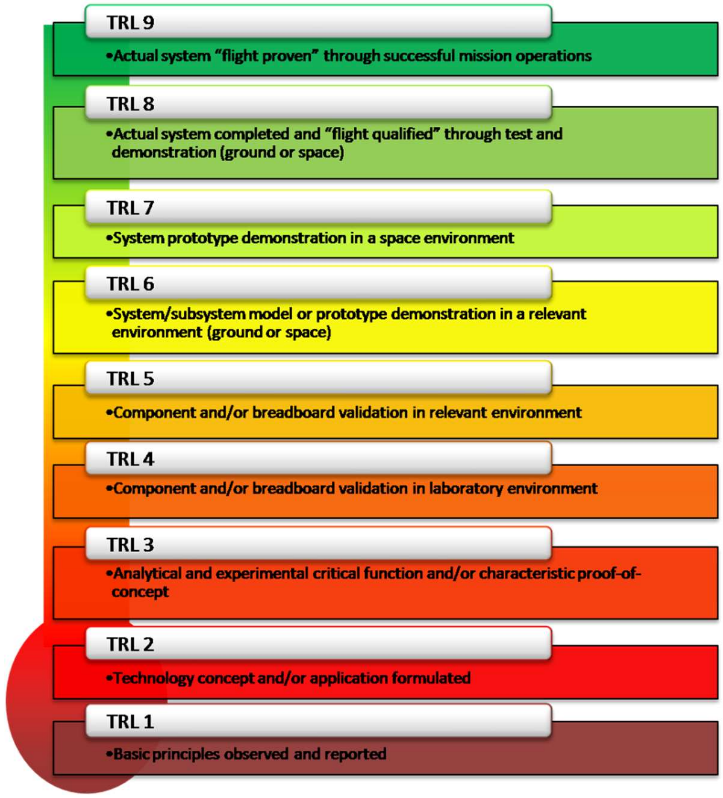

Figure 1: Technology Readiness Levels and definitions (Retrieved by [6])

Each level of the scale is characterized by a set of features that describe the extent to which the technology has been adapted and applied. Shortly explained, level 1 denotes the presence of theoretical research supporting an idea, level 2 introduces an initial investigation of practical issues while level 3 denotes the existence of a structured theoretical framework. The step taken forward in level 4 is the proof of concept, whereas a prototype is introduced at level 5. At level 6 of the scale, the prototype is implemented on full-scale realistic problems. At level 8 a final, fully integrated, verified and validated product is present, supported by standardization documentation. Last, at level 9 the final product operates in an actual mission, assisted by sustaining software engineering support. It should be clarified at this point that the notions of "system", "engineering unit" and "final product" of the scale refer to the whole plot of the physical and virtual counterpart as well as the connecting information layer, as implied by the definition of DT.

The applications found in the literature are assessed based on the level of their adaption and linked with the corresponding levels of the scale. Table II summarizes the characteristics of each level and classifies the DT applications to their respective levels.

Table II. Description of Technology Readiness Levels and classification of lifecycle applications

Level	Description	Application
9	The final product successfully operates in actual mission Fully integrated with operational hardware/software systems All documentation completed Sustaining engineering support in place	
8	Final product in its final configuration successfully operates in intended environment Fully integrated with operational hardware and software systems. User, training & maintenance documentation complete Verification and Validation completed	
7	High fidelity engineering unit operates in actual environment Integration with collateral and ancillary systems Limited documentation available	
6	High fidelity system prototype implemented on full-scale realistic problems Partially integrated with existing systems Limited documentation available Engineering feasibility fully demonstrated	
5	A medium fidelity system prototype operates and demonstrates overall performance Prototyping implementations in the target environment	D4.a, C1, C3, C6, OM3, OM4, OM5
4	A low-fidelity system operates and demonstrates basic functionality Proof of concept (demonstration, model, simulation)	D4.b, C5.a, C5.b, C5.c, OM1
3	Analytical studies put the technology put in an appropriate context	D1, D2, D3, D5.f, D4.c, D4.d, D4.e, C2, C4, C7.a, OM2
2	Speculative practical applications No experimental proof or detailed analysis	
1	Scientific knowledge generated	DM1

The reviewed DT application cases vary in the extent of their development. More specifically, some of the proposed applications were presented in forms of conceptual frameworks and methodologies accompanied by simple proofs of concept. These applications have been classified at level 3 of the TRL scale. The applications that have employed a standalone experimental pilot have been classified to level 4 of the scale. Level 5 includes the applications that have been applied at real projects as a decision-making tool. Finally, there is one case that has been theoretically reviewed for its potential use, but no structured framework has been presented. Therefore, this case has been assigned to the lowest level of the scale.

It can be observed that the majority of the Design related DT applications are proposed at a structured theoretical level, namely level 3. The applications regarding the Construction phase present demonstrated proofs of concept, but also implemented prototypes, assigning them to levels 4 and 5 of the scale respectively. Most of the O&M applications are assigned to the highest reached level 5. This observation is aligned with the fact that most of the DT applications concern that phase, hence achieving a relatively high maturity level is justified. Finally, the lowest level includes the Demolition phase, which, as stated also before, has not adequately been addressed.

Overall, the highest level achieved among the different applications is level 5, meaning that DT in the infrastructure sector has achieved medium-fidelity prototype applications. The system's fidelity in the context of infrastructure DT means the extent to which raw data is transformed into meaningful and insightful information, stored and visualized accordingly to enhance its usability. A medium fidelity at the system level means that the sensory data from the physical counterpart is not stored and presented in the virtual model in an explicit and comprehensive way, understood from both humans and computers. Raw measurements and document files are stored in piles, disconnected from the virtual objects they are related to. Hence, the potential of the virtual modelling tools such as 3D object libraries and 4D modelling, is not exploited to assist data usability. Reaching the next level of the scale, namely level 6, would mean updating the system's fidelity by means of meaningful storage and representation of information. Practically this could be addressed by structuring the virtual models in accordance to the sensory data accommodation needs. This way the virtual counterparts of DT will be able to host the information from the physical asset in a way that is easily interpreted by humans and computers. Furthermore, apart from upgrading the system's fidelity, level 6 implies implementation on full-scale realistic problems and fully demonstrated engineering feasibility. The first step would mean that contractors employ the proposed solutions in actual projects, while the second step would mean to link the scattered lifecycle cases in a common lifecycle holistic solution.

3.2. Situation assessment

Having analysed the maturity of different lifecycle DT applications, this chapter aims to assess the current application status and explore future directions. SWOT analysis is a strategic management tool used to help a person or organization identify Strengths, Weaknesses, Opportunities, and Threats related to business competition or project planning. In the context of this report, the Strengths refer to the things done well regarding the DT applications, the Weaknesses concern the points that require improvement, the Opportunities include positive future scenarios for extending the DT applications in the sector, and finally, the Threats cover the undesired future scenarios if action concerning the weaknesses and opportunities is not taken. Table III summarises the identified Strengths, Weaknesses, Opportunities and Threats regarding the application of DT in the infrastructure sector.

Table III. SWOT Analysis for the DT applications in the infrastructure sector.

Strengths	Weaknesses
• Variety of applications • Tool for decision making	• Applications on single lifecycle phases, lacking a holistic lifecycle approach • Potentials during demolition not explored yet • Fidelity of the system
Opportunities	Threats
• Lifecycle application • Multilevel optimisation • Sustainable & circular management • Exploitation of technology	• Abundance of raw and isolated data • Disconnected non-exploited pilots

The main strength of the DT in the infrastructure sector is the variety of applications. As reviewed in the previous sections, DT can assist design processes, safety and quality aspects, efficient and sustainable management, constituting it a valuable decision-making tool for different lifecycle phases. On the other hand, the fact that these applications concern single lifecycle phases and lack a holistic approach acts as a weakness. Another weakness regarding the lifecycle application is the unexplored potential of DT in the demolition phase. It is not possible to introduce a lifecycle DT if the demolition phase is missing. Furthermore, as denoted from the TRL scale, the achieved system's fidelity is medium and needs to be upgraded. The medium-fidelity in this context means that the raw retrieved data is not efficiently stored and communicated.

Addressing the weakness of incremental lifecycle applications creates the opportunity to implement an integrated lifecycle DT. Such a tool will be a fertile basis for multi-aspect optimisations regarding the lifecycle of assets. Aspects like time, budget, safety, sustainability and circularity can be enhanced and optimised with the continuity of data from one phase to another. Another opportunity regarding the integration of the lifecycle concerns the exploitation of technologies. Same sensors and data collecting units have been proposed for more than one use at more than one lifecycle phases. Hence, integrating the lifecycle DT applications exploits the investment in technologies. For example laser scanning techniques have been proposed for both scanning the surrounding environment during the design phase, but also for detecting defects during the O&M phase. Similarly, the location tags put on machines can both assist safety issues, and also be used for logistics purposes. On the contrary, failing to link the lifecycle applications in a common, holistic approach encloses the threat of ending up with several disconnected non-exploited pilots. In that case, the DT potential will not be adequately explored. Finally, another threat regarding the DT application is missing to upgrade the system's fidelity. Neglecting to structure, store and visualize information in a descriptive and explicit way may lead to unmanageable amounts of unstructured and unable to be transformed into insightful information data.

3.3. Next steps

The analysis conducted in the previous chapter has highlighted some critical points that need to be addressed in order to elevate the current status of DT application in the infrastructure sector. Future directions of DT applications should consider a lifecycle approach, where information continuity will allow information flow from one lifecycle phase to another. Such a next step would fully demonstrate the engineering feasibility of DT, as indicated in level 6 of the TRL scale. A lifecycle DT would also address the respective weakness as presented in the SWOT matrix, and subsequently would eliminate the threat of ending up with isolated and disconnected single applications.

Upgrading the system's fidelity has been identified as another threshold to reaching level 6 on the TRL scale. SWOT analysis has also highlighted the system's fidelity as a weakness, which if not addressed encloses the threat of unmanageable and unstructured data. This observation is aligned with findings from the literature. The need for a high-fidelity DT model that contains intricate information has been reviewed as a prerequisite for the development of full-scale DT where behavioural and rule models are incorporated [2], [3], [12].

That weakness can be confronted by means of semantic and topologic enrichment of the virtual counterparts of the DT. Semantic enrichment denotes the process of adding a layer of topical metadata to content so that machines can make sense of and build connections to it. By topologic annotation is meant the process of assigning geometrical properties and spatial relations unaffected by the continuous change of shape or size of the objects. Overall, these enrichment processes elevate the machine's comprehension capacity of the virtual models and create communication channels between humans and computers.

4. Research proposal

The author is currently developing a lifecycle Infrastructure DT. From the different directions of the proposed next steps, this research will address the need for elevating the system's fidelity. Since a DT is a living digital replica mimicking a real-world physical counterpart, we need to represent a large range of behaviour and visual aspects in a virtual model, to claim that we have achieved a high-fidelity DT of a road asset. Addressing the entire span of reality to be reflected in a virtual model is not possible in the scope of this research though. Therefore, this study will be focusing on representing asphalt condition information. More specifically, the objective of the research is to systematically link the asphalt failure modes with their influential properties and the forms of visualisation. This systematic link is expected to elevate the current system's fidelity by enriching the virtual model with semantic and topologic properties for the condition information of a road asset.

To this end, this research will attempt to propose a methodology to capture, store and visualize the failure modes of asphalt during the O&M phase, in a way that is consistent with the previous phases. This will be achieved employing failure modes' classification and subsequent semantics' definition. It is proposed that the failure modes alongside their influential properties, namely their semantics, will be standardized and incorporated in the virtual model. Additionally, modelling scalability will be considered to identify the appropriate modelling format to handle condition data in a macro, meso and micro level (see envisioning in Figure 2). Furthermore, regarding the modelling formats, currently, most modelling practices are restricted to 3D representations. However, this research acknowledges the strong time component of failure propagation and, therefore, aims to employ this fourth dimension of modelling as well. Overall, this research aims to propose a systematic approach to store and visualise asphalt condition information in a way that will enhance its usability.

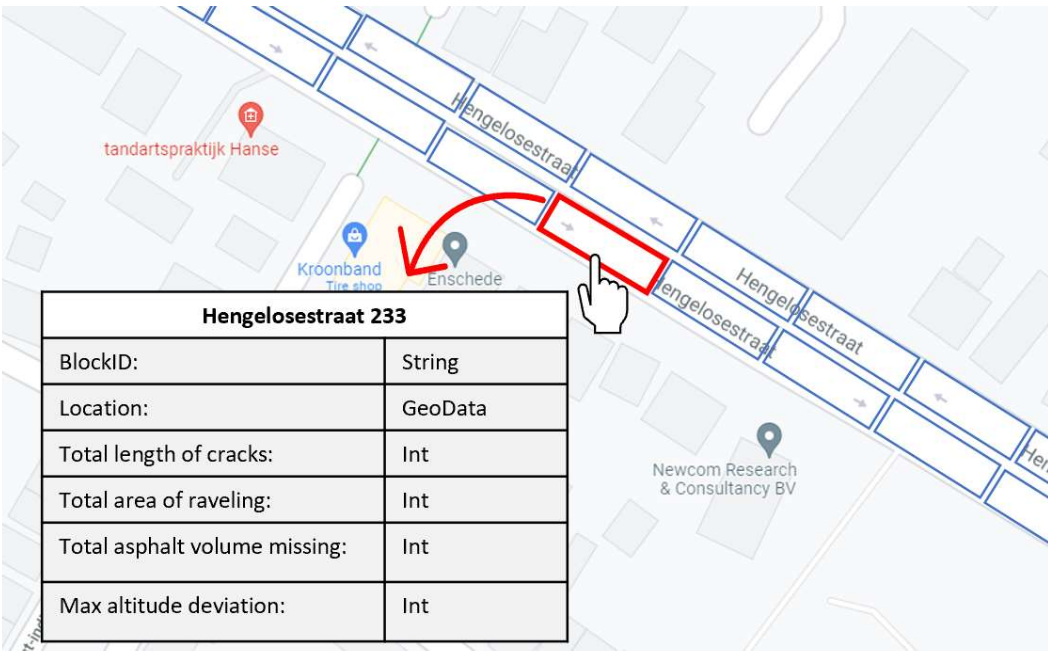

Figure 2 - Envisioning of macro twinning

5. Discussion

The DT concept designates a virtual model that imitates reality from diverse points of view. The creation of a lifecycle DT that assimilates all different points of view is impossible, especially regarding the scope and timespan of a PDEng project. Therefore, this research is restricted to a specific point of view and limited in incorporating the asphalt failure modes in the virtual model of DT. Even if the scope of the research is limited, it is expected that the proposed framework and methodology for storing and visualising asphalt condition data will be a significant step for elevating the current application status.

The semantic enrichment of the virtual model that this research proposes will enable the traceability of defects. As mentioned before, behavioural and rule models can be developed based on high-fidelity virtual models [2]. The proposed, semantically enriched virtual model will allow the application of several rules and the link with simulations. A valuable insight regarding the behaviour of failure modes can be gained, which will enable asset managers to conduct several types of optimisations, like maintenance planning or choice of material for subsequent projects. In other words, the upgraded model will be the first step for a holistic DT, including both the visual, behavioural and predictive modelling aspects.

Finally, regarding the relevance of the inclusion of this research in the conference, it is expected that the participants can share valuable insights from their perspectives as practitioners. More specifically, the conference attendees are invited to share their experiences about what modelling aspects are currently missing that could be linked with this research. Additionally, potential recommendations about existing efforts that this research could be linked with will be highly appreciated. Finally, potential technical expertise for defining the influential failure modes' properties will be a precious input for enhancing the preciseness of the result.

6. *Conclusion*

To summarise, this ongoing research targets in upgrading the modelling practices of road assets. The automation element introduced by the concept of DT serves as an appealing solution in different sectors, including infrastructure. However, the transition towards such an upgraded practice requires reaching intermediate milestones, and this research addresses one of them. By offering a methodology to systematically capture, store and visualise asphalt failure modes, it is expected to embrace the transition towards the DT practice for roads. This claim is further supported by a literature review, from which it has derived that the fidelity of DT is indeed a critical factor for implementing the DT concept. Finally, the updated virtual model will act as a base upon which the behaviour of the road can also be modelled. Overall, it is anticipated that this research will bring road modelling practices one step forward towards the application of DT.

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