Metaverse in Civil Engineering

Insights from an application for students

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Abstract— **The integration of the metaverse in civil engineering education offers transformative opportunities for enhancing learning outcomes through immersive and interactive digital environments. This study explores the implementation of metaverse-based teaching methodologies in civil engineering courses at Technische Hochschule Köln (TH Köln), focusing on "Digital Design and Construction," "Building Construction," and "Building Physics." A metaverse application was developed and tested, incorporating Augmented Reality (AR) and Virtual Reality (VR) technologies to facilitate interactive learning experiences. The study involved structured workshops, expert interviews, and student evaluations to assess engagement, comprehension, and skill development. Results indicate a significant increase in student confidence and motivation when using metaverse-based learning tools, though we did not find significant differences in exam performance compared to traditional teaching methods. Challenges such as technological accessibility, motion sickness, and content standardization were identified as key barriers to widespread adoption. The findings highlight the potential of the metaverse to revolutionize engineering education, emphasizing the need for further research on long-term learning effectiveness, scalability, and integration with Building Information Modeling (BIM) and Digital Twins.**

Keywords—Augmented Reality (AR), Virtual Reality (VR), Metaverse, Civil Engineering, Digital Learning

I. Introduction

The construction and real estate industry is undergoing a rapid transformation, driven in part by the increasing necessity to achieve climate targets. Currently, the construction sector is responsible for 37% of global CO_2 emissions [1]. To facilitate change, innovative digital competencies and teamwork-oriented skills must be embedded in education. Digital learning, in particular, presents a key opportunity to foster future skills and enhance the sustainability of building projects.

Despite the evolving landscape of engineering education, traditional teaching methods such as lectures and exercises remain predominant in civil engineering curricula [2]. As a result, many programs focus primarily on theoretical knowledge, often neglecting the development of critical future skills, which include analytical, social and digital competencies [3, 4]. Given the increasing complexity of the construction industry, civil engineering students must be equipped with advanced problem-solving abilities, interdisciplinary collaboration skills and digital proficiency [5].

To address this need, digitalization must be further integrated into civil engineering education. Institutions like the TH Köln have begun incorporating digital aspects into their curricula, particularly in the fields of building construction and building physics. These subjects require a deep understanding of structural behavior, material properties, and energy efficiency, all of which can be significantly enhanced through digital and immersive learning methods.

The metaverse offers a transformative opportunity to further digitize education. By merging virtual and real-world experiences, the metaverse facilitates interactive, immersive learning environments. At the TH Köln, two modules, "Building Construction" and "Building Physics," have incorporated metaverse-based teaching methods. This initiative aims to improve not only technical competencies but also communication skills, teamwork, socialization skills and the ability to hande new technologies, all of which are increasingly vital in a digitalized construction industry.

This paper explores the integration of the metaverse into civil engineering education, focusing on workshops and evaluations with students. Hereby, the study focuses on the courses “Digital Design and Construction”, “Building Construction” and “Building Physics”. The study examines the advantages and opportunities of utilizing the metaverse as a learning tool while also addressing the challenges associated with its adoption. Through a detailed analysis of student engagement, learning outcomes, and feedback, this research provides insights into the effectiveness of extended reality (XR) technologies in shaping the future of engineering education.

II. Background and Related Work

The integration of the metaverse into education has gained significant attention in recent years, particularly within Architecture, Engineering, Construction, and Operations (AECO) disciplines. This is due to an increasing interest about the metaverse in the AECO industry [6–8]. The metaverse, a virtual environment where real and digital worlds merge, offers innovative opportunities for teaching methodologies by incorporating Virtual Reality (VR) and Augmented Reality (AR) to enhance student learning experiences [9].

One aspect, that is mentioned in educational studies, is the improvement in design stages of buildings, e.g., architectural design [10]. Within the domain of civil engineering education, implementing the metaverse in the teaching has shown promising results in improving student engagement and comprehension, e.g. in studies about Building Information Modeling [11, 12].

A. Metaverse in Civil Engineering Education

The integration of the metaverse into the education of civil engineering, traditional teaching methods need to be broken down. Traditional teaching approaches in AECO education often include lectures, exercises, tutorials or project-based learning. However, these approaches may not always effectively convey complex concepts, particularly those related to spatial visualization and interdisciplinary collaboration. The metaverse presents an opportunity to overcome these challenges by providing a virtual, interactive space in which students can engage with teaching materials independent of time and date [13].

Studies have demonstrated that immersive technologies, including VR and AR, can enhance education by improving students' understanding of complex topics, increasing engagement and offering location-independent learning experiences. Furthermore, the metaverse has increased the study interest in the taught courses in various studies and improved the learning outcomes [14–16].

Also in civil engineering, the implementation of the metaverse could particularly be beneficial in teaching. Studies in courses about digital design and construction have shown, that the study interest and self-assessment regarding the understanding of the topic has increased, as the metaverse allows students to explore 3D building models interactively, analyze construction sequences, and collaborate in virtual environments (Bartels et al., 2024). Additionally, metaverse-based teaching provides opportunities for gamification, which has been linked to increased motivation and learning outcomes [17].

B. Implementation of the metaverse in BIM, Building Construction, and Building Physics

Several studies have explored the potential of the metaverse in teaching civil engineering. Regarding the three courses, that were implemented in this study, there can be found related work:

- Bartels and Hahne (2023) developed a metaverse-based educational framework in which students participated in virtual workshops and tutorials, focusing on BIM-related concepts. The findings indicated that students who engaged with metaverse environments exhibited a deeper understanding of BIM principles and improved collaboration skills [18].
- Regarding building physics, hardly any publications are available. Although there are a large number of publications dealing with classical physics, e.g., [19], the integration of metaverse and building physics in teaching is not yet very advanced or focusses on certain sub-areas of building physics [20].
- Also, regarding teaching building construction, hardly any publications are available. Nevertheless, studies show, that especially mathematical based courses can be implemented in the metaverse [21].

The studies show that integrating the metaverse into the courses enables students to interact with virtual realities and could better imagine the teaching subjects. For the courses „Building Construction" and "Building Physics" the following applications and use cases could be possible based on the literature review:

- Integrating the metaverse into Building Construction courses enables students to visualize construction sequences, simulate structural load transfers and interact with digital building elements. This interactive approach helps bridge the gap between theoretical knowledge and practical application.
- In Building Physics education, metaverse technologies facilitate the visualization of heat transfer, acoustics, and energy efficiency concepts, which are often difficult to grasp through traditional methods.

C. Challenges

Despite the benefits of incorporating the metaverse into civil engineering education, several challenges remain. One significant barrier is the high cost of hardware and software required for VR and AR applications. Additionally, concerns regarding digital literacy, data security and the potential for social isolation among students must be addressed [18]. Furthermore, there is a need for standardized methodologies and interoperable platforms to ensure seamless integration with existing educational frameworks.

Nevertheless, the use of the metaverse in civil engineering education, particularly in the teaching of BIM, Building Construction, and Building Physics, presents a transformative approach that enhances learning outcomes and student engagement. While challenges exist, ongoing research and technological advancements continue to refine and optimize Metaverse-based teaching methodologies, focusing on developing cost-effective application tools, enhancing digital literacy among students, and establishing standardized frameworks for integrating the metaverse into civil engineering curricula.

III. Methodology

To evaluate the integration of the metaverse in teaching civil engineering, a structured methodology has been used. An overview of the four steps are shown in Figure 1.

In the first step, the integration of the metaverse was evaluated in one course. The course "digital design and construction" was held in 2023 and integrated various workshops, lectures and tutorials regarding the metaverse. Besides the workshops, that were evaluated by quantitative surveys, the poster presentation reflected the learning outcome and knowledge of the students.

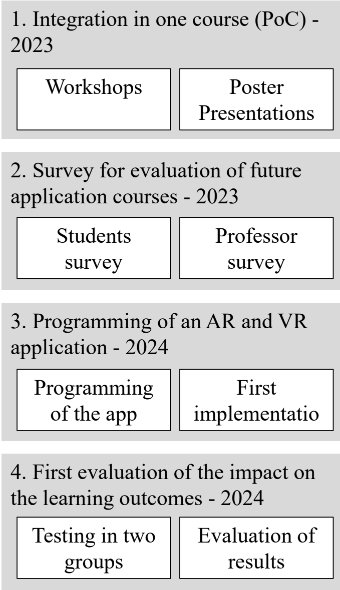


Fig. 1. Methodology

In a second step, expert interviews were conducted to analyze the potentials and challenges of engineering education in the metaverse. The expert interviews were done with professors and academic staff. The participants included four experts from civil engineering, two from architecture, and one from plant, energy, and machine systems, totaling seven interviewees with varying levels of knowledge about the metaverse.

The semi-structured interviews were analyzed using MAXQDA software, following the grounded theory approach. An iterative coding process identified three main categories: (1) general questions on teaching, BIM and the metaverse, (2) the implementation of teaching in the metaverse and (3) visualization using the example of a lecture hall at the university. The analysis was conducted in three phases: first, assessing the current state of teaching and knowledge on BIM, practical relevance and the metaverse; second, exploring the implementation of metaverse-based teaching using the lecture hall (see Fig. 2 and Fig. 3) as a case study to develop ideas and evaluate challenges; and third, deriving concrete recommendations for implementing education in the metaverse. The final discussion with the Center for Teaching Development further enriched the evaluation by integrating didactic perspectives.

Furthermore, the students of the first and third semester were asked in a survey, which courses they would implement into a metaverse application. In total, n = 89 students participated in that survey, that was conducted in November 2023. The results showed, that especially building physics and building construction are seen as possible applications for metaverse in civil engineering.

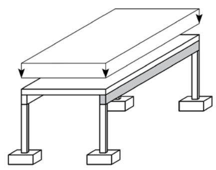
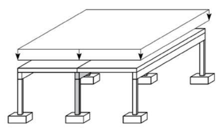
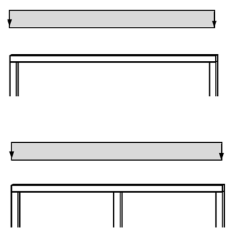
Based on that, an application was programmed in 2024 in step 3. The application was programmed by students from the Institute of Media and Imaging Technology and were supervised by professors from the aforementioned institute as well as professors from civil engineering. Two modules regarding "Building Construction" and "Building Physic" were implemented.

In the fourth step, the application of the area of "Building Construction" was evaluated and tested by students of the first semester. All in all, n = 82 students took part in an experiment consisting of a learning part and a follow-up questionnaire. A between-subject experimental design was employed, wherein participants were assigned to two distinct groups to evaluate the learning outcomes.

- Group 1 listened to a standardized classical lecture. The lecture lasted approx. 15 minutes and explained the topic of structural load transfers (load application area and single-span versus double-span girders).
- Group 2 proceeded in the same way, with the exception that group 2 was able to view what they had learned in the metaverse environment after the lecture.

After the lecture resp. the metaverse experience, the same mini-exam was done with both groups. The exam had three questions. It was followed by a self-assessment about how confident the students felt with the topic (see Tab. I). The group with exposure to the metaverse was additionally asked about the handling of the application. The results of the questionnaire were analyzed afterwards.

TABLE I. MINI-EXAM CONSISTING OF THREE QUESTIONS (TOTAL SCORE = 9 POINTS) AND A SELF-ASSESSMENT

Question	
Indicate the load application area for the beam marked in gray (2 points).	
Indicate the load application area for the beam marked in gray (3 points).	
Use arrows to qualitatively mark the forces in the supports in comparison (4 points).	
Did you feel confident in completing the tasks using the teaching method you chose (0 = not confident, 10 = very confident)?	

IV. SETTING OF THE APPLICATION

The application was programmed in 2024 by students of a computer science course. The following sections explains the technical details as well as the modules, that were implemented.

A. Technical details

The application was designed for a large lecture hall (400 sqm) at TH Köln. As hardware, the Meta Quest 3 with passthrough (video-see-through AR) was used. The application was programmed with the Unity game engine.

The application was based on an object-orientated model, that was modeled with the method of Building Information Modeling. The focus of that model was on the architectural, structural and technical components. Figure 2 and Figure 3 show the model, that was integrated in the metaverse environment from the outside and inside.

Fig. 2. Model of the lecture hall from the outside

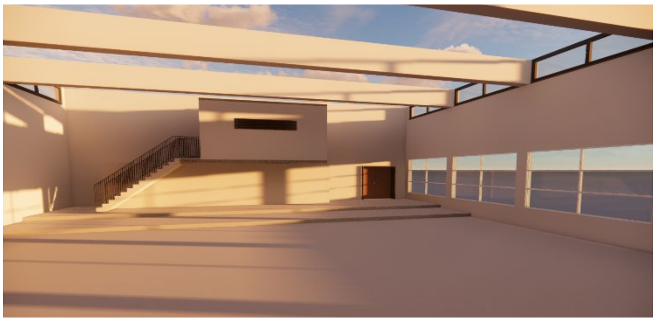


Fig. 3. Model of the lecture hall from the inside

B. Modules

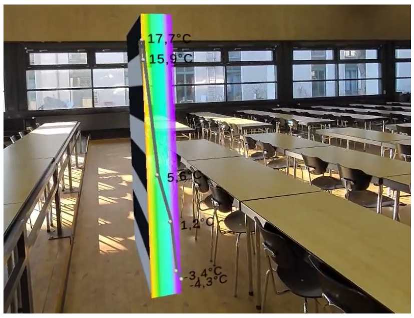
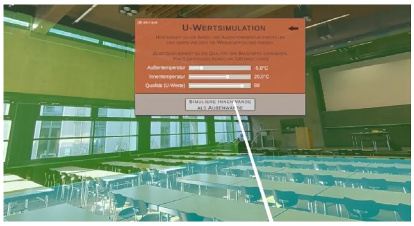
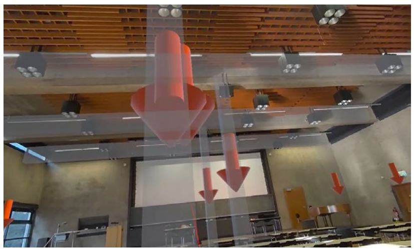
The application was developed in a modular way so that various modules can be integrated. As the first step, 4 modules with building construction and building physics content were integrated into the application:

- Dimensioning module
- Wall module
- U-value simulation
- Load transfer module

The modules and screenshots from the application are shown in Table II.

If the student is located in the lecture hall, all modules can be accessed via AR. Students can also use the metaverse application with VR to explore the metaverse environment at home.

TABLE II. REPRESENTATIVE SCREENSHOTS OF THE FOUR MODULES OF THE XR-APPLICATION, ILLUSTRATING THE USER INTERFACE AND CORE FUNCTIONALITY OF EACH COMPONENT.

Content	Picture
Dimension Module Students estimate dimensions of self-created lines, cubes and components in space	
Interactive structure of a wall Use of different insulation materials and visualization of thickness and thermal insulation	
Interactive visualization of the thermal insulation Setting temperatures and U-values (heat transfer coefficient) of the components and visualization as a transparent overlay over the real components	
Load distribution simulation Visualization of the load distribution, choice of several structural system and animation of the load distribution	

V. RESULTS

This section describes the results of the questionnaire, including the self-assessment and students' statements about the handling of the application, as well as the results of the written mini-exam.

A. Self-assessment of the students

In the questionnaire, students were surveyed about their self-confidence regarding the topic, using a Likert-scale ranging from 0 (low) to 10 (high). The group of students who utilized the metaverse application ($n = 40$) reported an average self-confidence score of 6.6, whereas the group without the application ($n = 42$) had an average score of 5.7 (see Fig. 4).

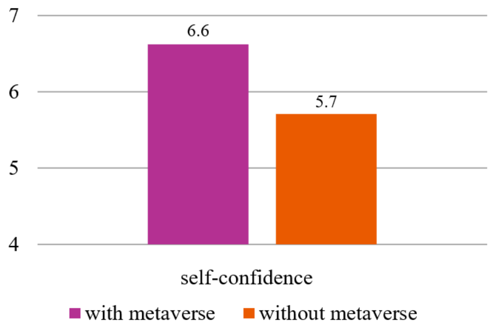


Fig. 4. Self-assessment regarding the confidence with the topic

A statistical analysis was conducted to compare the score distribution between the two independent groups using Likert-scale data. Given the ordinal nature of the data, normality was first assessed using the Shapiro-Wilk test. The results indicated that the metaverse group's scores were not normally distributed. Hence, the non-parametric Mann-Whitney U **test** was chosen for group comparison. Since our prior expectation was that the metaverse group would score higher than the group without the metaverse, a one-tailed Mann-Whitney U test was performed to assess whether there was a significant difference between the two groups. The results ($U = 990.0$, $p = 0.0812$) suggested that there is statistically significant difference at a less stringent $\alpha = 0.10$ level.

In conclusion, the results provide weak evidence that the students, who used our metaverse application, scored higher and hence felt more self-confident about the topic than the group of the students, who had no experience in the metaverse. However, given the ordinal nature of the data and the observed overlap in distributions, further research with larger sample sizes may be necessary to confirm this trend.

B. Handling of the application

Furthermore, the students were asked about their experience in the metaverse application.

- Nine of the students mentioned motion sickness by using the application.
- The handling of the application was described as easy and intuitive by the students (with an average of 3.76 on a 1-5 Likert-scale).
- Also, the handling with the controllers was described as intuitive.
- The visualization helped the students to deepen their knowledge in the taught subjects.

It should be noted that the teaching staff and tutors set up the lecture hall before the lecture started. Furthermore, the application was already loaded, when the students arrived.

C. Mini-exam results

During the mini-exam the students answered three questions. In total a score of 9 could be reached. The group of students who utilized the metaverse application ($n = 40$) achieved an average overall score of 6.9 and the group without the application ($n = 42$) achieved an average score of 7.3 (see Fig. 5). For further statistical analysis we proceeded similar to the self-assessment part of the questionnaire. Given the ordinal nature of the data, a Shapiro-Wilk test was performed to assess normality. The results indicated that both Group A ($W=0.7287$, $p<0.001$) and Group B ($W=0.7708$, $p<0.001$) significantly deviated from normality, necessitating the use of a non-parametric test for group comparison. To compare the two groups, a Mann-Whitney U test was performed. Given our prior expectation that the metaverse group would score higher than the other group, a one-tailed Mann-Whitney U test was conducted. But the results ($U=823.0$, $p=0.572$) provided no evidence to support the hypothesis that the metaverse group scored significantly higher than group without the metaverse.

We conclude, that the findings suggest that there is no statistically significant difference between the two groups in terms of their score distributions. Given the high p-values, further research with an alternative mini-exam may be required to explore potential differences more effectively. Since we observed that in both groups many students achieved the top score of 9, in a future work a more difficult mini-exam could reveal differences since the potentially gained additional insights into the learning topics by students exposed to our metaverse application could be beneficial for more demanding questions only.

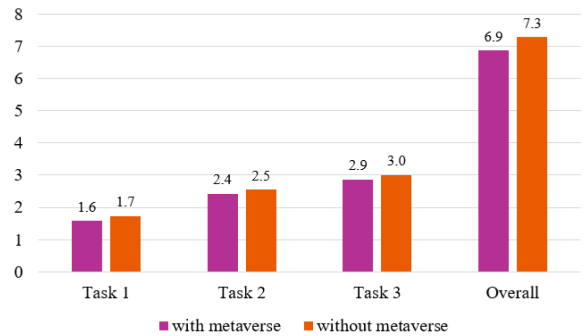


Fig. 5. Mini-exam results of each question as well as the overall score of the two groups

VI. Discussion

The study offers weak evidence that the metaverse application enhances self-confidence but does not improve academic performance as measured by the mini-exam. The lack of significant differences in mini-exam scores suggests that the complexity of the exam might not have been sufficient to assess the application's educational impact fairly. Future investigations should consider a more challenging set of questions and larger participant samples. Exploring different aspects of the application, optimizing user experience to alleviate motion sickness, and investigating long-term effects on learning and understanding could provide more comprehensive insights. In addition, the cognitive load associated with navigating virtual environments and the cost and infrastructure requirements for widespread implementation warrant further consideration. These factors could influence the usability and accessibility of the application, especially in settings with limited technical resources or users unfamiliar with immersive technologies. After the experiment, the results were discussed with a group of 12 researchers in a web conference. One of the researchers stated, that he had the same results regarding mathematical tasks. With regard to optical applications, e.g., estimating volumes, the students in his group who used a metaverse application showed slight improvements.

VII. Conclusion and Future Research

This paper presents a metaverse application for civil engineering to optimize the learning outcome of the students by using AR and VR technologies. Together with students, an application was developed that can be used both in a university context and at home. The results show that the self-confidence of the students increased when using the metaverse application, while the mini-exam results show no statistically significant differences. Therefore, further discussion, usage and testing is necessary regarding the application. Because the supervising teaching staff came from civil engineering or media technology, it is also necessary to carry out the tests again with teaching staff and at a larger number of universities. Furthermore, adaptions to more difficult questions asked in the mini-exam could reveal difference in the learning outcome. Beside the further testing of the metaverse application, new modules will be integrated in the Metaverse in civil engineering application. Key objectives are to integrate and strengthen collaborative learning environments to explore how multi-user metaverse platforms enhance teamwork and remote collaboration in engineering projects. Additionally, the potential of combining Building Information Modeling (BIM) and digital twins with metaverse technologies for interactive learning will be further investigated. This would also help to increase the readiness to integrate further modules easier and quicker, so that the application can be used during the whole curriculum of civil engineering. Currently, these insights are being further implemented in civil engineering education and are also transferable to related engineering disciplines such as mechanical engineering.

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