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BIM-based immersive meetings for optimized maintenance management of bridge structures

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Abstract

Along the long service life of the approximately 65,000 bridges in Germany of more than 50 years, it requires the execution of many meetings under the participation of many different parties. These meetings are still location-bound and run very manually using analog inventory documentation. For an optimization, further digitization as well as dissolution of the location dependency at the structure, immersive technologies can be used in connection with digital twins of bridge structures.

This article presents an approach for a location-independent meeting at the bridge structure under the integration and possibility of interaction of all actors and linking of the digital and physical world. A digital building model of the bridge serves as the data basis and immersive technologies such as augmented and virtual reality as the output and interaction technology. In the first section, the status quo is elaborated based on a literature review. This is followed by the presentation of the theoretical concept. In the next step, the concept is implemented and validated by using a real bridge demonstrator. Finally, further development possibilities as well as still existing challenges are derived.

The result of the article shows a concept and the first feasibility of location-independent meetings in the maintenance management of a bridge by merging the following elements.

Keywords

Immersive Meeting, Augmented Realty, Virtual Reality, Extended Reality, Building Information Modelling, Bridge structures, Digital Model, Maintenance Management

1 Introduction

In recent years, virtual reality (VR), augmented reality (AR) and extended reality (XR) technologies have evolved from a niche technology to an accepted technology for visualization and interaction capabilities. Today, the potential applications span many different industries. For example, the technology is used in education, information and communications, healthcare, or manufacturing and construction industries [1]. XR can be used to visualize, test, and optimize complex structures and processes in immersive environments [2–4]. As a result, the basic comprehensibility of the interrelationships is increased and, in the same course, the associated costs are reduced [2, 5–7]. In contrast, challenges to integrating immersive technologies exist at the procedural and informational levels [8–10]. In order for a communication to be perceived as natural and simple, it consequently requires the use of elements of a natural conversation in the interaction space. For this purpose, special devices (augmented reality glasses / VR headset) offer different possibilities of interaction [11–14], such as marking, speaking, commenting, highlighting, etc. [15–17]

There are approximately 65,000 bridges in Germany [18–20]. Many of them are complex structures [21] with an expected service life of more than 100 years [22]. For an efficient and realistic maintenance management, a continuous exchange between different actors about details and facts is necessary. For this purpose, defining a common time and place often proves to be extremely difficult. In addition, the steps performed in maintenance management are largely manual in practice [22]. The basic processes are defined according to DIN 1076 [23]. The goal is to achieve the highest possible immersion and thus acceptance of the user in the context of the technology used (VR/AR/Desktop) and to enable interactive meetings independent of location.

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2 Methodology

This scientific article presents the development of a concept for conducting immersive meetings based on digital twins for optimized maintenance management of bridge structures. It is divided into three parts: (i) related work, (ii) development of the concept, and (iii) validation of the concept. At the beginning, the status quo of the use of extended reality (XR) is reviewed and presented based on a literature review. In the first subsection, the general use of immersive technologies is considered. Subsequently, the focus is directed to the construction industry and a human-technology interaction with immersive technologies in the specific use in the life cycle of bridge structures is characterized. After identifying the research gap in the status quo, the concept is developed in the second part. The focus is on linking human-technology interaction for location-independent meetings through the use of AR and VR. Location independence connects the real world with the digital world. Digital twins of the buildings are used as the basis for the meeting. The concept in this article focuses on bridge buildings. The chapter describes the concept in detail and visualizes it in a system model. A validation of the first concept for immersive meetings on bridge structures is provided on the basis of a real demonstrator, a pedestrian bridge in Aachen, Germany. This demonstrates and confirms the basic feasibility of the concept. At the end of the article, a critical evaluation of the results is made and an outlook on the resulting research questions is given.

3 Related Works

3.1 General about immersive and meetings

With the further development of XR technology, meetings are becoming increasingly virtualized, merging the real and virtual worlds [24]. This requires the use of special AR glasses (e.g. Microsoft Hololens) [25] or VR headsets (e.g. Meta Quest 2) [26]. In addition, a special collaborative platform serves as the basis of the interactions as well as the provider of the necessary data fundamentals (e.g. Microsoft Mesh Platform) [27] . This allows users to work together agnostically. Regardless of the end device used, users can enter a session with their own avatar and jointly perform rudimentary tasks on a virtual object, as well as verbally and gesturally exchange information about it. The corresponding "object" is purely virtual for each user and is projected into his or her room [24, 28].

An AR device usually orients itself to measured position differences relative to its environment, and projects holograms in relation to it. However, when using SLAM algorithms, the environment is unknown in advance [29]. As a result, association or mapping of virtual contexts to the environment can usually only be implemented during the actual runtime. To address this problem, special frameworks have been developed to fix the coordinate system for optimized centering and projection of the virtual world into the real environment, titled as "world-locking" [30–32]. This enables the provision of clear reference points, also called "anchor points", from the real world (e.g. QR codes) to the AR glasses. This allows the location of real world anchor points to be completed with predefined points of the virtual model [31, 32]. For example, there exists a framework developed by Microsoft called "World Locking Tools" [33] that is used in the context of research projects [31, 34, 35].

Approaches and implementations of immersive and collaborative meetings are being explored in different scenarios in the scientific community. Lee et al. present an approach of an immersive collaboration environment for craft implementation using AR, VR & LiDAR scan techniques [36]. Thanyadit et al. developed an immersive virtual labour environment for testing and training collaborative lab work using different toolsets [37]. Furthermore, Lee and Yoo present an XR remote collaboration system and its application to the case studies of remote maintenance and ball valve replacement [38]. In addition, Mourtzis et al. describe a cloud-based platform for an immersive meeting environment for collaborative product design in terms of a digital learning factory [39]. A special use case of the Microsoft Mesh platform for immersive meetings is addressed in the scientific article by Dong and Liu [28].

3.2 Immersive technologies in the construction industry

In the progressive establishment of the BIM method in the construction industry and the creation of a qualitative data basis for further technologies, immersive technologies are already being applied in various areas. For example, AR technology is already being applied across the complete lifecycle -planning, execution, operation and deconstruction [40]. Thereby the technology is used for visualizations and simulations [41, 42], for communication [43, 44], information processing [45, 46] but also for training and education [47, 48] and safety inspections [49, 50]. Furthermore, there are applications of the technology directly in the construction execution phase, for example in the construction progress monitoring [51] and the damage identification [49, 52, 53]. In contrast, AR technologies can also be used for evaluation [54], updating [44] and validation of digital models [55]. In addition, approaches exist for using AR devices for data collection and communication on the construction site [56].

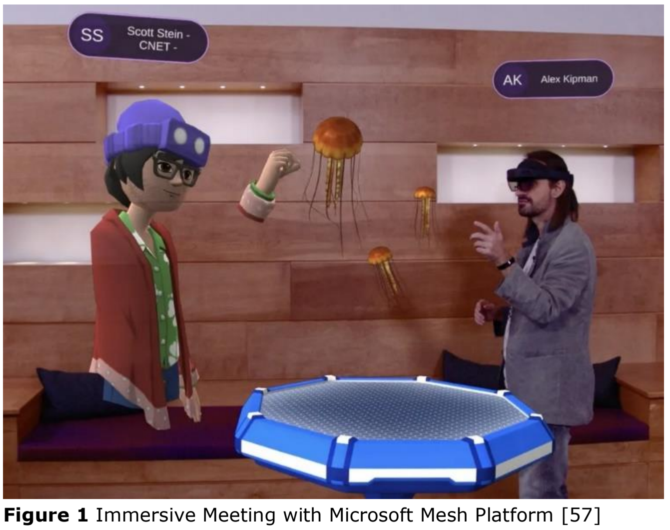

Figure 1 Immersive Meeting with Microsoft Mesh Platform [57]

At the same time, VR technology also has a wide range of applications in the construction industry. It is used for VR for example for design reviews in the planning phase; visualization and presentation of BIM models, as well as for obtaining feedback from external persons [58, 59]. In addition, VR-based training and education [60–62] and construction site monitoring are held in conjunction with the BIM model [63].

If both technologies (AR and VR) are used in combination, this is also referred to as mixed reality. In this area, too, there are initial approaches in the construction industry, with a digital BIM model of the construction site or structure serving as the data basis. Catbas et al. present various applications of the use of XR for condition assessment of complex building structures in building construction and infrastructure [64]. Al-Adhami et al. use XR debuggers for quality assessment between the real structure and the digital model source [65]. In addition, XR approaches are also applied to the field of construction site safety and summarized by Salinas et. al. in their scientific article [66]. Furthermore, Alizadehsalehi and Yitmen describe an XR-based approach for a novel progress control using digital twinning at the construction site [67].

3.3 Immersive technologies in the bridge life cycle

In the field of bridge inspection focused in the scientific article, immersive technologies (AR and VR) are also applied in combination with more advanced technologies. For example, VR technology is used during bridge inspection for project documentation [68], for detailed display of captured damage images in the virtual environment [69] or for training objectives in the office environment [70] as well as in interaction with drones [71]. In addition, it is used for an optimized inspection process and VR Technology with a laser scanning method [72]. Furthermore, more advanced approaches of AR-based bridge inspection exist. For example, the AR device can be used as a stand-alone system for damage detection with a BIM-Model as a data base [73, 74]. In addition, AR glasses can be coupled with drones [75, 76] or as a visualization medium for displaying recorded data from inspection procedures in structural diagnostics [77, 78].

The first approaches to immersive meetings are already possible and promote the collaboration of project participants by linking the real world with the virtual world. In the construction industry, the first use cases in immersive technologies (VR/AR/XR) are already being used, but the possibility of a location-independent meeting based on digital BIM models is not yet possible. This research gap is closed within the scope of the article and a first approach of an immersive meeting in the context of the BIM method is conceptualized and validated using the example of a bridge meeting in maintenance management.

4 Concept Development

In order to create a demarcation and a simultaneous merging of partial work already done in this field, the core aspects of collaboration in XR are identified following and integrated/attributed by means of a virtual bridge inspection. Thereby, three main domains are distinguished in the concept:

1. Coherence of virtuality and reality
2. Information exchange of the involved parties (verbal and non-verbal communication)
3. Visualization and production of contextual information

The first domain of the concept describes the coherence of virtuality and reality. Coherence (in our sense, the correspondence of virtual and real environments, synonymous with synchronization) depends on the degree of the output device used (VR/AR/desktop computer). While a navigable, detailed 3D model on a monitor may seem sufficient for a desktop user, the requirements for an implementation in AR are incomparably higher. If the 3D model of the bridge is to be projected onto its real counterpart on site, a precise overlap must be ensured. With the help of the "World Locking Tools" toolkit [33] and six printed QR codes on the super structure, the virtual data should be given a fixed reference point in reality. This increases the coherence of both levels (virtuality and reality) and the degree of immersion of the user. Once coherence is ensured for each user individually, the positions of each user relative to the building are synchronized via a newly set up network. The result is a synchronized space in which each user perceives his or her position relative to the virtual model to be coherent. Moreover, the visual representation of the other users in the form of their avatars is also perceived as coherent with their positions. This is a basic requirement for information exchange in the immersive meeting.

The second domain of the concept focuses on the exchange of information between the parties involved. This implies verbal and nonverbal communication. While verbal communication (speech and writing) is standard in many areas of digital work, nonverbal communication is the key factor of an immersive meeting. In this context, a precise gesture, e.g. a "pointing" to an object to be viewed, is more effective than a description of the context. Thus, the immersive meeting ideally provides both verbal and nonverbal means of communication. These possibilities are always dependent on the terminal device used. In the context of the developed concept in this scientific article, both means of communication are considered. Both the possibilities of voice control and the use of gestures are possible in the immersive meeting at the bridge structure. The basis of the immersive meeting at the bridge structure is a digital, object-oriented, digital BIM model. This is the basis for the collaboration and serves as a consistent database. This means that the same, up-to-date data is always transparently available in the model to all participants.

The last domain considers the viewing and production of contextual information during the immersive meeting. A digital and efficient method for planning, modeling and control in the construction sector is Building Information Modeling [79]. The immersive meeting builds on the BIM method and provides a bidirectional data exchange between the XR-environment with a Common Data Environment (CDE). Thus, insights gained during the meeting can be located as semantic information on the model and transferred to the CDE.

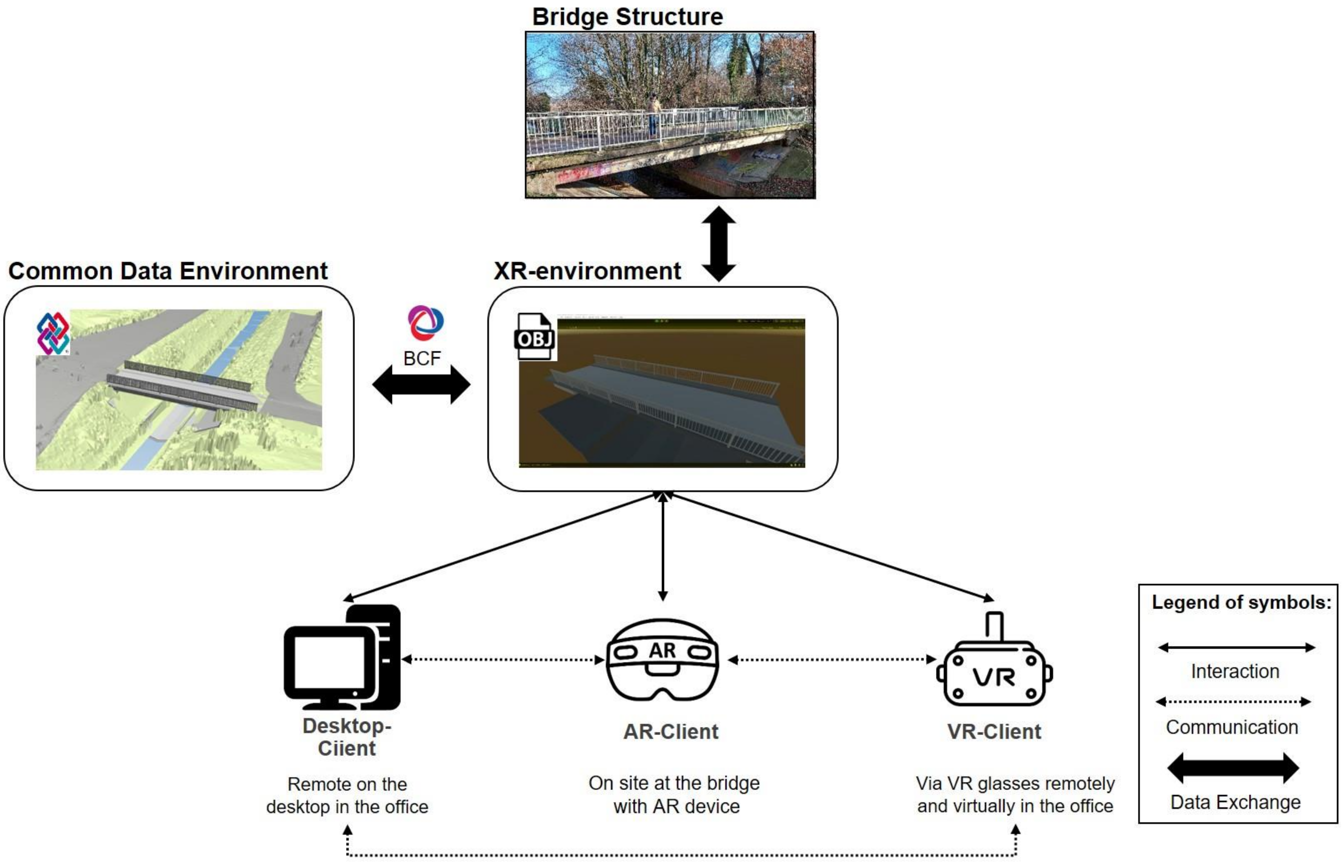

Figure 2 System model of the immersive bridge inspection

The same applies to the use of new data from the CDE during the immersive meeting in the XR-environment. In this way, the concept of the immersive meeting also supports the idea of a single source of truth [80]. Via the technology of the different end device applications, all participants have the possibility to communicate in real time on the basis of a uniform and transparent database (BIM model). This can be done by voice, chat, or iterative gestures in the real world. In addition, an exact visibility of one's own location in relation to the building can be perceived by the other participants in the conversation. Each registered user can log in to the XR-environment via a VPN client and participate in the immersive meeting with the corresponding end device. The current BIM model of the bridge with all relevant information is displayed for all participants. In this way, everyone in the meeting can learn about the condition of the structure by exchanging facts about it or damage patterns as well as jointly discussing further measures. Furthermore, it is possible to create annotations in BIM Collaboration Format (BCF) directly on the digital model in the XR-environment. These annotations are then also transferred to the CDE in real time as a BCF issue via the bidirectional data interface.

Table 1 Description of the immersive meeting participants

User-Name	Description
Structural Inspector  On site at the bridge with AR glasses	On site at the bridge, the structural inspector stands with augmented reality glasses and performs the structural inspection. Before recording a new damage, he wants to check whether this damage has already been recorded in previous inspections or whether it has increased. Instead of handwritten or isolated database notes, he would ideally like to transmit the damage recording directly to the digital twin - in this case as a topic note in the CDE of the BIM platform.
Asset Owner  Remote at the desktop in the office	The asset owner - if necessary, with the participation of an extended team of experts from different specialist roles - follows the structure inspection live from his desktop computer. This enables the operator to find out the current condition of the bridge structure and to

	react and intervene directly in critical situations.
	From a third location, e.g. an engineering office, another specialist engineer (e.g. with a focus on welding/concrete technology) also follows the structure inspection and uses VR goggles to examine the exact damage site in the virtual model. This allows the maintenance manager to directly examine the detected damage, draw conclusions about the condition of the bridge, and to directly intervene if required. If necessary, she can ask questions in real time to the structure inspector as well as to other colleagues on site and simultaneously view the damage in the model.

5 Implementation and Validation

The basic feasibility of the immersive meeting is illustrated by the example of a bridge inspection through the implementation of a proof-of-concept. It is carried out directly on a demonstrator, a pedestrian bridge in Aachen. For this purpose, a digital model of the bridge (s. Fig. 2) was created on the basis of a laser scan. In the first step, the digital model is stored in a Common Data Environment in the open data exchange format Industry-Foundation-Class. When the immersive meeting is conducted on the bridge inspection example, the BIM model is transferred from the CDE to the XR-environment. The XR-environment is based on a game engine, in this case Unity. During the transformation, the IFC data format is converted into an OBJ data format and a meshing algorithm is executed.

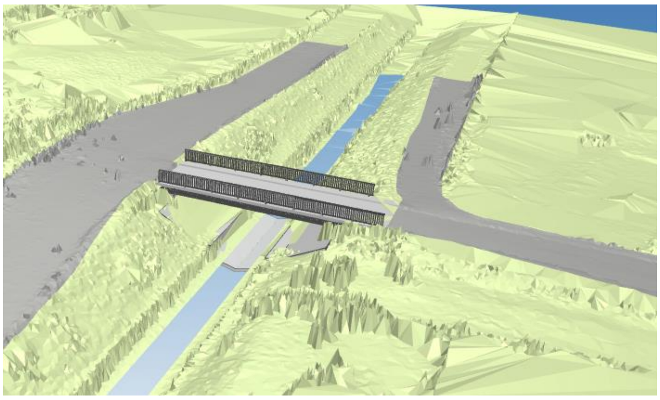

Figure 3 BIM-Model of the bridge structure

Meshing generates an additional "mesh layer" (s. Fig. 3) over the digital model from the digital bridge model. The digital model in OBJ format of the bridge serves as an interaction layer in the AR environment on the real object. Interaction in the VR environment and web-based platform is based on the digital building model in IFC format. Before the actual immersive bridge jump, the bridge is prepared for matching the digital model and the real object. For this purpose, printed QR codes serve as anchor points for the synchronization of the real and virtual coordinate systems (see Fig. 5).

Figure 4 Mesh-Layer of the digital model

At the beginning of the meeting, the QR codes on the real bridge were scanned with the AR glasses (Microsoft Holens 2). In the same course, the "World Locking Algorithm" [33] was executed and the digital mesh model in the XR-environment was aligned with the real bridge. As a result, a coherence of the real world with the virtual world was generated. Thus, the real coordinate system is superimposed on the digital coordinate system and there is an exact overlap between the real bridge and the digital model. This guarantees low deviation tolerances when interacting with the model. During the implementation, a deviation of 3 cm was found between the real object and the digital model.

Figure 5 Scan of the QR-codes with the AR-Device

For the proof-of-concept, three users are considered for the immersive meeting at the bridge structure (s. Table 1). An AR client located directly in front of the real bridge while performing the inspection. As well as two users, each in a VR environment and a web-based platform to participate via the digital model. All users receive individual access to the platform via a VPN client. To conduct an immersive meeting, an on-site cellular connection is essential. During validation, the existing LTE network of the mobile operator is sufficient. Each participant in the meeting receives his or her own avatar. The AR client is displayed as an avatar with its exact position on the digital model on the XR-environment (see Fig. 6).

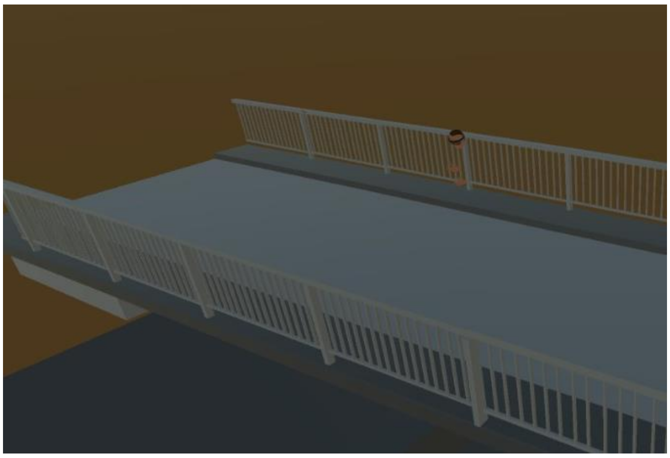

Figure 6 AR-client avatar in the XR-environment

The other two clients (VR and desktop) are displayed in augmented reality with their exact viewpoint as icons. Thus, all participants know the exact positions as well as the viewing angle of the others. This ensures transparent collaboration. All participants, in total three people, were able to successfully participate in the meeting and communicate via gestures and speech in the model. In this first prototype, the representations of semantic information in the model or use of a BCF data point in bidirectional data exchange with the CDE are not yet possible. The aim here was to demonstrate the basic feasibility of an immersive meeting based on a digital BIM model using the example of a bridge structure.

6 Discussion

The article presents the approach of an immersive meeting on the example of bridge structures using digital BIM models. By implementing the concept as a proof-of-concept on a real demonstrator, the basic feasibility was shown. All clients can participate and interact in the immersive meeting via different end devices using a secure VPN access. In addition, the digital model was synchronized with the real model in a passable manner with a minimum deviation of 3 cm. Future use of the immersive meeting will allow processes, meetings, and inspections to be conducted regardless of location. Thus, in case of acute problems, experts can always be called in via the immersive meeting. Furthermore, the immersive meeting strengthens the collaboration of all stakeholders in the operational phase of bridge structures. On top of that, the idea of a single source of truth and the openBIM approach in the context of the BIM method is strengthened by the bidirectional interface with a real-time data exchange between the XR-environment and a CDE as well as the use of open data formats. Furthermore, the establishment of a digital twin is also promoted, as the immersive meeting approach more closely merges the real and digital worlds.

In addition to the positive aspects of the implemented concept, the approach also has limitations. One limitation of the approach is the existing deviation between the real object and the digital model. Although the deviation is approximately three to four centimeters, the printed QR codes as reference points have a high error rate. This can be optimized by using a GPS device for accurate georeferenced synchronization. Another limitation is the need for a mobile data network to perform the approach. This can cause problems if the bridge is located in rural areas. In addition, limitations exist in the existing robustness of the system. At the moment, this approach is still a specific "single solution" without a full practicality for the operational processes of maintenance management. In the article, the first approach was presented and only the basic feasibility of the approach was presented to an immersive meeting.

Further research steps are derived from the existing limitations. In the future, the reality will be synchronized with the virtual environment via GPS. Furthermore, the system architecture will be further developed in order to increase robustness. In addition, the interface of the bidirectional data exchange in real time with a CDE will be further developed. Another important point in further research activities is the representation, processing and modification of semantic information of the digital model directly on the XR-environment. To ensure qualitative practicability, further validations on real demonstrators will be implemented for the optimization cycles and expert opinions will be obtained. Furthermore, the approach of an immersive meeting can also be transferred to other structures of the transport infrastructure or building constructions.

7 Conclusion

The scientific article presents the concept of a location-independent meeting on bridge structures using digital models and immersive technologies. The theoretical basics and the general approach of the immersive bridge meeting are described and presented in a system model. This was followed by the implementation on a real demonstrator to show the feasibility and initial validation. Subsequently, the results obtained were discussed, added values were shown, and limitations and further research activities were identified.

The new approach of an immersive meeting using digital models and XR technologies promotes the further digitization of the transport infrastructure sector and supports the further area-wide implementation of the BIM method. Furthermore, collaboration between stakeholders in the operational phase, but also in other lifecycle phases of a structure, are strengthened. The interaction between man and technology in bridge construction is also optimized. This improved collaboration results in increased process quality and efficiency. This also supports the goal of increasing the service life of existing bridge structures.

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