Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Predictive twin for steel bridge in The Netherlands

G.A. de Raat & J.D. Bakker
Rijkswaterstaat, Utrecht, The Netherlands

G.T. Luiten & J.H. Paulissen
TNO, Delft, The Netherlands

B.Q. de Vogel, H. Scholten & S. de Graaf
Geodan, Amsterdam, The Netherlands

ABSTRACT: Predictive digital twins can support asset managers in assessing the end-of-service life phase of infrastructure. This paper reports on the development of a standardized Digital Twin System Architecture integrating various system layers, which can help asset managers in effectively and efficiently deploying (new) digital technologies to manage their asset networks. A Field-Lab in the Moerdijk bridge region allowed to perform the experiments, research and development of relevant building blocks towards the implementation of this digital twin architecture for steel bridges. This includes the chain from sensor-data, data-management, data-processing towards 3D visualization in a geospatial environment.

1 INTRODUCTION

1.1 *The Renovation & Replacement research program*

Rijkswaterstaat is the executive agency of the Ministry of Infrastructure and Water Management in The Netherlands that manages and develops the main road and waterway network plus the main water systems. These networks include 178 steel bridges amongst many other structures, roads and waterways. The majority of these objects have reached their designed lifespan and need to be replaced or renovated in the upcoming decades. It is important that these measures are timed well: too late and the network cannot be used due to safety concerns, too early and unnecessary destruction of capital will occur. As the wave of upcoming replacements will require a great effort of Rijkswaterstaat and other involved parties (e.g. engineering firms, contractors), an optimal order of measures is required. Since the degradation of an object may have been different than expected (e.g. due to higher traffic loads), it is not justifiable to simply use the initially established end-of-life. For that reason, a research program was started. One of the avenues to explore is how data and digitization can be used to more efficiently predict the end-of-service life. A complete re-calculation of a bridge takes time and effort. Therefore, the process for steel bridges is threefold. At this moment expert-judgement and quick scans are used to determine the order of the re-calculations. By using sensors and predictive digital twin techniques we aim to accelerate the calculations and make them more accurate. Throughout the infrastructure sector (and other sectors) many definitions of digital twinning are used. In the framework of the long term end goal of this research a predictive digital twin of a bridge is defined as a digital replica of the physical bridge that contains, connects and carries various types of relevant data and simulation tools over the whole life cycle of the bridge. The digital twin is connected to the physical bridge through data, e,g, inspection data and/or (near real-time) monitoring data about the current state of the bridge, and contains models to transfer these data into predictions regarding structural safety and technical end-of-life. The digital twin also contains a visualization tool to

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retrieve information and insights in a user-friendly way. This definition is based on the work of Cambridge Centre for Smart Infrastructure and Alan Turing Institute (Ye et al 2019).

2 TOWARDS DIGITAL TWINS FOR END-OF-SERVICE LIFE PHASE

2.1 *Vision on application of digital twins*

Over the last decades, academia, engineering companies and asset managers have started to adopt a variety of digital technologies (e.g. models, sensors, data-analysis methods) to address end-of-service life questions for infrastructural objects like steel bridges. For example, there are detailed finite element models (FEM) to calculate the stress levels in bridge components. Another example are advanced fatigue crack growth models that can be updated by inspection and sensor data to monitor real-time loads and stresses on bridges. Until a few years ago, most of these methods were predominantly based on expert knowledge. During the last years, however, the availability of data, data-driven methods, computational power and visualization technology has increased rapidly. This raises the question how these digital technologies can be effectively and efficiently applied for the end-of-service life challenges of asset-managers.

Digital twinning is one of the upcoming data-driven approaches that is receiving increasingly more interested. A digital twin bridges the gap between the physical and the digital by bringing real world data and models in a virtual environment. Such a virtual replica of the physical world can facilitate data-driven working and lead to more efficient decision-making and asset management in an ever digitizing society.

In the built environment, digital twins are starting to receive more interest, being mainly useful for inspection purposes (Pan & Zhang 2021) and predictive maintenance, especially when combined with sensor data and model results (Khajavi et al 2019). Building information models (BIM) can play an important role in digital twins, as these models hold detailed information on the properties of all components of a construction on an architectural level (Lu et al. 2019, Menassa 2021).

The aforementioned examples feature digital twins of a single physical system. A next step is to develop comprehensive digital twins that bring together data from multiple physical systems. An example of this upscaling are Digital Twins for the Physical Living Environment (DTFL), which integrate geospatial data of physical and geographic objects on a regional scale along with data of the dynamic processes (e.g. through sensor data) that are taking place.

The incorporation of BIM models in the wider context of a DTFL remains relatively unexplored. Importing a BIM model into a DTFL is challenging as it requires accurate geospatial positioning of the BIM model. This is complicated as BIM models are often stand-alone models that lack georeferencing. Bringing a BIM model into a DTFL can have great added value for a construction or infrastructure object. For example, the interaction can be established between the model and factors like subsurface, weather or real-time traffic flow. Also, it can facilitate assessing the impact of planned construction work on the external living environment.

2.2 *Standardization of architecture*

A standardized Digital Twin System Architecture (Figure 1) is essential to efficiently develop and apply current and future digital technologies. Creating object specific DT's from a standardized architecture/framework will prevent the need to start from scratch with each new digital twin and it allows to create digital twins for specific types of assets and problems in a flexible and repeatable way. It also contributes to standardization and interoperability amongst the many stakeholders involved in life cycle of the asset. The system architecture consists of various building blocks like data, models and visualization. Decoupling of system layers and standardization of the interfaces will prevent vendor lock-in. This way, digital twins of assets can become a an instrument to better retain information and insights throughout the (remaining) life cycle.

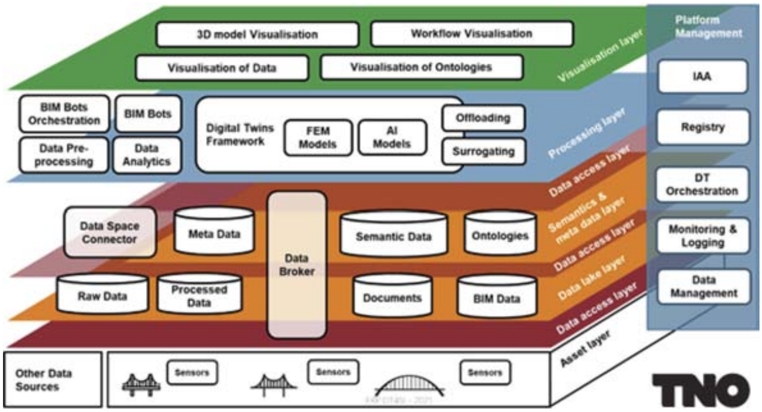

Figure 1. Standardized Digital Twin System Architecture.

3 USE CASE END-OF-SERVICE LIFE PHASE STEEL BRIDGES

3.1 *Use case Field-Lab Moerdijk bridge*

Rijkswaterstaat and TNO started a Field-Lab in the Moerdijk bridge region to facilitate collaborative experiments, research and development towards the implementation of Digital Twins for the end-of-service life phase of steel bridges. For this stage in the life cycle structural safety and fatigue (crack growth at specific hotspots in the steel structure due to cyclic loads) are important risks. The current practice at Rijkswaterstaat is to manage these risks with various types of inspections, structural assessments and continuous monitoring (Paulissen et al, 2018). The data and models involved in in this Field-Lab have been used as input for the experiments within the Digital Twin System Architecture and building blocks for steel bridges.

This chapter of the paper summarizes the progress so far. The focus was mainly on the modelling and visualization of data. A DTFL portal was developed to visualize both the data and models results of the bridge within a geospatial context (see 3.5). Furthermore we have prototyped two data management solutions (3.2) and applied three distinct analytical approaches to model stresses on the bridge (3.3).

3.2 *Building blocks*

On the **Asset layer**, a monitoring system was used that continuously records the dynamic strains resulting from trucks. The sample rate of the recordings is 100 Hz to capture the effect of individual truck wheels. Besides these continuous monitoring, a controlled load experiment was done to record the effect of a known load on the bridge. This type of monitoring can be used to calibrate the structural analysis models. The calibration is done by comparing the recorded load effects to assumptions from assessment standards. In the context of the Digital Twin development, the data were used as input for the Data -and Processing layer.

3.3 *Data management*

On the **Data layer,** two data management solutions were investigated and prototyped. The first focuses on robust and efficient storage and handling of large-scale time series datasets. This was done using Microsoft Azure Cloud storage and TimescaleDB, which is a database based on PostgreSQL. Once uploaded to the database, the data can be handled, queried and visualized much quicker than traditional CSV-files. TimescaleDB also allowed for easy interfacing with analytical tools and dashboarding software. The second solution holds a more broad oriented data management system that focuses on registering and organizing various types of datasets along with the relevant metadata in a single portal. The prototype is based on the open-source data management system CKAN. The prototype includes links to geometric datasets and models (i.e. point clouds & BIM), inspection data, time series data and a structural analysis models. Both data management solutions aim to make data available in a Findable, Accessible, Interoperable and Reusable way. This is important for being able to make more efficient use of the available data for the life cycle asset-management. It also contributes to innovation once datasets become more easily accessible to organizations doing R&D.

3.4 *Data processing*

On the **Processing layer,** three data-analysis tools were investigated.

Bridge Weight in Motion (Rodenburg et al, 2022), is an analysis tool that extracts truck load parameters (e.g. axle configurations, axle loads and gross vehicle weights) from the monitoring system as described before. This is important information to determine the loads that need to be assessed to determine the structural safety and fatigue life of the bridge. In current practice, this is done based on generic load models from European and National standards (e.g. Eurocodes including National Annexes). This results in uncertainties and possibly over-/underestimations of the loads that are used for the assessment of the bridge. Integration of this tool in a Digital Twin environment contributes to effectively determining bridge specific traffic loads, which can be used for the structural assessment and efficient long term monitoring of traffic loads on the bridge.

The second analysis tool is **ProbEye,** an open-source parameter estimation tool developed by TNO and the German knowledge institute Bundesanstalt für Materialforsuchung und -prüfung. The tool combines a model, prior knowledge about its input parameters and measurements to obtain the probability density function of model parameters (Vereecken et al, 2022). It explicitly accounts for model uncertainties and measurement inaccuracies. As such, models can be made more accurate by making use of measurement data. In the case of the Moerdijk bridge, the tool was used to calibrate structural assessment model constructed in FEA software DIANA. This models calculates the deformations, forces and stresses in the bridge structure. Because the method requires many model evaluations, computation time is a specific challenge. This is was overcome by surrogate modelling and parallel computing in the cloud. The latter was done in close collaboration with DIANA. Integration of this tool in the Digital Twin results in more accurate structural analysis models .

The third tool is **continuous automated analysis** and converts continuous monitoring data into interpretable parameters for assessing the structural safety and fatigue life of the bridge. This involves filtering, data cleaning, temperature correction and conversion of measured quantities (strains) into relevant quantities for structural assessment. The tool is directly interfaced with the Timescale database such that the analysis is automatically done when new data are uploaded in the database. This is valuable for continuous (trend) monitoring of traffic load effects during the life cycle of bridges.

3.5 *Visualisation of a DTFL*

For the **Visualisation layer,** we have focused on implementing the steel bridge in a comprehensive DTFL. A DTFL requires a 3D environment that integrates data in a geospatially accurate way. The open-source software library CesiumJS is a state-of-the-art tool that is becoming increasingly popular to visualize DTFLs. The CesiumJS software allows for displaying geospatial data in a full 3D environment in a web browser. As part of this study, we developed a generic Cesium-based application and interface that can be reused for different purposes.

Within a Cesium-based viewer, data can be displayed both as 2D map layers (e.g. WMS services) or 3D physical objects. For running in a web browser, the application is easily accessible for a wide public. At the same time, visualizing a 3D digital twin in a browser while maintaining a satisfying performance level is challenging when dealing with large quantities of data. Browser cache and performance can easily be overloaded. An important way to prevent this is through 3D tiling, which is a technique to subdivide 3D objects in a set of numerous tiles.

3D Tiles is an open standard of the Open Geospatial Consortium (OGC) and designed for streaming large 3D geospatial datasets. By using 3D tilesets, only the data that are close to the user's viewpoint are requested and visualized in the web application. In that way, the user only retrieves the necessary data, optimizing the performance of the application.

The conversion of data for display in the digital twin requires two main processing steps. First, the data is processed to 3D objects through a mesh tessellation or triangulation and set to the specific geodetic system for Cesium (EPSG: 4978). Secondly, the 3D objects are converted into a 3D tileset. This processing pipeline is not yet standardized and can vary substantially between different data types like point clouds, BIM models or other custom 3D objects. Especially for BIM, there is a large variety of file formats, which complicates the establishment of a uniform data processing protocol.

The digital twin environment that we developed includes a number of nation-wide data sets for the Netherlands. Within the Netherlands, a wide variety of data is openly available in a number of key registries. We processed a set of these data sets into the viewer, including all buildings and trees. Furthermore, a nation-wide digital elevation model (DEM) is available and can be loaded into the Cesium environment as a tiled mesh to visualize the terrain in 3D. Any map layers are then draped over the 3D terrain.

The visualization platform provides a custom user interface, which allows users to intuitively switch between different map layers, data sets and model results. The so-created digital twin infrastructure can be used for variable applications in the field of the physical living environment.

For the Moerdijk bridge, we used the Cesium-based web application to visualize the results from FEM. The Moerdijk bridge itself is visualized in the viewer as a BIM model, which was available in Revit file format (.rvt) (Figure 2). The elements of the BIM model were first converted into 3D geometries using FME while retaining the BIM attributes and then stored in a PostgreSQL database. Subsequently, a 3D tileset of the BIM model was generated using the tool pg2b3dm and stored in a cloud-based service. A separate 3D tileset was generated for nine different structural elements of the bridge to enable visualization of distinct parts of the construction. The subdivision consisted of the vertical web, inclined web, top flange, bottom flange, overlay, diaphragms, cantilever beams, cantilever beam sidewalls and top stiffeners.

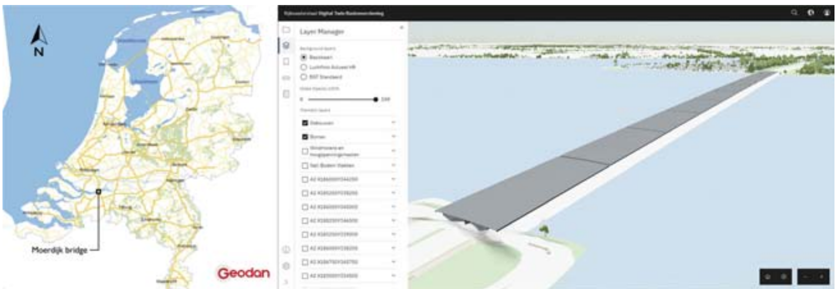

Figure 2. Location of the Moerdijk bridge in the southwest of the Netherlands (left) and the BIM of the bridge positioned in the digital twin environment (right). A user interface allows for selecting which data are being visualized.

Model results from the FEM were projected directly on this detailed representation of the bridge from the BIM model (Figure 3). Multiple FEM model results can be attached to a single element so that it is possible to dynamically switch between them. The precise model outcomes for each component of the BIM model can also be retrieved by clicking on a specific structural element to get the corresponding object information.

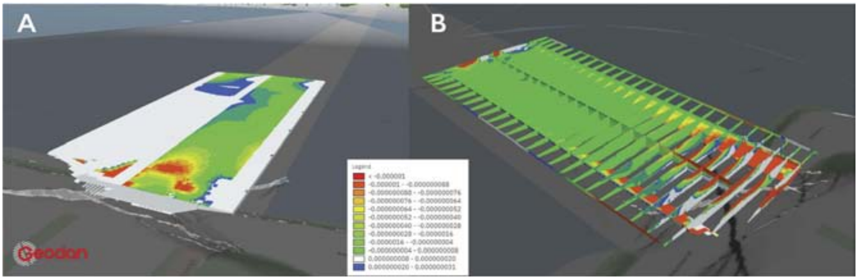

Figure 3. Results of the FEM for a truck passing over the Moerdijk bridge are visualized in the digital twin for one bridge section. A. FEM results for the overlay displayed within the entire BIM. B. FEM results displayed on only the vertical web, inclined web, diaphragms, cantilever beams and sidewalls. The other bridge elements are hidden to have a clear view of the internal structure of the bridge.

In addition to the model results, inspection photos of the bridge can be retrieved from the digital twin. The locations where photos are taken are indicated by an arrow symbol, whose orientation corresponds to the direction in which the photo was taken. The corresponding image file can be retrieved by clicking on the arrow symbol. The entire set of inspection photos comprises more than 19.000 files. Visualization and retrieval of photos from the digital twin helps to maintain a clear overview of the available images.

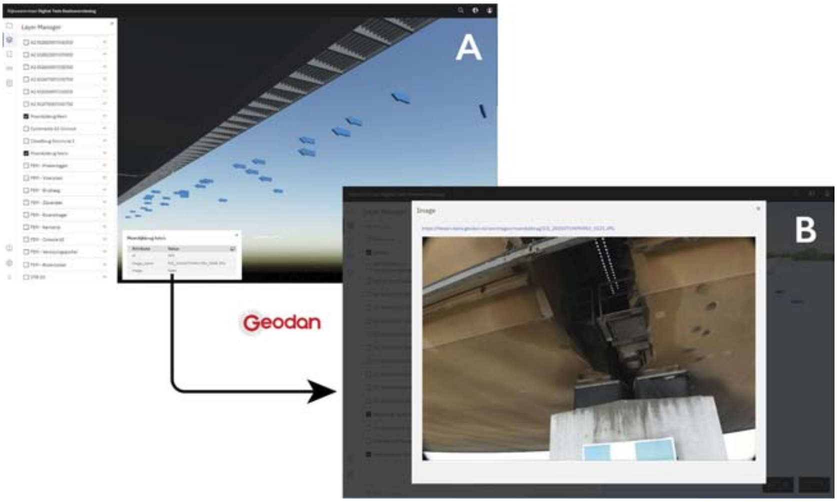

Figure 4. The BIM of the Moerdijk bridge viewed from below. The arrows indicate the position and direction of photos taken during inspections. The photos can be retrieved by clicking on the corresponding arrows.

4 CONCLUSIONS

The digital twin of the Moerdijk bridge presents a first step towards developing a virtual environment for managing the end-of service-life phase of the bridge. At the moment, the prototype offers the BIM integration along with two data sources: a set of FEM results and georeferenced inspection photos. Visualization of the FEM in the digital twin environment can facilitate the monitoring and prediction of the structural safety and fatigue life of the structure through time.

The developed digital twin offers a platform to incorporate a wide variety of other additional data types that may be of interest for monitoring purposes. For instance, 3D meshes obtained through laser scanning or photogrammetry techniques may have added value for the detection of fractures and deformations. Another important aspect for bridge monitoring would be the time component. Real-time information from sensors (e.g. strain monitoring) and results of data-analysis (e.g. fatigue spectra, traffic loads) can be incorporated into the digital twin through API implementation, while time sliders can add a 4D component to the viewer to gain insight into changes in the bridge through time. Displaying a high-performance digital twin in a browser was long considered impossible, but is now becoming achievable thanks to state-of-the-art software libraries like CesiumJS.

By bringing together relevant data from multiple sources, the digital twin can provide a comprehensive overview of the current state and potential risks. This can lead to better decision-making and cost reductions regarding the maintenance of infrastructure objects.

So far we have adopted a wide approach, to be able to test a broad spectrum of techniques. In due time cost-effectiveness analyses will be made so the best tools can be selected. We will also take the possibilities of implementing the necessary processes into account. For example a technique to determine parameters for re-calculations that cannot be widely used by engineering companies in their assessment of an object is less likely to be used in the long term.

The next goal is that the digital twin platform for the Moerdijk bridge can be easily reused for other infrastructure objects. The use of a standardized Digital Twin System Architecture can contribute to the effectiveness and efficiency of further developing and applying this potential.

So far we have learnt that the main challenges to achieve this mainly revolve around standardization and interfacing. Much of the data processing has to be automated to expand the implementation of the digital twin infrastructure. For example, the transfer of FEM results into the viewer is still manual work at the moment. Ideally, however, FEM results are directly coupled to the digital twin. This automatization would facilitate model results to easily be reflected in the viewer. Furthermore, as more data become available, model results may be updated through machine learning algorithms. Such model updates must also be able to be fed back easily into the viewer (top layer in the suggested system architecture from Figure 1).

Altogether, the entire spatial data infrastructure has to mature, from data storage to data management, supported data types, data processing and user interfaces. Only then it can effectively be deployed in the working processes of the bridge managers. Nevertheless, the developed prototype shows the potential of a geospatial digital twin portal for bridge managing purposes.

Another lesson is that it might be better to gather different companies and stakeholders at the start of building a digital twin. With our current DT each stakeholder started in their own area of expertise and these data sources had to be merged together in a later phase.

In a later phase we aim to use the digital twin for the maintenance during the total life span.

Furthermore, while the initial development was focused on technical users (structural engineers, technical advisors), the imaginable uses of digital twins are broader. In future, it may be extended to other users (decision makers, modelers, etc.).

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