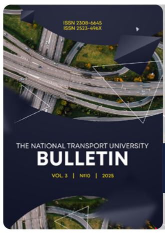

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Information modelling in the analysis of the condition of small bridge structures in rural road network: Challenges and solutions

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Abstract. The study aimed to identify effective approaches to the use of digital technologies for assessing the condition and planning the rehabilitation of small transport crossings, incorporating limited resources and data interoperability requirements. The methodology combined comparative analysis, Building Information Modelling, case studies of regional examples and systematisation of international experience. Digital methods have been shown to provide millimetre-level measurement accuracy, reduce data collection time, and can be used to create detailed 3D models, as well as predict wear using deep learning algorithms. In Zhytomyr, Volyn, Cherkasy and Odesa regions of Ukraine, defects in bridge structures were recorded: in Zhytomyr – damage from military operations, in Volyn – cracks in concrete and soil erosion, in Cherkasy – the effects of prolonged operation for more than 50 years, and in Odesa – corrosion of steel elements combined with an aggressive coastal environment. The study confirmed that the integration of data into the Digital Twin Building Information Modelling environment increased the accuracy of forecasts by up to 95% (in China), and a 40-65% reduction in time and labour costs was recorded when using deep learning algorithms in Germany. The use of unmanned aerial vehicles with Light Detection and Ranging and photogrammetry was used for the inspection of bridges with minimal impact on traffic and human factors, which is essential in remote or dangerous areas. Based on a synthesis of international experience in implementing innovative methods in bridge construction, the use of open formats and simplified models was recommended, which reduced survey costs and time for preparing documentation. The results can be used by road services to plan repairs, manage the life cycle of bridges and rehabilitate structures in Ukraine with increased transparency and lower environmental impact

Keywords: digital twins; open formats; lifecycle; cross-platform compatibility; wear prediction; semantic enrichment; automated monitoring

Introduction

Bridge management is undergoing a rapid digital transformation. Building Information Modelling (BIM), Bridge Information Modelling (BrIM), and Digital Twins (DT) technologies are becoming key tools for improving safety, optimising maintenance and reducing operating costs. The growth of infrastructure data and the emergence of affordable tools for processing it are creating new opportunities, even for facilities that were previously overlooked due to limited funding or remote locations. International initiatives on open data exchange standards (openBIM) are enhancing interoperability and facilitating collaboration between organisations. In the context of Ukraine, these technologies are gaining importance due to the combination of the challenges of rebuilding infrastructure after destruction and the need to utilise limited resources. Remote bridge inspections have become more efficient by combining data from condition monitoring systems with DT to provide early detection of defects, reduce the number of visits and accelerate decision-making. A. Hagen & T.M. Andersen (2024) demonstrated that the accuracy of

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assessments is not lost, and the safety of inspections is improved. The study noted the consistency of vibration indicators with damage indicators in the digital model, which enhances the reliability of triggers for unscheduled inspections. This confirmed the effectiveness of the approach in conditions of limited access to structures, when traditional inspections are risky or expensive. The implementation of open BIM in infrastructure is hampered by uneven standards, the lack of a unified Employer's Information Requirements (EIR)/BIM Execution Plan (BEP) and gaps in staff training. This was illustrated by a systematic review by A. Salzano *et al.* (2023), summarising a large body of work and outlining the priorities of open formats. The study demonstrated the need to start with unified EIR/BEP-light and standard IFC templates to reduce the cost of coordination and ensure cross-platform compatibility at the level of regional services.

In the Ukrainian context, information modelling is seen as a catalyst for transformation in design and management. A study by O.M. Protsenko *et al.* (2024) proved that regulatory consolidation of BIM processes and the launch of industry digital platforms are key to practice scaling. They showed managerial steps that can accelerate digitalisation, which formed the institutional prerequisites for adapting BIM/BrIM to small bridges. The widespread use of BIM in Ukraine is constrained by CAD/BIM compatibility, regulatory gaps, and a lack of government support. This was highlighted by M. Surianinov *et al.* (2024), proposing steps to standardise requirements and training. Removing these barriers creates the conditions for deploying solutions on a network of small facilities. The study demonstrated what system conditions should be provided for solutions to be operational on a network of small facilities. In addition, rapid damage assessment in crisis conditions is possible through multi-level schemes that combine satellite data, deep learning, and crowdsourcing, as demonstrated by N. Kopiika *et al.* (2025) by generating rapid damage maps to prioritise interventions. The approach is compatible with integration into BIM/DT life-cycle loops, providing a realistic channel for cheaper data collection that is compatible with further integration into BIM/DT life-cycle loops. Over the life cycle of a bridge, DT technology delivers significant economic and environmental benefits, reducing downtime, optimising resource consumption and stabilising the intervention schedule. T. Cherniavska & B. Cherniavskyi (2025) proved that the integration of DT into the reconstruction and management of infrastructure in Ukraine can increase the efficiency of the use of funds and provide more predictable planning of repair work, even in conditions of limited resources. This directly supported the focus on small bridge networks, where such practices yield economic benefits without the need for excessive expansion of information models.

Integration of data into a common Digital Twin-BIM environment improves the accuracy of condition forecasts and the timeliness of repairs through connectivity and traceability of information. The study by Z. Dvulit *et al.* (2023) demonstrated that the use of DT for planning and forecasting resource requirements in the post-war reconstruction of Ukraine would ensure the scalability of models from a single facility to a portfolio of structures, while maintaining the accuracy and relevance of the data. This approach was in line to create a single "point of truth" for geometry, defects and performance parameters, which was identified as a key efficiency factor. The scalability of BIM in bridge construction depends on cross-platform compatibility and clear information requirements. The study by A.I. Bielova *et al.* (2020) emphasised that the implementation of BIM in Ukraine on the path to European integration is impossible without the unification of standards and the harmonisation of the regulatory framework with European requirements. For the regional road services of Ukraine, this meant the expediency of starting with simple IFC/EIR templates and gradually expanding their functionality without being tied to one software.

Despite a wide range of research in the field of BIM/BrIM and DT, the issues of scaling them up for small bridges in rural road networks remain insufficiently studied, especially in conditions of limited resources, increased risks of military operations and economic constraints. There is also a lack of practical cases of openBIM implementation in public infrastructure projects in Ukraine, and the integration of low-cost solutions into national reconstruction programmes is still at an early stage. Therefore, the study aimed to identify and justify effective approaches to the implementation of BIM/BrIM and digital twin technologies in small bridge rehabilitation projects in Ukraine, incorporating limited resources, interoperability requirements, and the potential of low-cost solutions.

Materials and Methods

The study was conducted from December 2024 to July 2025 and covered the substantiation of approaches to the implementation of digital technologies in the design, inspection and operation of small bridges in Ukraine in Zhytomyr, Volyn, Cherkasy and Odesa regions. These regions were selected due to the representativeness of their bridge structures: in Zhytomyr region due to significant damage caused by military operations, which assessed the effectiveness of digital methods in restoring bridges after combat impacts (State Restoration Service of Ukraine, 2024b), in Volyn region – problems with soil erosion and cracks in concrete (State Restoration Service of Ukraine, 2024a), in Cherkasy region, an example of bridges in critical technical condition due to long-term operation (over 50 years), which verified approaches to wear forecasting and prioritisation of repairs (Cherkasy Regional State Administration, 2023), and in Odesa region, the impact of aggressive coastal environment and corrosion of steel elements (Odesa Regional State Administration, 2021). This sample incorporated different types of structures and a wide range of damages to form a representative base and develop practical recommendations.

The international experience of such countries as Canada, Portugal, China, Egypt, USA, Brazil, Poland, Germany, Great Britain was incorporated, which was used to adapt effective practices to Ukrainian conditions and to align them with the world practices of bridge infrastructure management, and the current regulatory requirements (DBN V.2.3-26:2024, 2025; BN01:4868-1755-9511-2275, 2025), which define the basic principles of design and assessment of bridge structures in Ukraine, European Union (EU) standards (Eurocode 1, 2003; Eurocode 2, 2005), Guideline for the implementation… (2019) and materials on the national implementation of ISO 19650-1:2018 (2018) in Ukraine.

The study included 5 stages. At the first stage, a method of comparative analysis of traditional and digital methods was conducted to determine the differences between approaches to the inspection of small bridges in terms of measurement accuracy, data collection speed, economic costs and ease of use of the information obtained. At the second stage, the method of step-by-step detailing was used to describe the process of creating BIM models of small bridges, formed as a theoretical generalisation of existing approaches and confirmed by international experience. The data collection and preparation involved the analysis of geometric characteristics such as length, width, height, span, structural materials (concrete and steel classes), as well as information from inspection reports and archival drawings, following applicable standards and guidelines. To determine the modelling tools, the literature was analysed, which justified the use of UAV photogrammetry, light detection and ranging (LiDAR) and computer vision algorithms to obtain the output data. For 3D geometric modelling of bridge structures, examples included Autodesk Revit, Civil 3D, Allplan Bridge, and Tekla Structures software. For the semantic enrichment of the models, standardised Property Sets (IFC 4.3) were used to ensure the unification of attributes. The models were validated using CloudCompare, Navisworks or Solibri to check their accuracy and compliance with the requirements. Integration with the life cycle involved the use of IoT platforms to monitor the condition of structures and Life Cycle Assessment (LCA)/5D (5-Dimensional) BIM methods to assess sustainability and life-cycle costs.

The third stage was to classify a matrix of key parameters to establish quality and interoperability requirements for BIM models in bridge construction. It incorporated the level of detail (LOD), interoperability, reliability and safety indicators, as well as environmental aspects of the life cycle. This was necessary to formulate uniform criteria for evaluating models at different stages of their life cycle and integrating them with digital counterparts. At the fourth stage, a case study method was used to analyse the technical condition and rehabilitation needs of small bridge structures, which involved consideration of regional examples of small bridge structures from Zhytomyr, Volyn, Cherkasy and Odesa regions of Ukraine. At the fifth stage, the method of systematisation of international experience in the implementation of innovative technologies in bridge construction and operation was applied. Examples from Canada, Portugal, China, Egypt, the United States, Brazil, Poland, Germany and the United Kingdom were selected for analysis, reflecting trends in this area. The study systemised the technologies: Bridge Information Modelling (BrIM) with LCA and Life Cycle Costing (LCC) integration, Building Digital Twins (BDT) with Internet of Things (IoT) and Artificial Intelligence (AI)/Machine Learning (ML), Digital Twins (DT) with Geographic Information Systems (GIS) and BIM integration, BrIM framework for Reinforced Concrete (RC) bridges, unified DT framework for bridges, BIM with Mixed Reality (MR) Immersive Digital Twin Platform (IBDTP), Deep learning for geometry reconstruction from drawings, Long Short-Term Memory (LSTM) with BIM for management, data integration framework for RC bridges. Sources for generalisation highlighted the experience of applying these technologies in different countries to outline the range of modern digital solutions of the 21st century in bridge construction. This was necessary to adapt effective practices to the Ukrainian context of small bridge rehabilitation, as well as to formulate practical recommendations for the implementation of digital technologies in the design and operation of small bridges in Ukraine.

Results and Discussion

Design features of small automotive bridges and comparison of traditional and digital methods for their inspection

Small road bridges in the rural road network are structures with a span length of up to 25 m, designed to maintain the continuity of traffic flows on local roads that are not part of main arteries. Typical structural solutions include reinforced concrete girder bridges (monolithic and prefabricated), metal girder and frame structures made of steel profiles, as well as combined systems for the joint operation of steel (reinforcing steel of A400C class and structural steel of S235-S355) and concrete (classes B20-B30). BIM in bridge construction is an integrated approach to the creation, management and operation of digital models at all stages of the construction life cycle (Guideline for the implementation..., 2019). There are two main approaches to bridge inspection and condition assessment: traditional methods (visual inspection and instrumental measurements) and digital technologies, including BIM, laser scanning, photogrammetry and the use of unmanned aerial vehicles (UAVs). Traditional methods provide only moderate accuracy, with results heavily dependent on the engineer's skill and equipment quality, while visual inspection can miss hidden defects, and instrumental methods provide localised but not comprehensive data (Alsharif *et al.*, 2025). These approaches are slow and labour-intensive, but their affordability makes them relevant for baseline surveys. Data are usually recorded in reports and acts, which makes further analysis and long-term use difficult.

Digital technologies, on the other hand, are much more accurate and efficient. Laser scanning can be used for detailed 3D models with millimetre resolution, while photogrammetry and drones provide high accuracy of geometric measurements, although less informative about materials (Jrade *et al.*, 2023). BIM technologies act as an integrated environment for processing and analysing this data, ensuring effective information management throughout the entire life cycle of a building (Nhamage *et al.*, 2025). Studies show that digital twins can radically improve the quality of bridge management and monitoring by combining data from different sources into a single system (Gao *et al.*, 2024). The integration of BIM with GIS is already being used for practical operation and maintenance tasks, providing centralised management and planning of repairs. The unification of digital approaches is emphasised, as common frameworks for digital bridge twins that enable standardised data exchange and application in different contexts are being developed. New solutions also include the use of mixed reality for visualisation and inspection of bridge structures in a BIM environment (Martins *et al.*, 2024). In addition, 3D reconstruction methods from 2D drawings show the potential to create digital bridge models, which is especially relevant for the reconstruction and modernisation of existing structures (Poku-Agyemang & Reiterer, 2023).

The creation of BIM models of small bridges is a step-by-step process that combines the collection of primary data, the formation of 3D geometry, semantic enrichment of the information model, data validation and federation, and integration into the full life cycle of the structure. Each stage has specific tasks, tools and methods, the choice of which depends on the technical requirements, LOD level and available resources. Table 1 demonstrates the data in detail.

Table 1. Stages and tools for creating BIM models of small bridges

Stage	Characteristic	Tools and methods
Data collection and preparation	Analysis of available documentation: 2D plans, archive drawings, inspection reports. Digitise analogue drawings with a resolution of 300-600 DPI for accurate reference. Field surveys to identify areas of interest (ROI) where the structure has critical or potentially dangerous defects. Photogrammetry (UAVs, cameras) and/or LiDAR scanning to create georeferenced point clouds. Computer vision algorithms (OpenCV) for semi-automatic selection of bridge elements from photos and videos.	Equipment: UAVs with a camera, LiDAR laser scanners, and high-resolution digital cameras. Methods: photogrammetry, LiDAR scanning, algorithmic image processing (OpenCV).
3D geometric modelling	Creation of a parametric 3D model from the main components (beams, supports, abutments, roadway slab). Semi-automatic reconstruction from 2D plans: vectorisation, topological analysis, transition to 3D space, interpolation of curves by cubic splines. Model optimisation to reduce file weight without losing critical data. Export to IFC 4.3 format with appropriate property sets for interoperability. Convert to GLTF or 3D Tiles for integration with GIS and web visualisation.	Software: Autodesk Revit, Civil 3D, Allplan Bridge, and Tekla Structures. Formats: IFC 4.3, GLTF, 3D Tiles. Methods: parametric modelling, spline interpolation, and topological analysis.
Semantic enrichment and data integration	Adding non-geometric data: materials, strength classes, repair history, inspection results. Modelling defects (cracks, corrosion, deformation) digitally, for example, through JSON structures. Use of ontologies and standard property sets (Psets) to ensure uniformity. Integration with structural analysis software (FEA) for verification of residual load-carrying capacity. Colour coding of elements by degree of damage.	Tools: JSON, Abaqus, Midas Civil, IFC ontologies. Methods: semantic modelling, integration of FEA results, colour coding of defects.
Model validation and federation	Geometric verification of the model by overlaying an as-built point cloud on the BIM model. Model checking – automatically checks for collisions and BEP compliance. Combining submodels of different disciplines (architecture, structures, engineering) into a single CDE. Model versioning for tracking changes and updates. Update the model from IoT sensor data or after inspections.	Tools: CloudCompare, Navisworks, Solibri, CDE platforms (Trimble Connect, BIM 360). Methods: geometric analysis, collision control, model versioning.
Integration with the life cycle	Extend the model to 4D (time schedules) and 5D (cost) for repair and maintenance planning. Creating reports and visualisations for customers and operational services. Integration with digital twins for continuous status monitoring. Connecting IoT sensors (deformation, humidity, temperature) to obtain real-time data. Performing a life cycle analysis (LCA) to assess long-term performance.	Tools: Xeokit, Caesium, Twinmotion, IoT platforms. Methods: 4D/5D BIM, LCA analysis per ISO 14040, Digital Twin integration.

Source: compiled by the author based on Y. Xenidis *(2021), M. Fawad et al.* (2024), B. Faltin *et al.* (2024)

The stages of creating BIM models of small bridges combined survey data, 3D modelling and digital twins into a single system. For rural regions of Ukraine, in particular Zhytomyr and Volyn, this is relevant as it can rapidly digitalise outdated bridges, integrate the results into CDE platforms and connect IoT sensors for monitoring. This approach improves the accuracy of the assessment of the condition of structures and facilitates effective planning of repairs in remote communities. The quality and functionality of BIM models for small bridges are determined by a set of requirements covering the level of detail, interoperability and data management, reliability and safety of structures, as well as consideration of environmental factors and the entire life cycle of the structure. In accordance with international (Eurocode 1, 2003; Eurocode 2, 2005) and Ukrainian standards (DBN V.2.3-26:2024, 2025; BN01:4868-1755-9511-2275, 2025), each of these parameters is of practical importance for the design, operation and modernisation of bridge structures. The parameters are listed in Table 2.

Table 2. Requirements for the level of detail, interoperability and life cycle of BIM bridge models

Parameters	Description	Practical application
LOD	LOD 300-400 – used for the detailed design stage, when precise element geometry and attributes are required. LOD 200-250 – used in the conceptual and preliminary stages to save resources. All key parameters are specified: materials, compressive strength class, geometric dimensions, and data from previous inspections and repairs. For as-maintained models, LOD 350 can be used with an emphasis on the elements to be maintained.	Inclusion of attributes in the model for analytical calculations. Minimisation of detail at an early stage to save time and money. Gradual increase in LOD as the project develops.
Interoperability and data management	Support of export and import in IFC 4.3 format to ensure compatibility between different software products. Use of CDE (Common Data Environment) for centralised storage and management of models. Models should incorporate limit states, deformation effects, as well as hydraulic and environmental factors (flow velocity, flooding, ice drift).	Establishment of constant data exchange between the project and operational teams through CDE. Modelling of the impact of water flow on pylons to predict scour. Use of standard Psets for data transfer.
Reliability and security	Estimated service life of 50-100 years, covering the possibility of replacing individual elements (e.g., guardrails, expansion joints). Access for inspections (integration into the model of ladders, inspection platforms). Use of a colour coding system to indicate the status of elements: red – critical defect, yellow – warning, green – satisfactory condition.	Design of accessible points for maintenance. Automatic visualisation of the state of elements in a digital twin. Priority of repairs based on colour coding.
Environmental and life cycles	Integration of LCA to assess the environmental impact of materials (concrete, steel). Use of simplified functional units for small bridges, e.g. 1 m² deck. Environmental scenario modelling to assess long-term impacts and optimise materials.	Comparative analysis of material options based on LCA. Reduction of the carbon footprint by choosing more environmentally friendly materials. Preparation of reports for environmental certification.

Source: compiled by the author based on R.K. Raya & R. Gupta (2022)

The stages of creating BIM models of small bridges provide a full cycle, from data collection to integration with digital twins. For the rural regions of Ukraine, this can be used for rapid digitisation of bridges, centralised data storage, and increased efficiency in monitoring and maintenance. Therefore, the integration of BIM, DT and remote monitoring can streamline the process of assessing the technical condition of small bridges, reducing costs and increasing the safety of inspections. These observations correlate with the study by D.R. Polania *et al.* (2025), developing an integrated BIM methodology for bridge monitoring and assessment. The authors showed that combining data from different sources, from inspections and sensors to geospatial models, in a single digital environment can be used for high accuracy of assessments and efficient planning of repairs. They emphasised the flexibility of the methodology, which can be applied to large infrastructure assets as well as small bridges in local networks. The current results confirmed this conclusion, as the implementation of such integrated models in rural regions of Ukraine ensures that they work even with a limited set of attributes, gradually expanding the data model.

Safe remote access and inspection of bridges in the study by F. Luleci *et al.* (2022) were implemented by combining a monitoring system with virtual reality, which created a virtual reality (VR) environment for virtual inspections and provided safe access to complex or damaged areas of structures. The study demonstrated that this approach reduces risks to personnel and increases the detail of defect detection without physical contact with the object, and the results are in line with current research that also confirms the effectiveness of safe remote inspection methods, in particular for bridges in restricted areas or in war zones. The approach of

F. Luleci *et al.* can be effectively adapted to the Ukrainian realities, where the issue of inspection safety is becoming more relevant in this context. G. Hodge & J.M. Gattas (2026) highlighted the use of variable aerial photogrammetry data for semi-automated detection and measurement of geometric parameters of bridges. The study demonstrated that the use of LiDAR point cloud processing algorithms improves accuracy of identification of key structural elements and significantly reduces the amount of manual work during engineering surveys. The current study results also confirmed the value of this approach for rural regions of Ukraine, where the speed of data collection determines the possibility of conducting repairs in a short time. Moreover, such methods can be effectively integrated into the BIM environment, ensuring compatibility with international standards such as IFC 4.3.

H. Abdel-Maksoud (2024) proved the effectiveness of combining UAV-LiDAR and photogrammetry to improve accuracy, flexibility of access, and reduce inspection costs. Following the study, the use of UAVs for data collection significantly reduces the duration of inspections and reduces the impact of human error. This correlates with the current research findings: the use of drones with LiDAR and photogrammetry can be used for rapid initial inspections of bridges without stopping traffic and with minimal human intervention. In conclusion, this approach can be considered promising for the sustainable management of bridge infrastructure in conditions of limited resources. Thus, the introduction of integrated digital solutions in bridge monitoring and management optimises the life cycle of structures and reducing the risk of accidents. The combination of BIM, DT and remote inspection methods is a versatile and scalable tool for improving the efficiency of bridge maintenance in various operating conditions.

Regulatory and technical aspects and digital strategies for effective management of small bridges in Ukraine

In Ukraine, the implementation of BIM is regulated by Eurocode 1 (2003) and Eurocode 2 (2005), harmonised with the Guideline for the implementation… (2019) and ISO 19650-1:2018 (2018). The regulatory framework for the design of small bridges includes DBN V.2.3-26:2024 (2025) and BN01:4868-1755-9511-2275 (2025). The current policy of adapting standards is aimed to harmonise with European standards to improve compatibility with EU engineering practice. According to DBN V.2.3-26:2024 (2025), small bridges are regulated by separate requirements for loads, structural solutions and durability.

The main defects of small bridges in the rural network of Zhytomyr, Volyn, Cherkasy and Odesa regions of Ukraine include corrosion of steel elements (due to lack of proper protection in aggressive environments), deformation and wear of the pavement (cracks, damage to the protective layer, fatigue cracks). These problems are exacerbated by long-term operation, insufficient maintenance in remote areas and environmental influences (erosion, vibrations from transport). In reinforced concrete structures, there is a loss of stability of secondary elements, excessive plastic deformation and damage to drainage (Kirichenko, 2024). The analysis of specific regional examples of rehabilitation of small bridges in the rural road network of Ukraine was used to assess the characteristic design solutions, technical condition and typical problems of these facilities. In the Zhytomyr region, major repairs were conducted on the bridge over the Litky River at km 169+189 of the M-07 Kyiv-Kovel-Yagodin motorway (State Restoration Service of Ukraine, 2024b). This structure is a single-span reinforced concrete structure with a length of up to 25 metres and provides transport links to rural areas. The main problems with the structure were damage caused by military operations, in particular, deformation of the superstructure and corrosion of the reinforcement elements, which led to a reduction in its load-bearing capacity. In the Volyn region, a major repair of the bridge at km 35+085 of the M-19 Domaniv-Kovel-Chernivtsi-Terebleche motorway was conducted (State Restoration Service of Ukraine, 2024a). The bridge, which is 25 metres long, is a reinforced concrete beam structure that are substantial in connecting rural areas and ensuring interregional transport links. The main defects were worn and tear of the road surface, cracks in the concrete and a reduction in traffic capacity due to erosion of the soil foundations of the supports.

In the Cherkasy region, the 2024 infrastructure development programme envisages the rehabilitation of bridges on local roads in the rural network (Cherkasy Regional State Administration, 2023). Most of them are reinforced concrete structures up to 25 metres long, located mainly across small rivers. The main problem with these facilities is their emergency technical condition, caused by more than half a century of operation, corrosion damage and the destruction of individual elements under overload. In Odesa region, the Regional Development Strategy for 2021-2027 plans to reconstruct small bridges in rural areas (Odesa Regional State Administration, 2021). These are mainly slab or beam structures made of concrete or reinforced concrete up to 25 metres long. The main problems are soil erosion in the coastal zone, corrosion of steel elements, and cracks in the top layer of the road surface. Examples from the regions of Ukraine have shown that the problems of small bridges are common, ranging from corrosion damage and cracks in concrete to erosion of foundations and the effects of warfare, and their rehabilitation is integrated into the broader context of post-war reconstruction and digital transformation of infrastructure.

Existing technologies in bridge engineering cover a wide range of digital solutions, from information modelling and digital twins to artificial intelligence and mixed reality (Shen *et al.*, 2023). Their application aims to improve the accuracy of surveys, optimise the planning and life cycle management of bridge structures, reduce operating costs and ensure safety. Table 3 provides a comparative analysis of the implementation of key technologies, demonstrating their potential and limitations in bridge rehabilitation and maintenance.

Table 3. Characteristics and examples of implementation of innovative methods in bridge construction and operation

Technology/ Method	Advantages	Disadvantages	Implementation
BrIM with LCA/ LCC integration	Improved data integration for performance evaluation, reduced errors, time savings (up to 4.5 months of construction), better stakeholder collaboration, and data visualisation for monitoring.	Lack of standardisation for O&M, data compatibility issues, high upfront costs (70% of total cost), difficulties with data exchange for older bridges.	In Canada, a bridge reconstruction project was considered as part of the Construction 4.0 concept, where the BIM model of the bridge was integrated with LCA/LCC data to assess the carbon footprint, maintenance costs, and optimise design solutions. As a result, the construction period was reduced by approximately 4.5 months, and the choice of materials was optimised in terms of durability and sustainability.
BDT with BrIM, IoT, AI/ML integration	Improved visualisation, interoperability via IFC, automated damage monitoring, real-time analysis, and hybrid models for accuracy.	Lack of standardisation, interoperability issues, complexity of data processing, high hardware costs (laser scanning), and manual intervention for components.	In Portugal, a digital twin of a large transport bridge was introduced, integrating sensors and a BrIM model for automated defect detection and wear forecasting. The system provided timely detection of fatigue damage to components and reduced inspection costs by automating data collection and analysis.
DT with GIS and BIM integration	Real-time monitoring, optimisation of Operations and Maintenance (O&M) (drones for inspection), better visualisation of defects, graph algorithms for logistics, forecasting.	Limited extensibility of defect modelling (JavaScript Object Notation (JSON) instead of Industry Foundation Classes (IFC)), platform compatibility issues, and loss of detail in BIM-GIS integration.	In China, a digital twin project was implemented for the River Neath Swing Bridge, where drone data was integrated into a GIS-BIM platform to plan repairs, optimise traffic routes, and predict technical condition. The system was used for real-time traffic redirection and increased the efficiency of inspections.
BrIM framework for RC bridges	Improved visualisation of defects (3D models), automated report generation, centralised database for exchange, prioritisation of repairs through colour coding.	Limited for O&M (focus on design), complexity for inspectors, equipment costs (Unmanned Aerial Vehicle (UAV) with 3D scanners), narrow focus on RC bridges.	In Egypt, a BrIM model of a reinforced concrete bridge in Cairo was developed, which integrated survey, photo and laser scanning data. The model classified defects according to a colour-coded repair prioritisation scheme, which increased planning efficiency and reduced decision-making time.
A unified DT framework for bridges	Automated assessments, reduced inspection costs, data reuse, integration of UAVs and robots for monitoring.	The need for significant initial investment in the creation and maintenance of DT (data collection infrastructure, software systems, staff training), the complexity of processing large amounts of raw data, the lack of unified BrIM standards and incomplete source information.	In the US, the DT approach is used to analyse and prevent catastrophic failures, based on the experience of the I-35W bridge collapse in Minneapolis. The DT system was used for remote monitoring of the condition of structures and automatic assessment of the risk of failure, which could have prevented the tragedy if it had been used at the time.
BIM with MR (mixed reality)	Improved communication, accurate defect identification through augmented reality (AR), simplified inspection, data standardisation (IFC, BIM Collaboration Format (BCF)).	High upfront costs for equipment (UAVs), need for specialised knowledge, budgetary barriers for agencies, and dependence on BMS.	In Brazil, MR technology was used on the Coimbra I Viaduct by inspectors to visualise defects in the reinforced concrete structure in augmented reality, which significantly improved diagnostic accuracy and reduced the time required for inspections (no quantitative performance indicators available).
Immersive DT platform (IBDTP)	Automation of structural health monitoring (SHM), improved visualisation through AR, scalability, integration with IoT for monitoring.	High implementation costs and the need for skilled personnel; compatibility issues with different sensors and BIM standards; dependence on a stable internet connection; limited scalability with many objects.	In Poland, a digital model with IoT sensors was created for a concrete arch bridge, which provided real-time data on loads, deformations and damage to be obtained and visualised in an AR interface. This ensured accurate damage verification and accelerated repair decisions.
Deep learning for reconstructing geometry from drawings	Automation of 3D model creation from archived 2D drawings, fast digitalisation of old bridges, integration with BIM/openBIM (IFC), and reduction of field measurement costs.	The need for high-quality drawings, limited accuracy in the absence of some drawings, the need to adjust algorithms to local standards, and initial costs for developing a pipeline.	In Germany (Freiburg), deep learning was used to automatically reconstruct the 3D geometry of three bridges over the Dreisam River. The algorithm generated BIM models from PDF and CAD plans, which reduced the volume of field measurements by 65% and reduced the time required to prepare documentation by 40%.

Table 3, Continued

Technology/ Method	Advantages	Disadvantages	Implementation
LSTM with BIM for control	3D visualisation of defects, degradation prediction accuracy (95%), low error rate (0.15%).	The need for a large amount of historical data to train models; difficulty in setting up and integrating with existing BIM systems; high computational cost for long-term forecasts; risk of errors with incorrect or incomplete data.	In China, a condition prediction system has been developed for small concrete girder bridges on highways that can predict the wear rate of elements with an accuracy of 95%. This optimised repair schedules and reduced operating costs.
Data integration framework for RC bridges	Automation of BIM-FE data exchange, visualisation of results, resource optimisation, DT support.	Increased resources for detailed assessments, manual data exchange, need for expertise, and interoperability issues.	In the UK, Revit-Dynamo-Abaqus was used for the automated analysis of damaged reinforced concrete bridges. The system was used to quickly create a damage model and perform calculations to select the optimal repair strategy.

Source: compiled by the author

Innovative methods in bridge construction show significant potential for improving the accuracy of surveys, automating monitoring and optimising costs. The experience of the countries listed in Table 3 confirms the effectiveness of such technologies in reducing design and repair time, improving safety, and increasing the durability of bridges. For Ukraine's rural regions, the implementation of such solutions could become the basis for rapid digitalisation and more efficient use of limited resources. Based on international experience and Ukrainian realities, practical recommendations for the adaptation of BIM/BrIM technologies for small bridges in the rural road network have been developed. The presented areas include the determination of the minimum required data, the use of simplified models and open standards, the integration of digital solutions into the work of road services, as well as the harmonisation of national requirements with international standards (Table 4).

Table 4. Practical recommendations for the implementation of digital technologies in the design and operation of small bridges in Ukraine

Area	Description	Examples of implementation in Ukraine
Minimal dataset	Definition of the basic attribute composition for the bridge model: geometric parameters (length, width, height, span), materials (concrete, steel, wood), condition of elements (visual assessment, defects), operational characteristics (load capacity, date of last repair). Minimisation of data reduces the cost of collecting and processing information, which is especially relevant for rural bridges.	Use of IFC 4.3 Property Sets (Psets) with a limited set of properties for bridges in rural areas. Pilot bridge passports in the DREAM system with a minimum data structure for inventory. Minimal Information Data-Modelling (MID) approach using a low-cost monitoring system (~£370) for a short span bridge, providing a basic set of attributes for further integration into a BIM/openBIM environment.
Simplified models and standards	Use of the LOD 200300 levels of detail in the initial stages to quickly create models. IFC 4.3 format as the main format for data exchange, use of open libraries of typical bridge elements (spans, piers, guardrails), support for free viewers to increase accessibility.	Modelling of typical girder bridges in open viewers for regional road services; implementation of modular libraries in university curricula. Use of the openBIM (IFC 4.3) approach for modelling typical girder bridges, ensuring interoperability and integration with other engineering platforms.
Integration into the work of road services	Organisation of pilot projects using available technologies: UAVs for surveying, photogrammetry, and simplified 3D reconstructions. Involvement of construction students in training and practical work. Gradual incorporation of models into the maintenance planning system.	Pilot modelling of 1-2 bridges in each region using photogrammetry, cooperation with universities that use LSTM+BrIM for condition monitoring.
Adaptation of international standards	Development of unified BIM model templates for bridges in accordance with EU standards, integration into the DREAM platform. Marking of combat damage zones in the model (considering the requirements of recovery after military operations).	Development of IFC regional templates synchronised with DBN V.2.3-26:2024 (2025). Use of BEP/EIR to coordinate restoration projects in regions.

Source: compiled by the author

The integration of BIM/BrIM technologies into the design and operation of small bridges in Ukraine is justified for several key reasons. Firstly, small bridges form the basis of transport accessibility in rural areas, where the speed and cost of surveys are critical. The use of BIM/BrIM with minimal data sets can reduce the burden on local budgets while maintaining the required level of accuracy (O'Higgins *et al.*, 2023). Secondly, simplified models and open standards (IFC 4.3, openBIM) ensure interoperability and accessibility for regional road services, which is substantial in a resource-limited environment. Thirdly, integration into the DREAM system and harmonisation with European standards create a single digital ecosystem for bridge inventory and rehabilitation, including battle damage marking. These technologies improve the efficiency of repair planning and ensure the long-term operation of facilities in the post-war environment. At the same time, Ukraine still faces significant challenges in restoring infrastructure after military destruction and the need to work with limited financial and technical resources, which necessitate adapted digital solutions.

The results of the study showed that the introduction of a minimal set of data in BIM models of bridges, only key geometric parameters, materials and basic operational characteristics, can significantly reduce the cost of collecting and processing information, which is relevant for rural bridges. This was correlated with the findings of Z. Sun *et al.* (2024), proving that even a limited set of attributes in digital twins can support efficient maintenance and repair forecasting that combines multi-source data and expert knowledge without losing the accuracy of the estimates. The study determined that this approach helps to optimise resource consumption and extends the service life of structures without increasing the budget. The current results confirmed this effect in the context of the Ukrainian reality, where access to bridges in rural areas is often limited and a rapid inventory is needed. The use of simplified models with a level of detail of LOD 200-300 and open libraries of standard elements in the pilot projects ensured quick model creation and the ability to integrate them into repair plans. This proved to be effective for regional road services working with a large number of small facilities and limited funding. This was confirmed by K. Clute (2023), who found that standardised information templates greatly simplified the exchange of data between contractors and customers and guaranteed long-term compatibility of models between different software platforms. The study showed that eliminating redundant elements in the early stages of design speeds up the approval of working documents and reduces transaction costs. The results of this study also showed that this approach can be used to scale modelling from single objects to entire regional bridge networks without significant modifications.

The results of the study demonstrated that the pilot implementation of BIM templates adapted to the IFC 4.3 standard, with the marking of combat damage zones, showed the possibility of effective integration of these solutions into the DREAM platform and regional management systems. This correlated with the results of E.E. Tita *et al.* (2023), demonstrating that the scalable Digital Twin-BIM architecture creates a single source of reliable information and ensures interoperability between all bridge management stakeholders. The study emphasised that the gradual increase in detail can avoid overloading the model and maintain its suitability for long-term use. This methodology can be successfully used in the context of a limited data set, typical for post-war reconstruction in Ukraine. DT bridges are evolving towards practical application and efficient management. The review by V. Mousavi *et al.* (2024) highlighted the current conceptual obstacles and proposed a multi-level framework for digital twins in bridge management, with the integration of decision support systems and data fusion technology. This complements the current findings that a sustainable and scalable DT-BIM architectural approach with the ability to dynamically evaluate and automate the interaction of life cycle elements is a key direction for the development of bridge digitalisation.

Thus, the implementation of the proposed areas of BIM/BrIM adaptation for small bridges in Ukraine will significantly optimise the inspection and repair planning processes, reducing the cost of data collection and processing. The use of standardised models and open formats will ensure interoperability between organisations and create a basis for scaling digital solutions to other transport infrastructure facilities, from culverts to overpasses. Additionally, it will improve the accuracy of engineering calculations, transparency of rehabilitation investments, and the introduction of long-term condition monitoring.

Conclusions

The results of the study of the structural features of small road bridges in the rural road network of Ukraine and the possibilities of digital technologies for their inspection showed that most of these structures have significant wear and tear due to long-term operation, insufficient maintenance and the impact of aggressive natural and man-made factors, including military operations. Traditional survey methods provide only local and fragmented data, while digital technologies (BIM/BrIM, laser scanning, photogrammetry, UAVs) ensure the creation of complex 3D models integrated into a single information environment, speeding up surveys, increasing the accuracy of technical condition assessment and optimising operating costs. Their use has proven effective in Canada, where construction time was reduced by about 4.5 months; in Germany, the volume of field measurements was reduced by 65% and the time for preparing documentation was reduced by 40%; in China, the accuracy of predicting the degradation of bridge elements reached 95% with an error of 0.15%; in the UK, the use of minimal sensors for short-span bridges limited monitoring costs to 370 GBP.

Several strategic measures were recommended to adapt digital solutions to the conditions of Ukraine, including reducing the amount of data to save resources, using models with a basic level of detail of LOD 200-300, introducing tools into the activities of road services, harmonising standards with European norms, and testing technologies through pilot projects in different regions. The systematic application of BIM/BrIM with open data exchange formats will ensure consistency between participants in the design and operational processes, create a basis for the expansion of digital solutions to other transport facilities, and increase investment transparency. The integration of digital twins and IoT technologies into bridge monitoring will help to quickly detect damage and improve the safety of their operation. The use of digital technologies to analyse the life cycle of bridges will help select environmentally sustainable materials and reduce environmental impact.

Limitations of the study include the lack of a unified national methodology for collecting and processing data for small bridges, as well as the high cost of equipment, which can complicate implementation in remote regions. Further research should focus on creating national open libraries of typical bridge elements, developing low-cost sensor monitoring systems, and expanding DT integration with road infrastructure management systems in Ukraine.

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Conflict of Interest

None.

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Інформаційне моделювання в аналізі стану малих мостових споруд у сільській дорожній мережі: виклики та рішення

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Анотація. Метою дослідження було визначення ефективних підходів до використання цифрових технологій для оцінки стану та планування відновлення невеликих транспортних переходів з урахуванням обмежених ресурсів та вимог сумісності даних. Методологія поєднувала порівняльний аналіз, створення Building Information Modelling, кейс-стаді регіональних прикладів та систематизацію міжнародного досвіду. Було встановлено, що цифрові методи забезпечують міліметрову точність вимірювань, скорочують час збору даних та дають змогу створювати детальні 3D-моделі, а також прогнозувати знос завдяки алгоритмам глибокого навчання. У Житомирській, Волинській, Черкаській та Одеській областях України були зафіксовані дефекти мостових споруд: у Житомирській – пошкодження від воєнних дій, у Волинській – тріщини в бетоні та ерозія ґрунтів, у Черкаській – наслідки тривалої експлуатації понад 50 років, а в Одеській – корозія сталевих елементів у поєднанні з агресивним прибережним середовищем. Підтверджено, що інтеграція даних у середовище Building Information Modelling Digital Twin підвищувала точність прогнозів до 95 % (у Китаї), а також фіксувалось скорочення часу та трудових витрат на 40-65 % при використанні алгоритмів deep learning у Німеччині. Застосування безпілотних літальних апаратів із Light Detection and Ranging та фотограмметрією дозволило обстежувати мости з мінімальним впливом на рух і людський фактор, що суттєво у віддалених чи небезпечних районах. На основі узагальнення міжнародного досвіду впровадження інноваційних методів у мостобудуванні було рекомендовано використання відкритих форматів і спрощених моделей, що сприяють зниженню витрат на обстеження та скороченню часу підготовки документації. Результати можуть бути використані дорожніми службами для планування ремонтів, управління життєвим циклом мостів та відновлення споруд в Україні з підвищеною прозорістю й меншим екологічним впливом

Ключові слова: цифрові двійники; відкриті формати; життєвий цикл; міжплатформна сумісність; прогнозування зносу; семантичне збагачення; автоматизований моніторинг