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Interactive Application as a Teaching Aid in Mechanical Engineering

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Abstract: This paper examines the integration of interactive 3D applications into the teaching process in mechanical engineering education. An innovative interactive 3D application has been developed as a teaching aid for engineering students. The main advantage is its easy availability through a web browser on mobile devices or desktop computers. It includes four explorable 3D gearbox models with assembly animations, linked technical information, and immersive virtual and augmented reality (AR) experiences. The benefits of using this application in the teaching process were monitored on a group of students at the end of the semester. Assessments conducted before and after the use of the interactive 3D application measured learning outcomes. Qualitative feedback from students was also collected. The results demonstrated significant improvements in engagement, spatial awareness, and understanding of gearbox principles compared to traditional methods. The versatility and accessibility of the application also facilitated self-directed learning, reducing the need for external resources. These findings indicate that interactive 3D tools have the potential to enhance student learning and engagement and to promote sustainable practices in engineering education. Future research could explore the scalability and applicability of these tools across different engineering disciplines and educational contexts.

Keywords: interactive learning; 3D models; gearbox mechanisms; digital twins; engineering education

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1. Introduction

The rise of digital technologies and interactive tools has revolutionized various sectors, including education [1]. In the realm of engineering education, this technological integration is pioneering a new era of pedagogical approaches, particularly through the incorporation of interactive teaching methodologies [2]. These methodologies leverage tools such as simulations, virtual reality (VR), AR, and digital twins, thereby reshaping the landscape of engineering education. By fostering student engagement, enhancing learning outcomes, and promoting a deeper understanding of complex concepts, these interactive tools are proving to be invaluable assets in modern engineering classrooms [3–5]. The importance of interactive teaching in engineering education is underscored by its potential to address some of the persistent challenges in the field. Traditional teaching methods, often characterized by passive learning and a lack of practical exposure, have been criticized for their limited effectiveness in preparing students for real-world engineering challenges [6,7]. In contrast, interactive teaching provides a more engaging and dynamic learning environment, enabling students to actively participate in the learning process, experiment with different approaches, and receive immediate feedback [8,9]. This approach not only enhances students' understanding of fundamental engineering principles but also equips them with critical problem-solving and decision-making skills that may be essential for their future careers [10]. The integration of interactive tools such as 3D visualizations, simulations, and virtual environments has proven to be particularly effective in engineering education. These tools enable students to visualize and manipulate complex systems, explore different design options, and simulate real-world scenarios, thereby bridging the gap between theoretical knowledge and practical applications [11,12]. For instance, Carbonell et al. [13] demonstrated that the use of interactive simulations in engineering mechanics courses can significantly improve students' understanding of concepts such as force, motion, and energy. Similarly, Ong and Mannan [14] found that the use of VR simulations and animations in manufacturing engineering modules enhanced students' spatial visualization skills and their ability to analyze and interpret complex data. Moreover, interactive teaching methodologies have been shown to foster a more inclusive and equitable learning environment in engineering education. By providing multiple avenues for engagement and catering to diverse learning styles, interactive teaching can help to level the playing field for students from different backgrounds and with varying levels of prior knowledge [15]. For example, Voreopoulou et al. [16] examined the use of AR escape room games to enhance English language learning, demonstrating the potential of immersive technologies to create engaging and effective learning experiences. Similarly, Roman et al. [17] found that the use of interactive tools, such as Socrative in chemistry and chemical engineering courses, promoted active learning and enhanced student engagement. Bruno et al. [18] explored the visualization of industrial engineering data in augmented reality, highlighting its potential to enhance the comprehension and analysis of complex technical information. Xu [19] provided insights into the use of virtual reality for social events during the pandemic, demonstrating the adaptability and effectiveness of VR in creating engaging and immersive experiences under restrictive conditions. Jin et al. [20] examined multi-stakeholder perspectives on the integration of VR in higher education, showcasing how VR can revolutionize classroom learning by facilitating deeper engagement and interaction with educational content. Incorporating interactive teaching applications in engineering education also prompts questions about the role of teachers and their relationship with students. Some argue that interactive tools may diminish the importance of teachers and lead to a more impersonal learning experience [21]. However, others contend that interactive teaching can enhance student−teacher interactions by creating opportunities for more personalized feedback and guidance [22]. Moreover, the use of interactive tools can free up instructors from routine tasks, allowing them to focus on higher-order activities such as mentoring, facilitating discussions, and providing individualized support [23]. Considering these challenges and controversies, it is crucial to conduct further research to evaluate the effectiveness of interactive teaching in different engineering disciplines and contexts. It is also important to investigate the factors that influence the successful implementation of interactive teaching, such as instructor training, curriculum design, and student readiness [24]. Additionally, future research should explore the potential of emerging technologies such as artificial intelligence (AI) and machine learning (ML) to enhance interactive teaching and personalized learning experiences [25]. The integration of interactive learning tools in engineering education has gained prominence due to their potential to enhance student engagement, improve learning outcomes, and address the limitations of traditional teaching methods [26]. These tools, often incorporating 3D visualizations, simulations, and virtual environments, offer a more immersive and interactive learning experience, enabling students to actively participate in the learning process and develop a deeper understanding of complex engineering concepts. Guzman et al. [27] and Pando Cerra et al. [28] have shown that the use of interactive applications is particularly effective in areas such as automatic control and engineering drawing. Pantelidis [29] identifies VR as a valuable tool for education and training, offering immersive experiences that can enhance learning outcomes. Porter et al. [30] found that collaborative and competitive challenges that leverage interactive tools have been found to promote teamwork and problem-solving skills among engineering students. Additionally, the incorporation of AR in engineering education, as explored by Jiwoo et al. [31], Criollo-C et al. [32], and Kaur et al. [33], has demonstrated potential in enhancing student motivation and engagement, fostering a deeper understanding of complex concepts and bridging the gap between theoretical knowledge and practical applications. Furthermore, the interactive nature of these applications is crucial for effective learning. Corral Abad et al. [34] emphasized that interactive teaching applications significantly improve student engagement by enabling direct interaction with educational content. This interactivity helps in retaining student attention and allows for immediate feedback, which is critical in understanding complex engineering concepts. Sprenger and Schwaninger [35] explored the technology acceptance of various digital learning tools, including mobile virtual reality, demonstrating their potential to enhance student engagement and improve learning outcomes in higher education. Additionally, Gattullo et al. [36] discussed the design of mixed reality applications for STEM education, noting that the interactive elements in these applications make distant learning laboratories more effective and engaging. Khachan and Özmen [37] also supported the use of interactive mobile learning applications, showing how these tools can support student learning outside the traditional classroom environment, providing continuous engagement with and reinforcement of concepts learned during regular class hours.

This article aims to contribute to the ongoing discourse on interactive teaching in engineering education by presenting a case study that examines the impact of an interactive 3D application on student learning and engagement in a mechanical engineering course. The study focuses on the use of the application as a teaching aid for understanding gearbox mechanisms, a complex topic that often poses challenges for students due to the intricate interplay of gears, shafts, and bearings. It can also be applied to other mechanical devices. By evaluating this interactive tool, including its 3D models, animations, and AR features, the study aims to reveal how such technologies can enhance engineering education. It specifically investigates whether the application improves students' understanding of gearbox mechanisms, increases their engagement with the course material, and fosters a deeper appreciation for the practical applications of theoretical concepts. The case study involves two groups of students, one with access to the application and one without, to assess its impact on learning outcomes and engagement. Ultimately, the goal is to assess the potential of interactive 3D applications to better equip future engineers with the skills and knowledge necessary to thrive in the ever-evolving technological landscape.

2. Materials and Methods

The case study, conducted between September and December 2023, aimed to assess the impact of an interactive 3D application on student engagement and understandings of gearbox mechanisms. Two groups of seventeen engineering students, with an average age of 19 and a gender distribution of 88% male and 12% female, were selected for the study. A total of 74% of the students graduated from technical high schools, while the remaining students graduated from gymnasiums. One group had access to the interactive 3D application, which allowed them to explore four gearbox mechanisms interactively (Figure 1). The other group followed traditional teaching methods. Prior studies have indicated that immersive technologies significantly improve student engagement and understanding [38–40]. Building on the extensive body of literature that highlights the benefits of interactive tools in educational settings, this study tested the following hypothesis:

- The interactive 3D application enhances student motivation and comprehension of gearbox mechanism assignments.

The interactive 3D application was developed to be compatible with various platforms, ensuring accessibility for all students. This included compatibility with both web browsers and downloadable desktop versions. The application could also be accessed through AR environments on students' mobile phones. To evaluate the impact of the application on student learning, a multifaceted data collection approach was employed. To gain insights into students' experiences and perceptions of the application, qualitative feedback was collected through surveys and interviews. Additionally, direct observations of student engagement during the course were conducted to assess the level of interaction and interest generated by the application. It was hypothesized that the group utilizing the interactive 3D application would demonstrate a higher level of knowledge acquisition and engagement compared to the group relying solely on traditional methods. The objective of the study was to provide insights into the effectiveness of interactive technologies as a pedagogical tool in engineering education. The findings were intended to inform and enhance instructional strategies.

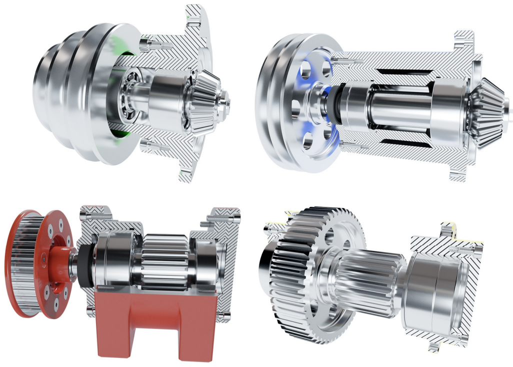

Figure 1. The four gearbox models in the assignment.

2.1. Development of the Interactive 3D Application

The interactive 3D application was developed through a meticulous process involving Blender for 3D modelling and animation, Verge3D for the implementation of the interactive functionalities, and HTML/CSS for the creation of the user interface (UI). This multifaceted approach ensured a comprehensive and engaging learning experience for students exploring gearbox mechanisms. The web-based application runs on WebGL, allowing for broad accessibility across various devices. Future plans include upgrading Verge3D to WebGPU [41], which will offer enhanced performance and graphics capabilities. The app can be accessed on mobile phones (Figure 2), tablets, and PC desktops, providing flexible engagement options.

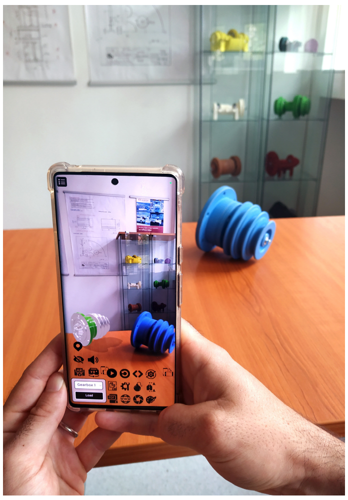

Figure 2. Using the application on a mobile phone.

In the case study, students used various devices. These varied platforms provided diverse interaction experiences, though the specific device type was not a critical factor in the study's outcomes. This also ensured an inclusive and adaptable learning environment.

- 3D Modeling and Animation in Blender.

Three-dimensional models of four distinct gearbox units were meticulously crafted in Blender (Figure 3), leveraging existing models where available and creating new ones based on technical specifications. The models were designed to faithfully represent the details and functionalities of each gearbox component, with texturing techniques being employed to enhance their visual realism. Blender was also employed to create detailed disassembly animations, which afforded students a step-by-step visualization of the deconstruction of each gearbox. These animations were designed to ensure clarity and accurately represent the disassembly sequence, thereby providing students with a valuable resource for understanding the assembly process in reverse.

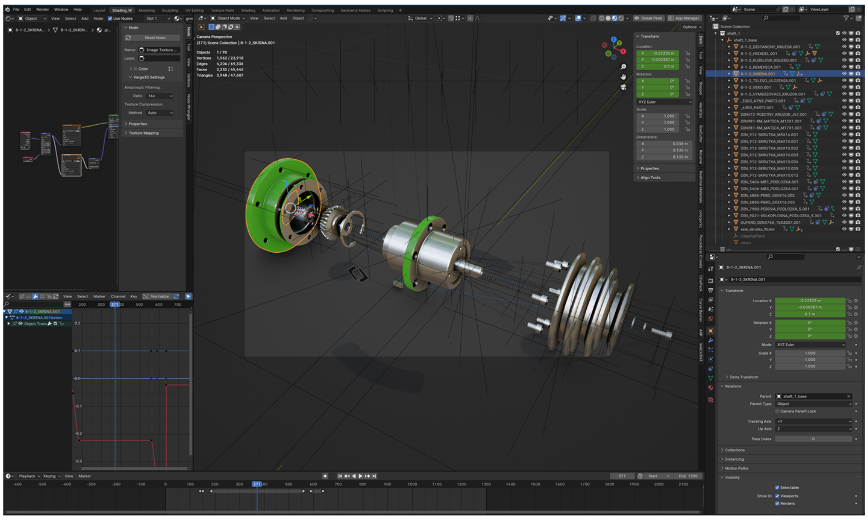

Figure 3. The gearbox 3D model in Blender environment.

- Integration with Verge3D.

Once the 3D models and animations had been finalized in Blender, they were exported in the glTF (GL Transmission Format), a format compatible with Verge3D. Verge3D, a powerful JavaScript library (Figure 4), served as the bridge between the 3D models and the user interface, enabling the creation of interactive experiences within the application. Within the Verge3D framework, a multitude of functionalities were meticulously implemented to enrich the learning experience. These functionalities are accessible via both the standard interface and AR.

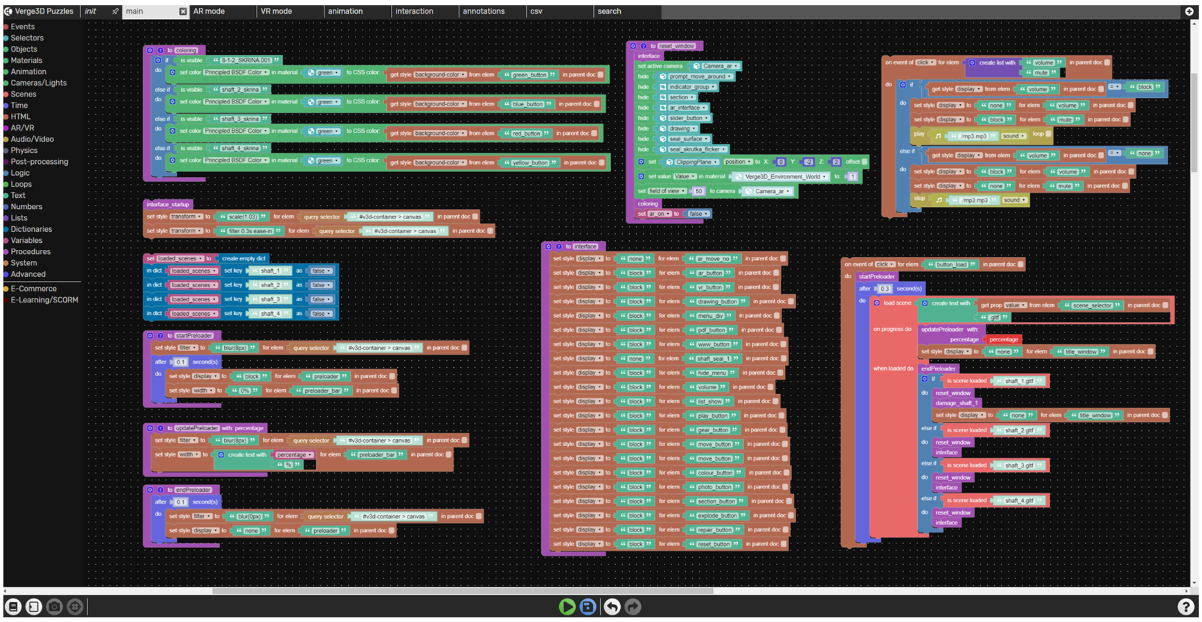

Figure 4. Creating interactions within Verge3D utilizing Blender 3D models.

Creating the user interface (UI) for this application involved using HTML, CSS, and JavaScript. The initial design and layout were conceptualized in Notepad++ (Figure 5), allowing for efficient coding and real-time preview of changes.

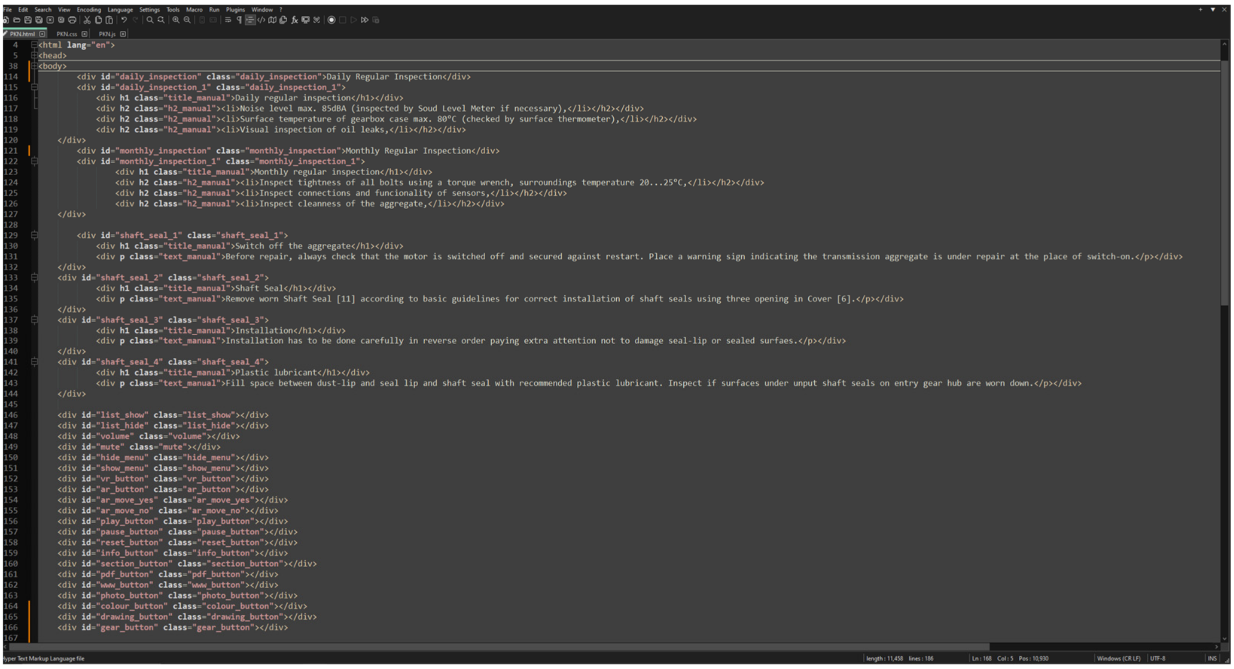

Figure 5. Creating graphic user interface using HTML, CSS, JS.

Upon launching the application, users were greeted with a user-friendly dropdown menu, which allowed them to navigate and explore each of the four available 3D gearbox models with ease. The initial view also included a text description of the application. The dropdown menu served as the entry point to the application's main functionalities. To optimize the viewing experience, particularly on smaller or portable devices with limited screen space, an interactive feature was included to allow users to toggle the visibility of individual gearbox components. This provided a layered approach to understanding the internal workings of the gearboxes, as students could selectively reveal or hide specific components to focus their attention. In order to further enhance the overall viewing experience, a "Play background music" button was integrated, allowing users to activate background music while exploring the gearbox models and related content. The genre selected was instrumental ambient music, chosen for its minimalistic and non-distracting qualities, which are conducive to maintaining focus during learning activities. This aimed to create a more engaging and immersive environment for learning. Research indicates that background music can enhance immersive experiences and improve cognitive focus by providing a soothing auditory environment [42,43]. The decision to use instrumental ambient music was influenced by its ability to increase immersion without causing cognitive overload or distraction, as supported by studies such as Feradov et al., which evaluated features in detection of dislike responses to audio–visual stimuli from EEG signals [44]. For future development, the capability to leverage VR functionalities was envisioned. This would enable students to become fully immersed in a virtual environment through VR, further deepening their understanding of spatial relationships within the gearboxes. The AR functionality (Figure 6) has already been implemented and maintains the same functionality as the standard interface. This enables students to access each functions in the same way as via the standard interface.

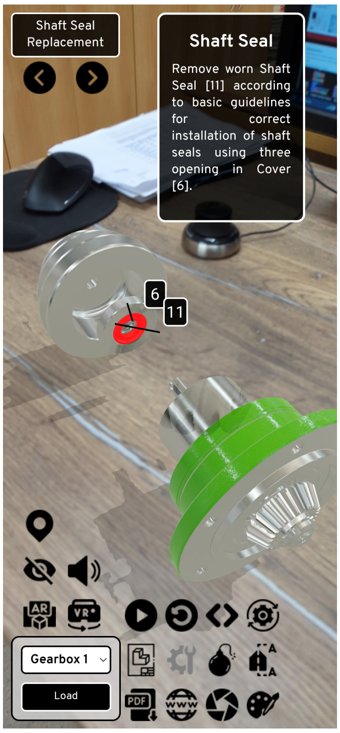

Figure 6. AR environment.

The application currently offers a "Play" button to initiate the disassembly animation of the selected gearbox unit. This animation provides students with a dynamic understanding of the gearbox's inner workings by showcasing the functions and different components in detail. Once the animation is playing, the "Play" button is replaced by a "Pause" button, allowing users to pause the animation at any point. Additionally, a "Move" button was incorporated to permit users to navigate the animation manually by dragging a slider, thereby affording greater control and a more focused examination of specific stages in the disassembly process. A "Process animation" button was included to demonstrate the function of the 3D model in action, showcasing the rotation of gears and bearings. This interactive feature allowed students to visualize the dynamic behavior of the gearbox, thereby aiding their comprehension of its operational principles. To provide additional context and information, a "Drawing" button was included, which displayed the assembly drawing of the selected gearbox unit. This drawing could be zoomed in and out, dragged, and manipulated in a manner similar to that of a PDF viewer, offering students a detailed reference for understanding the gearbox's structure and component relationships. Furthermore, a "Repair" button was integrated to introduce students to other aspects of gearbox maintenance and inspection. This feature presented the daily and monthly regular inspection procedures, thereby affording students insights into the routine tasks and practices that are necessary for ensuring the gearbox's proper operation. Step-by-step instructions and corresponding animations were provided for shaft seal replacement, guiding students through the entire repair process and highlighting relevant components. For rapid visualization of the gearbox's internal structure, an "Explode" button triggered a rapid disassembly animation. This feature was accompanied by three additional buttons. The application also allows users to view component position numbers, which are displayed using the "Part numbers" function. These position numbers correspond to the parts list, thus indicating specific component number. This feature is particularly useful in the explode mode (Figure 7), where users can easily identify and locate each component. Additionally, the "Service interval" feature allows users to view components that are due for maintenance based on pre-defined schedules, which are read from a CSV table containing this and other relevant data. Finally, the "Inspection needed" function indicates components that require inspection.

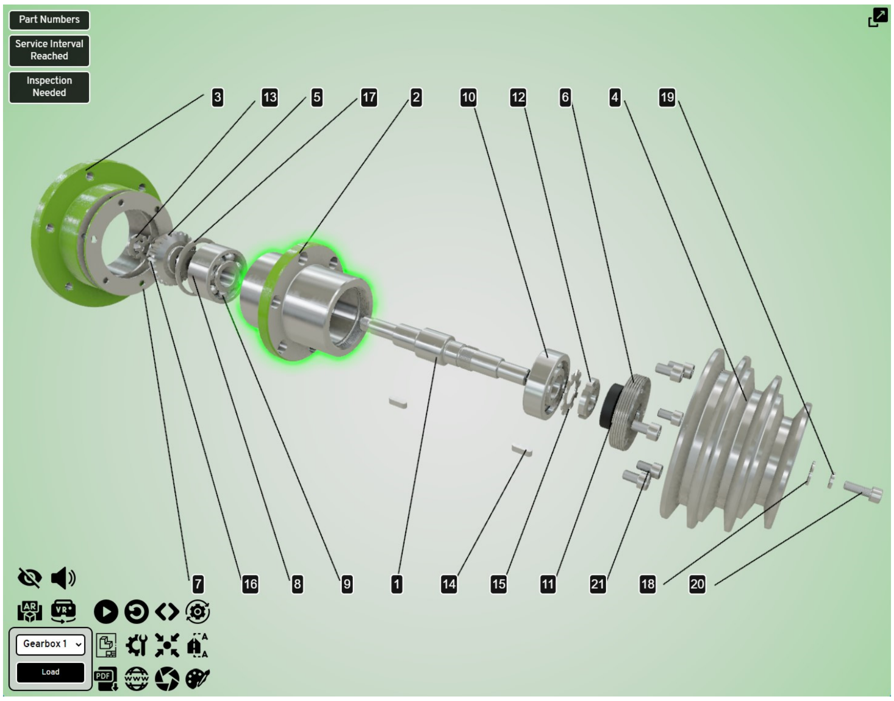

Figure 7. Explode animation with a highlighted component scheduled for maintenance.

The "Cross section" button enabled users to view the 3D model in an interactive cross-section view (Figure 8), providing a more comprehensive understanding of the internal arrangement of the gearbox. An interactive arrow allows for the manipulation of the cross-section plane's position, thus enhancing the visualization experience.

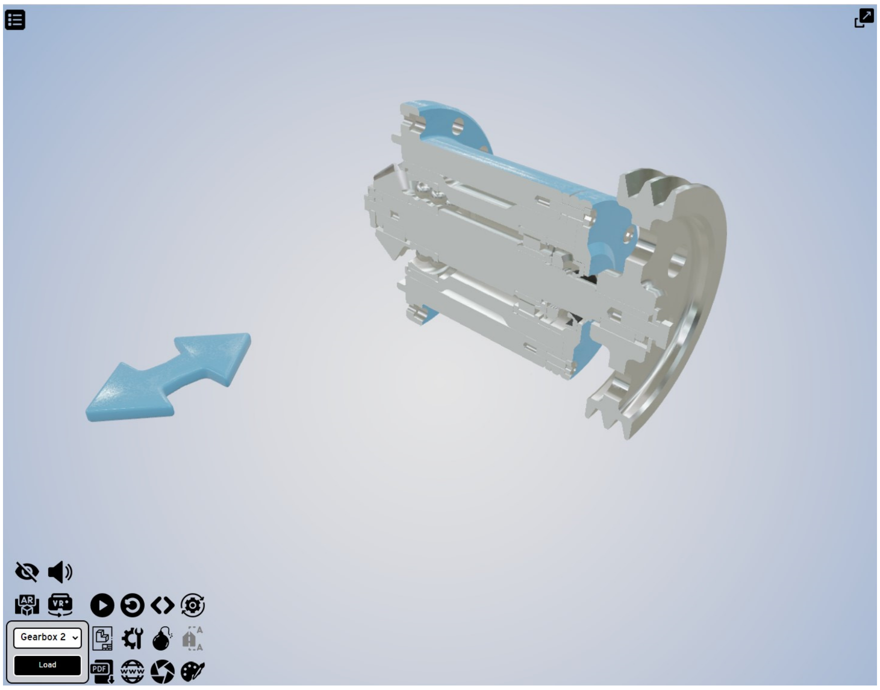

Figure 8. Interactive cross-section mode.

The application also offered two buttons labeled "PDF" and "WWW". The "PDF" button provided direct downloads of documents such as service manuals, spare parts catalogues, and FEM reports, while the "WWW" button linked to external resources like YouTube videos showcasing the 3D models in action. Additional features included a

"Photo" button for capturing screenshots, a "Paint" button for changing component colors, and a "Reset" button for restoring the application to its initial state. A convenient "List" button in the top left corner provided access to a parts list, divided into production and standardized parts. Selecting a component from the list isolated it for a detailed inspection, and a new "Drawing" button appeared, linking to the PDF drawing (Figure 9) of the isolated component.

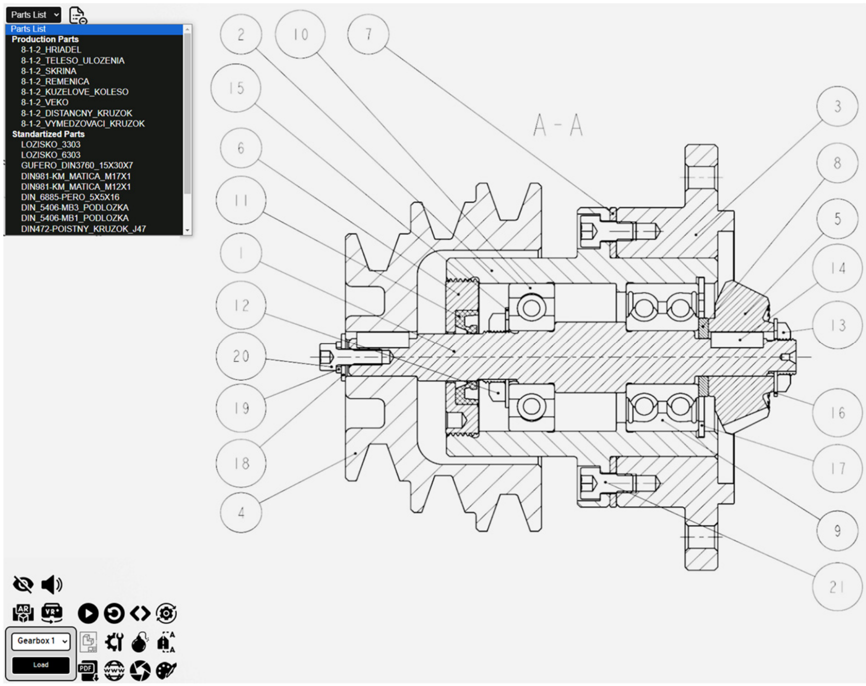

Figure 9. Dropdown menu and drawing inspection.

- Integration and Data Management.

All 3D models, interactive functionalities, and user interface (UI) elements were integrated within the Verge3D framework, creating a cohesive and user-friendly application that serves not only as a teaching aid but also as a simplified digital twin of the gearbox systems. A comma-separated values (CSVs) database served as the foundation for managing application data, storing critical information about gearbox units, components, descriptions, and links to supplementary resources. The data were retrieved and presented within the UI in a dynamic manner, ensuring seamless access to relevant information as users explored the application. Furthermore, the CSV database can be expanded to include real-time sensor data from various gearbox components, allowing the application to function as a basic digital twin. This would enable the visualization of real-time operating conditions, performance parameters, and even potential faults or anomalies within the gearbox system. By analyzing the sensor data, the application is able to identify components that may be experiencing wear, damage, or require maintenance. This provides valuable insights for predictive maintenance and troubleshooting.

2.2. Case Study Methodology

A controlled case study was conducted within the framework of a semester-long Design Project course at a university level, specifically focusing on the intricate mechanisms of gearboxes. This course is a standard part of the curriculum for first-year engineering students, typically encountered in their second semester. The participants in this study represented a diverse range of educational backgrounds, including both gymnasium and technical high schools. This resulted in varying levels of prior knowledge and experience in the field of machine design. Recognizing the potential for knowledge disparities, particularly among students from gymnasium backgrounds who may have had limited exposure to gearbox mechanisms, the study was designed to evaluate the efficacy of a newly developed interactive 3D application. The primary objective was to assess the efficacy of this innovative tool in bridging the knowledge gap and enhancing overall learning outcomes, engagement levels, and understanding of fundamental gearbox operation principles. To achieve this, thirty-four engineering students were randomly assigned to one of two distinct groups. The experimental group, designated as Group A (n = 17), was granted access to the interactive 3D application in addition to the traditional course materials, which comprised lectures, textbooks, and workbook exercises. Group A was actively encouraged to utilize the application throughout the entire semester, leveraging its interactive features to explore 3D models of gearboxes, manipulate individual components, visualize animations and technical drawings, and even experiment with AR functionalities where available. In contrast, the control group, designated as Group B (n = 17), relied solely on the traditional course materials for their learning journey. Both groups demonstrated active participation in the Design Project course, which culminated in the challenging task of designing and analyzing a specific gearbox mechanism. To assess the effectiveness of the learning interventions, pre- and post-tests were administered to all participants. These assessments were designed to measure knowledge acquisition in key areas, including gearbox components, their functions within the system, and the overall operational principles. Furthermore, the final Design Project submissions were evaluated in accordance with a set of criteria, including innovation, accuracy, and adherence to established engineering principles. To gain deeper insights into the user experience, a comprehensive post-semester survey was conducted exclusively with Group A. This survey sought to gather qualitative feedback on various aspects of the interactive 3D application, including its usability, effectiveness in facilitating learning, overall engagement level, and perceived value within the broader context of engineering education. Thematic analysis was employed to identify and extract key themes from the rich qualitative data collected.

The underlying hypothesis of this study was that Group A, having benefited from the interactive 3D application, would exhibit greater knowledge acquisition, heightened engagement and motivation, and a more profound understanding of gearbox principles compared to Group B, who relied solely on traditional methods. The research employed a meticulous and comprehensive methodology with the objective of providing a robust and conclusive assessment of the application's potential to revolutionize engineering education. This was to be achieved by making it more engaging, effective, and relevant to learners from diverse backgrounds and varying levels of prior knowledge.

3. Results

The case study yielded compelling results that support the transformative potential of interactive 3D applications in mechanical engineering education. The quantitative and qualitative data collected revealed significant improvements in learning outcomes, engagement, and motivation among students who utilized the interactive 3D gearbox application. To gain further insight into the student experience, a survey was conducted with the 17 students in Group A. The responses, quantified below, provide insight into their perceptions of the application's usability, effectiveness, and impact on engagement and motivation.

3.1. Usability

The application demonstrated a high degree of usability (Figure 10), with 94% of students reporting a positive user experience. The intuitive interface, built using Verge3D and HTML/CSS, allowed for seamless navigation through dropdown menus, access to the four gearbox models, and utilization of various interactive features. Furthermore, 88% of students found the information within the application easily accessible. A small number of students (12%) reported minor technical issues, primarily related to the AR functionality on certain mobile devices. However, these did not significantly impede the overall learning process. The ability to toggle the visibility of individual components, combined with the option to play background music, contributed to a personalized and immersive learning environment.

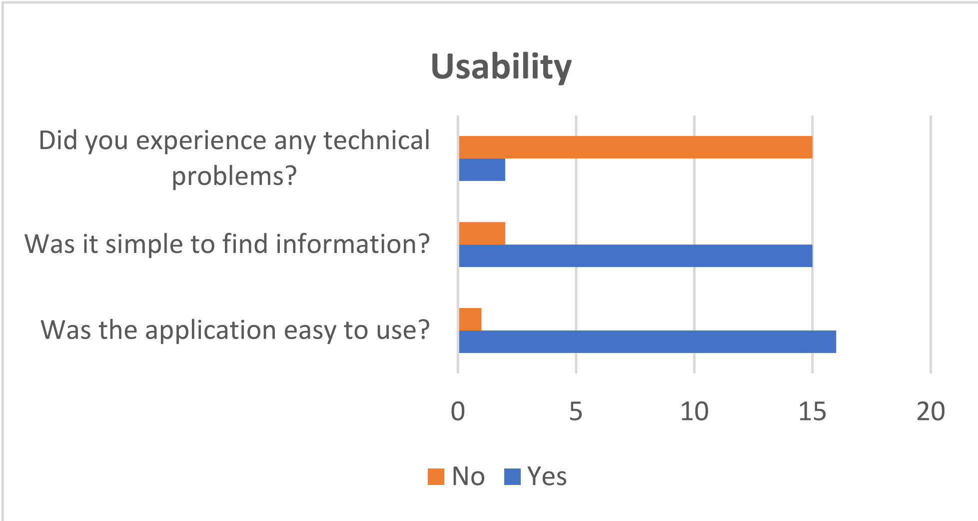

Figure 10. Students' responses on the usability of the application.

3.2. Learning Effectiveness

The interactive 3D visualizations proved to be an effective tool for enhancing the students' understanding of gearbox mechanisms (Figure 11). All students (100%) reported that the application assisted them in grasping the complex concepts covered in the gearbox assignment. A significant majority (82%) found the 3D visuals more helpful than traditional learning materials such as textbooks and 2D diagrams. The capacity to manipulate individual components, observe the dynamic disassembly process through animations, and access detailed technical drawings within the application significantly enhanced their comprehension of both theoretical principles and practical applications. Furthermore, the application facilitated a more profound understanding of the relationships between individual components and their roles within the overall gearbox system. This was evidenced by the 88% of students who reported an improvement in their ability to identify gearbox parts and their functions. Furthermore, 77% of students demonstrated enhanced confidence in their ability to analyze and troubleshoot gearbox issues, a crucial skill for future engineers.

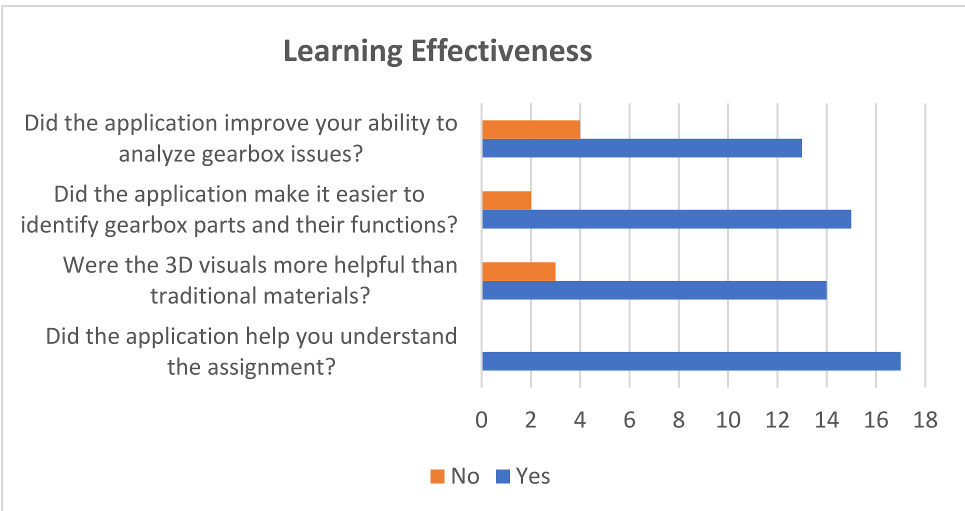

Figure 11. Students' responses on learning effectiveness within the application.

3.3. Engagement and Motivation

The interactive nature of the application, coupled with the visually appealing 3D models, fostered a high level of engagement and motivation among students (Figure 12). A significant majority (94%) found the application interesting to use, and 71% expressed a heightened interest in learning more about gearboxes as a result of their experience. All students (100%) indicated that they would recommend the application to their classmates, underscoring its perceived value as a learning tool. Qualitative feedback from students further illuminated the impact of the application on their learning experience. Many praised the ability to manipulate individual components, highlighting the value of hands-on exploration in solidifying their understanding. The dynamic disassembly animations were also lauded for their ability to visually convey complex processes, while the "Repair" feature provided valuable insights into real-world maintenance procedures. The application's impact extended beyond knowledge acquisition and engagement. A significant proportion of students (82%) indicated that the course material became more relevant to real-world engineering practices due to their interaction with the application. The ability to visualize and manipulate 3D models of gearboxes, coupled with the exposure to maintenance procedures, helped bridge the gap between theoretical knowledge and practical applications. This heightened relevance not only deepened the students' understanding but also increased their confidence in their ability to apply their knowledge to real-world engineering problems.

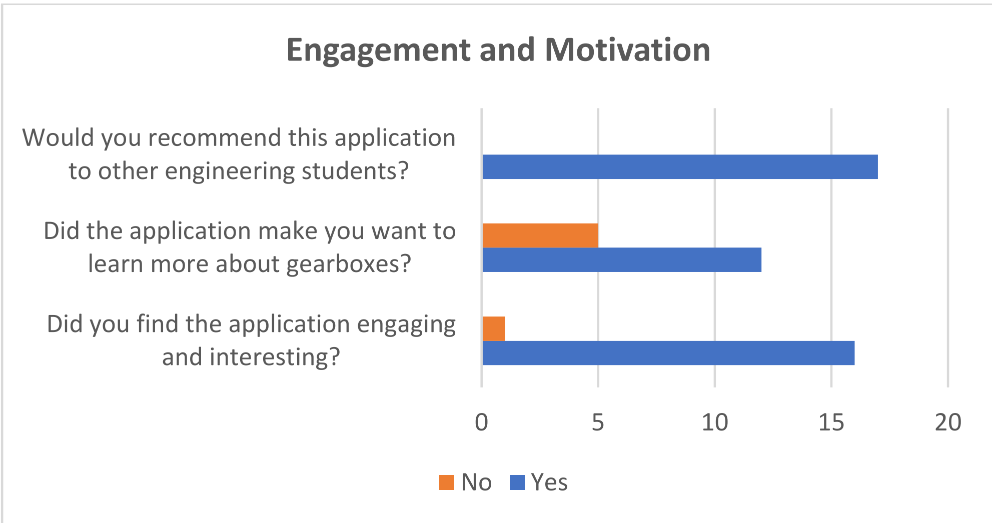

Figure 12. Students' responses to the aspect of engagement and motivation.

3.4. General Feedback

The feedback from students regarding the 3D application has been positive (Figure 13). The overwhelming majority of students (94%) indicated that they would like to see similar applications developed for other subjects. Furthermore, 65% of students reported a shift in their approach to learning mechanical systems as a result of using the 3D application. In addition, students found the course material more relevant to real-world engineering (84%) and felt more confident in their understanding of gearboxes (88%). A significant proportion of respondents commended the capacity to manipulate components, observe the dynamic disassembly, and explore maintenance procedures, emphasizing the application's efficacy in linking theoretical concepts with practical applications (77%).

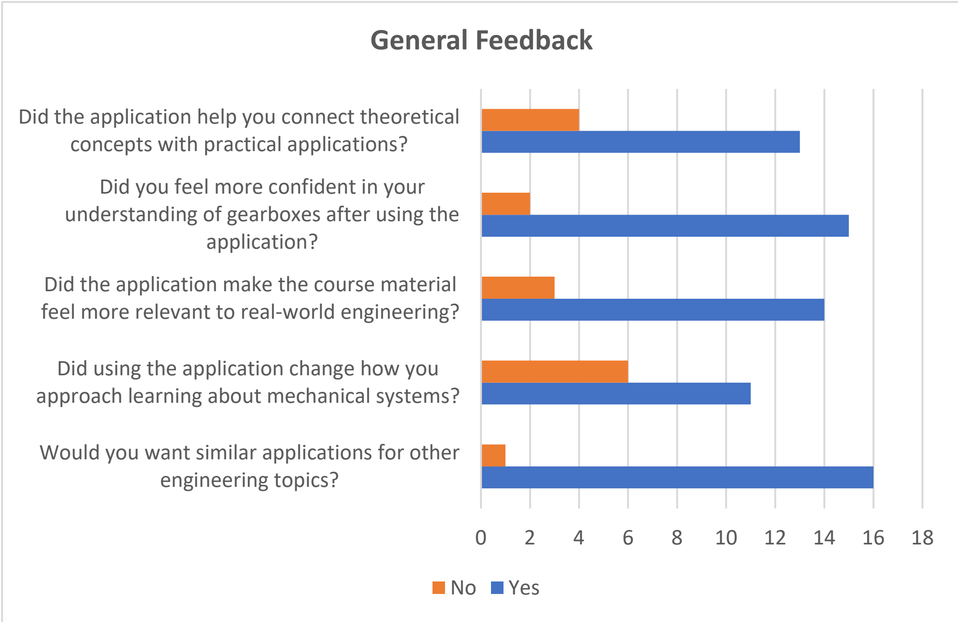

Figure 13. General Feedback from the students.

4. Discussion

The findings from this case study underscore the potential of interactive 3D applications in enhancing engineering education. The use of the 3D application in teaching information about gearbox mechanisms demonstrated significant improvements in student understanding and engagement. This aligns with the broader literature on interactive learning technologies, which facilitate active learning and improve educational outcomes in engineering disciplines.

The integration of interactive 3D applications provides a dynamic learning environment that bridges the gap between theoretical concepts and practical applications. Papaioannou et al. [45] emphasized the importance of creating interactive and engaging learning spaces in higher education, highlighting how technologies like augmented reality (AR) and mixed reality (MR) can transform traditional educational paradigms. Our case study supports these findings, showing that students using the 3D application were more engaged and performed better in understanding the gearbox mechanisms.

This study also connects to broader trends in educational technology. Broo et al. [46] argue that Industry 5.0 necessitates a rethinking of engineering education to incorporate more interactive and student-centered learning approaches. The positive outcomes of our 3D application demonstrate the efficacy of such approaches in preparing students for modern engineering challenges. Additionally, Li et al. [47] emphasize experiential learning, suggesting that students learn best through active engagement and hands-on experiences. The improved learning outcomes and positive feedback observed in our study align with experiential learning theories, highlighting the value of interactive tools in engineering education.

The implications of this study extend beyond teaching gearbox mechanisms. Hananto et al. [48] discuss the relevance of digital twins and 3D digital twins in Industry 4.0. The interactive 3D application used in our study can be seen as a precursor to more advanced digital twin technologies, which can simulate entire systems in real-time, suggesting potential applications in various engineering fields for training, design, and troubleshooting. Our findings resonate with these broader trends, suggesting that interactive 3D applications can significantly enhance engineering education.

Brinson [49] conducted a review on learning outcomes in non-traditional (virtual and remote) versus traditional (hands-on) laboratories, concluding that virtual environments can effectively support learning when well designed. Our study contributes to this body of research by demonstrating that interactive 3D applications can offer substantial educational benefits, even in regard to complex subjects like gearbox mechanisms.

In conclusion, this case study demonstrates the significant potential of interactive 3D applications in enhancing engineering education. By fostering active learning, improving engagement, and bridging the gap between theory and practice, these tools can play a pivotal role in preparing students for modern engineering demands. The connections to the existing literature and the broader context of educational technology underscore the relevance and importance of these findings, suggesting a promising future for interactive learning applications in engineering education. Future research could explore the use of interactive 3D applications in other engineering fields and assess their long-term impact on student learning and career readiness.

5. Conclusions

This case study demonstrates the considerable potential of interactive 3D applications, such as the one developed here using Blender, Verge3D, and HTML/CSS, in equipping the next generation of engineers with the skills and knowledge necessary to tackle the complex challenges of a rapidly evolving technological landscape. By fostering a more engaging, effective, and relevant learning experience, these tools can empower students to become effective problem solvers in the face of the ever-changing technological landscape. Future research should investigate the generalizability of these findings to larger and more diverse student populations across various engineering disciplines. The integration of advanced AR/VR technologies and the exploration of the application's potential as a simplified digital twin with real-time sensor data present promising avenues for future development. In the near future, the application will be further developed to incorporate real-time data visualizations, providing students with a simplified introduction to the concept of digital twins. Additionally, similar interactive applications will be developed and implemented for other subjects within the department, extending the benefits of this innovative approach to a broader student population. By embracing such interactive tools, educators can equip students with the requisite skills and knowledge to navigate the complex challenges of an ever-evolving technological landscape, thereby promoting a more sustainable and effective approach to engineering education.

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