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Contribution to the automatic recording and documentation of crossing events through the combination of BIM and SHM

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Abstract (250 words) Style Name

This contribution presents a practical use case demonstrating how Building Information Modelling (BIM) can be combined with Structural Health Monitoring (SHM) to support bridge management during the operation phase. A Python-based algorithm processes laser sensor data to automatically detect vehicle crossings and derive additional information such as direction and speed. This data is documented in BIM and used for event visualization. The approach illustrates the potential of integrating BIM and SHM for digitalizing routine tasks and extending existing methods, such as construction process simulation, into the operation and maintenance phases. [Abstract, Keywords Aptos, 9]

Keywords: BIM; SHM; Crossing Events; Automatic recording

Highlights

- The digital transformation of repetitive routine activities reduces the workload of bridge management personnel.
- Interoperability is achievable through open exchange formats.
- Practical demonstrations help stakeholders recognize the tangible benefits of digital methods.

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1 Introduction

The digital transformation of the construction industry is changing established production processes by increasing the degree of automation. Digital transformation enhances the efficiency and productivity and improves the cost control (Musarat et al., 2021). Most studies on the benefits of digitalization focus on the different technologies such as BIM, Internet of Things (IoT), artificial intelligence (AI) or extended reality (XR) and their fields of application. Currently, there is no fully integrated approach for all technologies. Only a few studies give application examples along with recommendations for action (Naji, Gunduz, Alhenzab, Al-Hababi, & Al-Qahtani, 2024). This contribution examines the use of BIM for the digital transformation of infrastructure management especially for bridges. While BIM is primarily used during the planning and realization phases of construction projects (Volk, Stengel, & Schultmann, 2014), it also holds significant potential for infrastructure management. This potential is further supported by the extension of the data format of Industry Foundation Classes (IFC) to IFC 4.3 which includes attributes intended specifically for infrastructure management (Borrmann, Beetz, Koch, Liebich, & Muhič, 2021). Despite this, the operation and maintenance phases are still underrepresented in BIM projects. A likely factor is that the operation phase of infrastructure projects is often connected with uncertainty relating to the current condition of the structure. Structural health monitoring (SHM), which enables the detection of changes in material or geometric properties throughout a structure's life cycle, offers a promising solution to address this information gap (Farrar & Worden, 2007).

An important step towards the success of digital transformation is the combination of different technologies in order to avoid developing different approaches that later contradict each other. This contribution focuses on the combination of data driven approaches with the automation of SHM systems in the context of BIM. The integration of automated SHM in BIM offers the possibility of overcoming the increasing workload associated with the increasing volume of data and some of the first approaches are already under development (Köhncke, Marsili, Henke, & Keßler, 2023; Valinejadshoubi, Bagchi, & Moselhi, 2019). In BIM, processes are organized into use cases that define the objectives and procedures for its application (Borrmann, König, Koch, & Beetz, 2021). In this contribution, SHM serves as the source of the data for the corresponding evaluation algorithms. The underlying principles of SHM are not addressed in detail, as the focus of this paper lies in the integration and automation of the data analysis. For further information on SHM, readers are referred to specialized literature (Farrar & Worden, 2007; Gharehbaghi et al., 2022).

BIM use cases are typically structured into different categories like goal, benefit, procedure, input and output. This system offers the opportunity to standardize use cases, make them comparable, and improve the implementation across different projects. Currently, there is a lack of use cases for the operation and maintenance phases, even if there are some that could be easily transferred from the planning and realization phase (Bundesministerium für Verkehr und digitale Infrastruktur, 2019). Such transfer could not only accelerate digital transformation but also support the use of BIM in the whole life cycle of infrastructure assets. A consistent use of BIM can help reduce inconsistencies in infrastructure management, particularly for bridges, where data format changes and the retrospective digitalization of documents often lead to inefficiencies. The main benefits of BIM are the improved design quality, reduced effort in searching and sharing information, avoidance of duplicate work or the minimization of data correction (Doumbouya, Gao, & Guan, 2016). These benefits are enabled through the concept of Single Source of Truth (SSoT) (Hijazi, Perera, Calheiros, & Alashwal, 2023), which ensures that all stakeholders access and work with a centralized and consistent dataset. While the implementation of BIM may require significant initial effort, the long-term benefits, especially during the operation and maintenance phase, often outweigh the costs. The extended duration of this phase underscores the value of early BIM integration. After a brief introduction to the topic, the article presents the research objectives and methodology followed by a discussion of the results and the conclusions.

2 Research Goals

The actual load on bridges remains often unknown because there is no practical method to document all crossing events over the whole life cycle. Sometimes the data from nearby traffic counting systems are used as a proxy. This data can deviate from the actual crossings in various ways, e.g. vehicles may exit the road before crossing the bridge or others may enter the road shortly before crossing, and simultaneous crossings of several vehicles can complicate detection. To achieve a realistic representation of the bridge loads, detection should take place directly at the bridge. However, the detection of a crossing typically only indicates that a load occurred, without revealing the actual weight of the vehicle. Although modern bridge weigh-in-motion systems (B-WIM) provide information on the weights of the vehicles and their classifications this contribution focusses only on the detection and documentation of the crossings. Further investigations into the identification and classification of traffic loads are necessary but lie beyond the scope of this paper.

For the documentation to be useful and interoperable, it must be recorded in a widely adopted data format that can integrate with other bridge-related information. To this end, the CSV- and IFC-Formats were chosen to support BIM. IFC also offers the possibility to use existing procedures for the visualization of construction schedules for the documentation of crossing events. This approach leverages established methods, avoiding the need for entirely new systems.

3 Methodology

For the development and test phase of the automatic detection of crossings, a simplified SHM system was used, consisting of two light barriers, one at the beginning (LB_East) and one at the end (LB_West) of a single lane bridge. The test phase included several controlled crossings using a truck with known dimensions and varying speeds to ensure reliable identification in the recorded data. All crossings were performed from east to west. Further information on the entire SHM system and the associated load tests is currently under review (Köhncke et al., 2024). The configuration of the SHM system is shown in Figure 1.

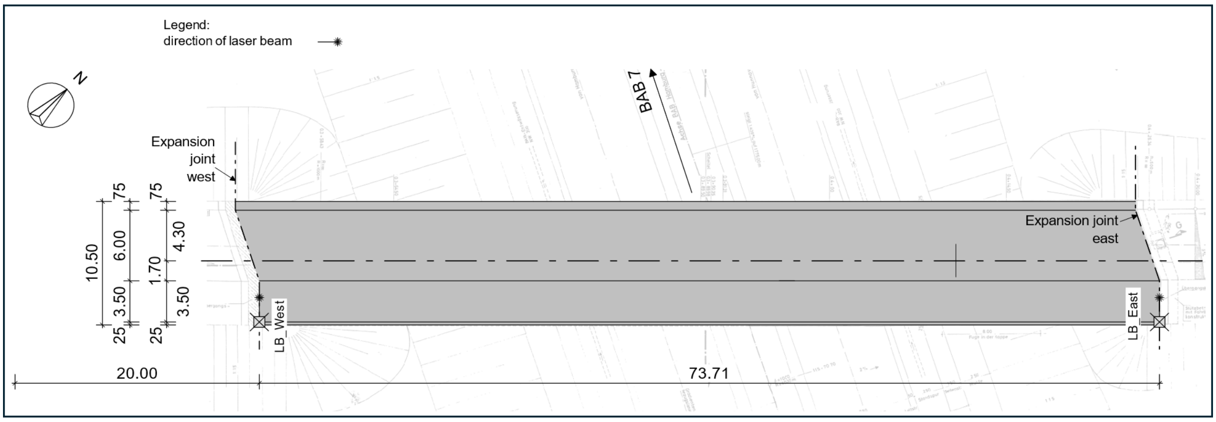

Figure 1 Overview of laser barrier positions

For demonstration purposes, a simplified BIM model of the bridge comprising only the relevant structural elements was developed... If all necessary geometric information is available, creating such a model requires only a few hours. However, the effort required to expand the BIM model depends heavily on the availability of source data and the desired level of detail. A visualization of the model is shown in Figure 2.

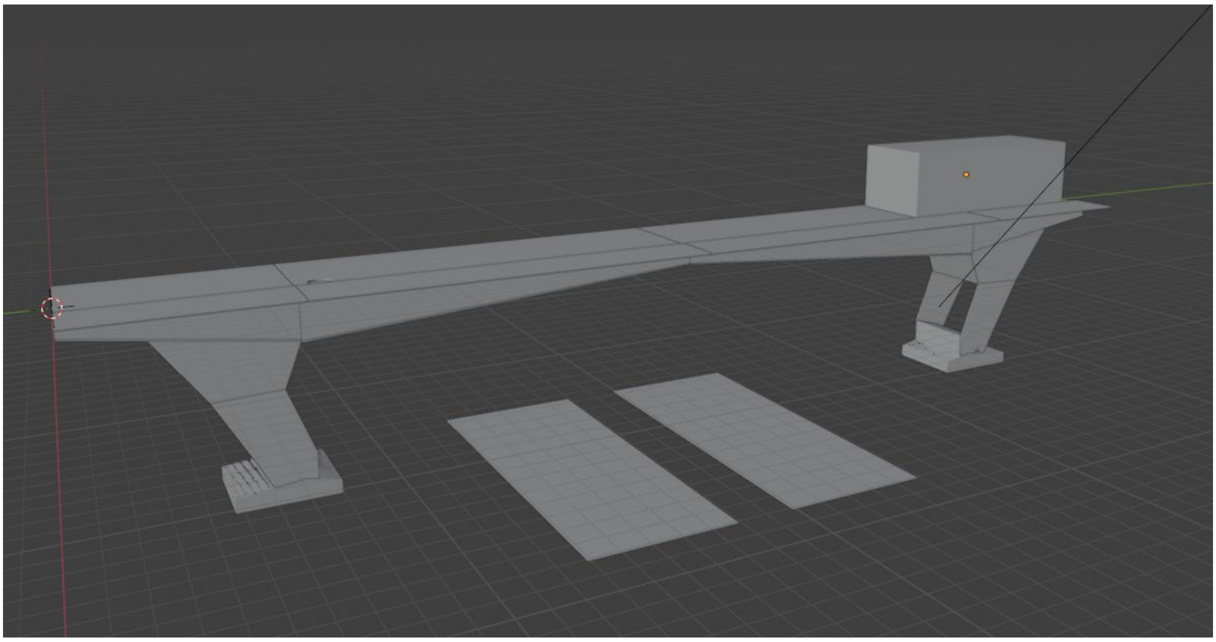

Figure 2 Example of the visualization of a crossing event

The light barriers operate at a frequency of 200 Hz to ensure that all events can be detected. The laser distance sensors using class 2 lasers are employed to eliminate any risk to personnel involved in the testing. Each crossing event was documented in a protocol, and the measurement data from the SHM system were organized into separate data files - one file per crossing. This procedure allows the extraction and analysis of parameters corresponding to different vehicle speeds.

The algorithm begins by calculating the median of the distance measurement data, as crossing events represent only a small portion of the overall dataset. The median is a good base value for the distance measurement in order to reduce noise. A data point classified as part of a crossing event if its value falls more than 500 mm below the median, ensuring that vehicles passing at varying distances from the laser sensor are still detected. The individual data points are grouped according to their temporal relationship to determine the time of each crossing event. A crossing event includes the first data point of the LB_East that deviates from the median and the last data point from LB_West that deviates from the median. Due to the time-synchronous recording of all sensors, the events can easily be displayed on the same time axis. For each crossing event, the direction of travel, average speed and vehicle length are recorded or derived from the measurement data. Vehicle length is estimated using the average speed and the duration of the light barrier interruption; as a result, it is an approximation and becomes less accurate at higher speeds due to increased measurement uncertainty. This information is saved as a CSV-file, which forms the basis for visualization of the crossing event. An example of this CSV-file is shown in Table 1.

Table I. Example for the results of the crossing detection algorithm

No.	Start	End	Direction	Average Speed [km/h]	Length Vehicle [m]
1	25.04.2024 10:31:46	25.04.2024 10:33:00	East to west	5	7.7

The crossing can be visualized using the software Blender (Blender Foundation). First, a static visualization of the position of the vehicle at the start and end times is generated. Subsequently the vehicle's movement is then animated using linear interpolation between these time and position markers.

For simplicity, the initial visualization used a single cube with the edge length representing the estimated length of the vehicle. Additional details, such as the number of axles, can be incorporated later as more information becomes available. The proposed procedure enables a quick and simple combination of documentation and visualization of crossing events utilizing methods commonly used in construction process simulations.

4 Discussion

The procedure presented in this paper supports the management of bridge structures through the automatic documentation of crossing events. The use of the CSV format for data storage ensures compatibility with other analysis and visualization processes, facilitating a more accurate estimation of the load acting on the structure. However, the SHM system used in this test setup did not include strain sensors, which would be necessary to infer the weight of the crossing vehicles. Incorporating such data could significantly enhance the informative value of the SHM system. Nevertheless, the results demonstrate that the integration of BIM with SHM offers valuable contributions to the digital transformation of infrastructure management.

The current procedure is based on a simplified BIM model into which the visualization is integrated. However, such models are not yet available for all existing bridges. Therefore, the rapid and straightforward creation of BIM models is a crucial factor for the broader adoption of BIM in infrastructure management (Bednorz, Hindersmann, Jaeger, & Marszalik, 2020). The current IFC standard does not take vehicles into account, which led to the use of IFCPropertySets in this study. These allow custom objects to be assigned relevant properties. However, this approach can lead to difficulties when visualizing in other software programs, as the handling of IFCPropertySets is not yet standardized and implemented in all software programs.

The procedure and SHM system presented here can be easily extended to offer even greater benefits for infrastructure operators. In particular, the automatic recording of crossing events reduces manual workload by consolidating measurement data into events. Based on this, further evaluation algorithms can be developed to determine the vehicle weight based on strain sensors or to estimate the load on the bridge more precisely on the basis of stochastic models for weight distribution. The procedure has been illustrated using a very simple SHM system, which kept the effort required for algorithm development and visualization very low. As the level of complexity and detail increases, the development effort increases accordingly. However, to foster acceptance of digital transformation in infrastructure management, it is essential to begin with straightforward, easy-to-implement examples. Such practical demonstrations help stakeholders recognize the tangible benefits of digital methods, motivating further adoption and development(BIM.Hamburg, 2021).

The procedure can be extended in two ways. Firstly, the algorithm can be quickly applied to other bridges. To do this, the simplified model of the bridge needs to be created and linked to the algorithm for creating the visualisation. It may be necessary to pay attention to the names and orientations if these are not the same for all BIM models of bridges. On the other hand, other sensors and their results can also be considered. All you need to do is ensure that the measurement data is correctly linked to the sensors and, if necessary, adjust the file paths accordingly.

Another aspect is the current reliability of the algorithm and the SHM system. The algorithm relies on derived measurements for the calculation of the vehicle length, which can lead to errors and inaccuracies. In this test phase, the vehicle velocity was predefined, however, in real-world scenarios, vehicles may accelerate or decelerate while crossing the bridge, further affecting the accuracy of speed and length estimations. Additionally, the laser distance sensors used are sensitive to reflective surfaces, and increased scattering from such materials can result in measurement inaccuracies.

Another important aspect is the integration of the presented solution into the national infrastructure management systems (in Germany SIB-Bauwerke). At present, the SIB-Bauwerke database does not yet have an IFC interface. In order to ensure that a link to the as-built data is still possible, the keys used for the individual components of the bridges should be considered in the BIM models. These are defined in the Road Information Database guide (Bundesministerium für Verkehr, Bau und Stadtentwicklung:, 2013).

5 Conclusion

Automation of the recording and documentation of crossing events using BIM and SHM was presented through a simplified example. While the capabilities of the developed application are currently limited by the SHM system used, its expansion holds significant potential for providing bridge operators with valuable information on traffic events. The digital transformation of repetitive routine activities, such as the aggregation of measurement data into events, reduces the workload of bridge management personnel without compromising data quality. The current accuracy of the algorithms and SHM systems still represents a challenge which can be addressed by integrating additional sensors and enhancing data acquisition. The level of detail of the visualization also depends on the availability of information for each crossing. However, since the effort required for more detailed visualizations often increases disproportionately to the added value, simpler visualizations are generally preferable for practical use. [Text (Body)-DFBI, Aptos, 11]

In addition to interpreting the results, the discussion should explore your study's practical and theoretical implications. Discuss how your findings can inform future research, policy-making, or professional practice in architecture and urban planning. Acknowledge any limitations encountered during your research, such as methodological constraints or data limitations, and explain how these factors may influence the interpretation of your results. Suggest areas for further investigation to address these limitations and build upon your work. Conclude the discussion by summarising the principal insights gained from your study and reiterating their significance, ensuring that your conclusions are well-supported by the evidence presented.

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Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest
The authors declare no conflict of interest.

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