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# VR Education Support System—A Case Study of Digital Circuits Design

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**Abstract:** Areas of experience allow for the acquisition and consolidation of both existing knowledge and skills. These are significant factors in the training of staff members for companies in the Industry 4.0 area. One of the currently available modern tools used in the teaching process is virtual reality (VR) technology. This technology, due to its high level of immersion and involvement of the different senses, and the need to focus on the performed activities, allows one to develop skills in solving various tasks and problems. The extended VR environment enables the creation of diverse teaching scenarios adapted to the needs of industry. This paper presents the possibility of building training scenarios in the field of digital techniques. The software solution, developed and presented by the authors, uses elements of computer game mechanics and is designed to familiarize students with the idea of digital circuits, their construction, logical implementation and application. This paper also presents a comparison of the features of different forms of education used in teaching digital techniques, as well as a comparison of these forms, from the point of view of the student and his/her perceptions.

**Keywords:** virtual reality; education; digital circuits; Industry 4.0; Education 4.0



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## 1. Introduction

The use of modern technologies in the teaching process seems to be natural. Over the past few decades, along with the development of computer technologies, they have become more widely used in education. As a result of the spread of computers and the development of the Internet, information systems have become an indispensable tool supporting the teaching process. In recent years, they have definitely strengthened their position, not only as an effective and efficient tool complementing the traditional methods and means used in education, but also as a primary source of knowledge and the building of professional competence [1–5]. However, the outbreak of the SARS-CoV-2 virus pandemic forced a sudden breakthrough, i.e., in many cases basing 100% of the education process on applications and information systems [6–8]. One of the consequences of the pandemic was the reduction in face-to-face contacts, which resulted in a lack of access to physical facilities, equipment, tools, etc. What is more, such an occurrence made it difficult to undertake, and for some time even limited various types of visits, internships and training in the real production environment. Taking into account globalization processes, we must be aware that such situations may repeat, and it is necessary to develop alternative forms of education based on modern teaching tools. One of the solutions that has great potential in this area is virtual reality technology [9].

Virtual reality is a form of environment simulated by a computer. Through the use of various components such as screens, speakers, sensors, and other elements (e.g., treadmills), the level of engagement and perception of diverse stimuli of the user in the virtual world, known as immersion, is increased. It is important to remember that the virtual environment created by the computer has the character of an illusionistic space. As a result, it is possible to acquire new skills. The research conducted so far indicates that the user who is in an immersive environment effectively acquires knowledge [10,11]. Due to its advantages, VR technology is widely used in research [12–16], industrial [17–22] and educational [21,23–31] areas. However, the literature review in this field in the case of existing solutions in Poland shows that this topic is quite new, and according to [23], we can see that there are not many Polish solutions that are widely used in the case of didactics at technical universities. The study [32] conducted by the Laboratory of Interactive Technologies of Polish National Information Processing Institute stated that in Poland, the knowledge about VR possibilities is very limited, and there are not any significant solutions used in teaching. The currently existing and known solutions include: in the High School of Banking in Wroclaw, there is a Pack Rage logistic game; in Leon Kozminski Academy in Warsaw, there are some classes related to forensics; and in the Warsaw University of Life Sciences, students can passively participate in animal surgery. The COVID-19 pandemic caused many serious delays in similar academic education activities, and our system seems to be one of the first proposed and used with the active participation of students. Its rapid development in recent times has evidently been conditioned by its great potential for application in entertainment, e.g., games, shows, etc. [33–35].

Obviously, there are many disadvantages of VR use in education [36–38]. These are related to: possible health and safety effects, the time necessary for the preparation of educational tools, the time needed to learn how to use the hardware, the software cost, and dealing with a possible reluctance to use the new technology.

Nowadays, we are witnessing and participating in an extremely important process, which is the development of the idea of Industry 4.0. Parallel to this process, we are observing an educational revolution called Education 4.0 [39,40]. This is a completely new experience-based education system that uses digital technologies instead of a memory-based system. The Education 4.0 approach responds to the needs of the new world through personalized education, anticipating the training of new generations to meet the needs of Industry 4.0, combining technology, individuality and discovery-based learning and gamification.

Education 4.0's offerings for Industry 4.0 include:

- Education independent of time and space
- Personalized learning
- Flexible learning
- Project-based learning (MAKER)
- Data interpretation
- Not based on a single exam, but rather continuous improvement
- Learning programs with student participation
- Mentoring

The new approach stems from the dynamics of change that are being observed in the labor market: will a person pursue an occupation that does not yet exist after graduation, or will they need to have multiple occupations throughout their career? New generations must respond dynamically to the needs of Industry 4.0.

The aim of this paper is to present a solution that meets some of the abovementioned conditions, and fulfills the needs of educating future engineers in the era of the fourth industrial revolution. This paper presents the results of research and development work which has been conducted in the field of the development of an educational environment, enabling the acquisition of knowledge and skills in didactics related to digital circuits on the basis of VR technology. Section 2 discusses selected issues related to the possible use of VR technology, and Section 3 relates them to digital technology education. In Sections 4 and 5, the prepared solution is discussed in detail, while in Section 6, it is evaluated. The evaluation was conducted through prepared questionnaires completed by students using the system. The paper is summarized in Section 7.

## 2. Educational Use of VR

The idea of virtual reality emerged many years before the development of modern computers. In the first half of the 19th century, Charles Wheatstone built an instrument for viewing spatial images and called it a stereoscope [41]. It can be said that he developed the foundations of future VR goggles. For the next solutions, bringing us closer to modern virtual reality, one had to wait more than 100 years until 1957, in which Morton Heilig created the “Sensorama” [42], and then in 1960 patented the device called the “Telesphere Mask” [43]. The 1970s and 1980s also saw major contributions to the development of this technology: MIT developed a solution enabling a virtual walk through the city of Aspen [44], or gloves with optical sensors to measure finger bend [45]. In the 1990s, a room-based immersive virtual reality environment was presented [46]. In 1995, Nintendo released the first console capable of displaying stereoscopic “3D” graphics [47], which already resembled the contemporary head-mounted display. However, it was not until Google introduced “Cardboard” [48], which enabled smartphones to be used as a display, that the potential of VR technology was triggered. Since then, there has been a rapid development of devices and systems that create VR environments.

VR technology and its different variations [49] have very high potential for implementation in various areas, including social [50], cultural [51–53], economic [54], medical [55–58] and military [59–61]. However, one common area that links all of the above is education. Considering the scope of this article, existing solutions for the use of VR in teaching processes are reviewed.

An excellent example to start with is the field of spatial education related to architecture. Owing to virtual reality, an architect can get a feel for how his or her project will be perceived even before construction begins. What is more, this form of project analysis allows one to check details which can be easily overlooked during the traditional design on a piece of paper or in computer programs. An excellent example of using VR in architectural design is the case of Sitterson Hall, a building of the Department of Computer Science at the University of North Carolina in Chapel Hill (USA), where one of the elements of the building was designed through the use of virtual reality methods. Another example is a virtual reality simulator that allows one to test user behavior in the context of construction site safety rules [62]. There are also already created systems that allow architecture students to create objects based on predefined materials [55], as well as to gain knowledge about reconstructed or distant buildings of interest [56].

One of the key areas of VR technology application in the teaching process is medicine. By planning spatial visualization, as well as providing opportunities for specific interactions with objects in the VR environment, doctors and medical students can learn and test medical procedures and treatments. This form of education enables not only the introduction of different scenarios of action, but also their numerous repetitions in order to improve efficiency, as well as to determine the best option from the patient’s point of view. Thus, novice doctors in particular, owing to virtual reality, have the opportunity to practice their skills. Systems of this type provide a three-dimensional presentation of organs in order to explore them or to accurately plan the distribution of radiation beams used in cancer treatment [54,63]. Some models available with this technology allow for a more detailed analysis of their anatomical structure [64,65].

Another area of VR use in education is in the widely understood industry of engineering. Engineers can learn how to speed up the design process, test products, and become proficient in performing service procedures. Very good examples include aircraft maintenance training [66,67] and civil aircraft pilot training [68]. Another example of using VR to train employees is a course dedicated to the operation of arm robots [69], which has shown great effectiveness in improving the professional skills of trainees. On the other hand, in [70], the authors presented a prototype VR system for training the operation of a system built for SmartFactory. In another work, one can see a solution supporting the customization process of visual features of city buses using a VR-based system. Certainly, there are also VR systems supporting general cognitive and didactic processes dedicated to different levels and scopes of education [23,71,72].

Keeping in mind that VR has many applications in universal design [73,74], where it helps to record the perceptions of the people, improve the usability of solutions, score the movement characteristics, the user's operability, and mental or physical stress, and evaluate whether the designed product is easy to use, we can also refer to the concept of universal design learning [75]. VR used in the case of inclusive design allows one to navigate in the designed space, assists during the design process, and improves the architect's understanding of different users' needs and interaction features with artificial elements as if they were real, especially for those that are older or disabled [76,77].

The examples presented above are only a small portion of the possibilities offered by the use of VR technology in education. However, despite numerous studies conducted in this field, there is still a visible lack of solutions for the education of computer engineering and electronics students. Therefore, effort has been made to develop selected forms of education in the design of digital circuits in the context of the needs of Industry 4.0.

## 3. Education in the Field of Digital Circuits

Modern technological development greatly influences the methods and means used in the didactic process. Nevertheless, each new tool needs to be tested in terms of its potential application to the transfer of specific educational content. The Rzeszow University of Technology educates, among others, IT engineers. The educational path dedicated to them also includes content on digital circuits under the subject name Elements of Logic and Computers Arithmetic. The course content is important not only from the point of view of the need for engineers to be familiar with the basic aspects of digital technology and its applications in the construction of modern computer systems, but also from the perspective of the general preparation of future engineers to address the needs of the job market, which must meet the needs of the Internet and its development, while the realization of Education 4.0 and Industry 4.0 concepts should also be taken into account. A general outline of the content of the course and the forms of education used is presented in Figure 1.

As shown in Figure 1, the subject area ranges from the theoretical basics necessary to understand the functioning of digital circuits used in computer systems to more complex circuits, up to entire arithmetic and logic units. The traditional academic educational process used for many years is mostly based on lectures with a whiteboard, which are necessary to convey the basic knowledge with examples [78]. Naturally, this stage of the didactic process can nowadays be replaced by modern e-learning courses, but it will still be the first stage in the process of learning and then acquiring new knowledge [31,79]. In the next step, simple practical exercises are carried out, the aim of which is to use theoretical knowledge to solve example tasks. At this stage, the knowledge is consolidated, and the ability to apply it in practice is verified. In the traditional approach, these classes are based on solving tasks on paper or the blackboard (obviously, this can be a blackboard in a computer application or word processor). The last stage (laboratory) involves building engineering skills based on designing, analyzing, synthesizing, and testing the correct functioning of digital circuits. IT tools become indispensable at this stage. Considering the great potential of VR technology in the field of education, it was decided to use it both in the research and in the educational process. This paper presents a selected part of the educational process in the field of digital circuits including the use of Boolean algebra, Karnaugh maps and the design and testing of multiplexers as combinational circuits. Thus, three different forms of education were used during the carried-out exercise-laboratory work: the traditional form, based on tasks and exercises performed on paper, computer-based education, based on computer applications, and the immersive form using virtual reality technology.

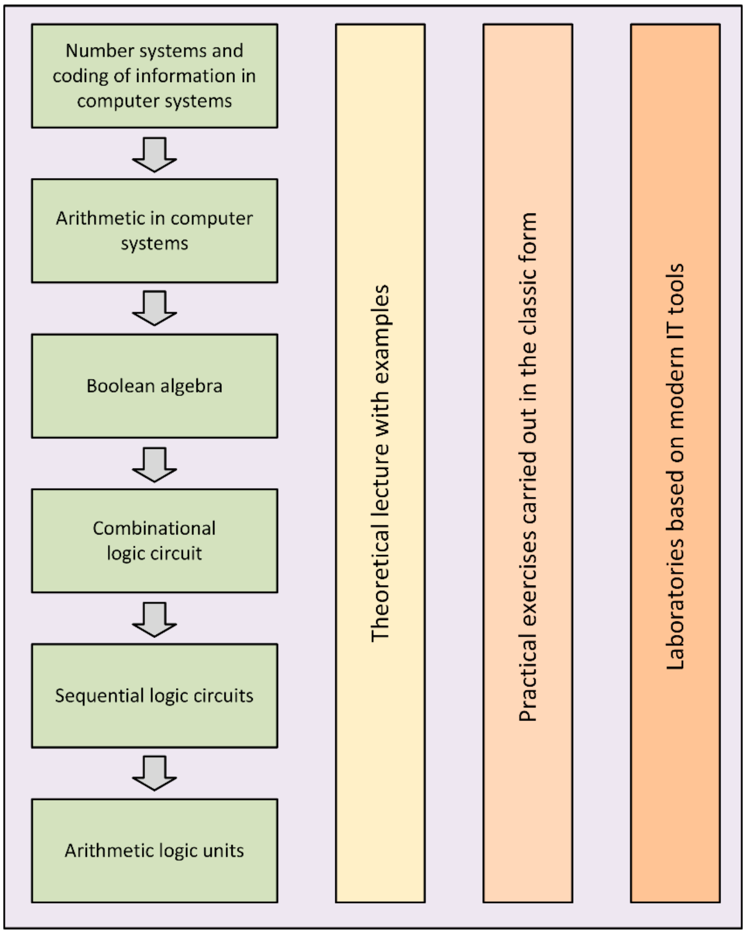



**Figure 1.** Content and learning forms used in digital circuit education (Elements of Logic and Computers Arithmetic course).

In the traditional method of education, the difficulty in writing out the tasks on a piece of paper, as well as the high probability of making possible mistakes, are the highest. In this context, one can consider a system of different prompts, which in traditional education occurs on a very limited level (for instance can be given by the teacher), while in the solutions based on information systems and VR technology, there is the possibility of implementing complex systems of prompts, as well as the automation of evaluation with the indication of errors, and the explanation of a workable solution. An important aspect is also the concentration of students during classes. In the case of traditional forms of education, concentration depends on many factors, but usually reaches at most an average level [80]. Attention is much better in the case of classes based on computer software, as the user is forced to make conscious actions in order to achieve the desired result. In contrast, the highest level of concentration on the task can be achieved by using VR technology [81]. This is due to the high level of immersion of the user, which also contributes to better learning results. Certainly, modern forms of education also have some disadvantages, such as the high costs of creating VR environments or purchasing specialized software, as well as the time required to prepare exercise scenarios and tasks [82]. However, a well-prepared environment enables a high level of exercise repetition without additional costs, which can also contribute to better learning outcomes.

Our choice related to digital circuits was in some sense motivated by similar existing solutions. For example, in [83], the authors presented the results of research where they compared the efficiency of a desktop VR learning environment with a conventional classroom in teaching about electrical/electronic technology. The outcomes confirm the effectiveness of using VR, especially in education, in the absence of adequately equipped laboratories with the latest technical solutions. However, their work was related to the physical fabrication of electronic circuits, not the design of digital circuits based on basic components. A similar use of VR in a technical laboratory is presented in [84]. When working in electronics laboratories, students often operate complex laboratory equipment. The authors of this work presented the results of research confirming that VR contributes to the development of students' knowledge, motivation to learn and learning about new solutions. However, the proposed approach covers only the area of using electronic devices and not designing digital circuits. Looking from the perspective of the wide-range of applications of VR in education, and also in technology, the solution proposed in this work confirms that it should also be possible to provide a complete VR-based educational path, from designing digital circuits, their production, to the use of ready-made devices in laboratories at technical universities.

Of course, when analyzing the achievements presented in the references mentioned above, as well as the research results presented in [85–89], one should consider VR technology, which has great potential in terms of the effectiveness of education at technical universities, as well as for Industry 4.0.

## 4. Work Environment

In Poland currently, the didactic environment and above all the exercise and laboratory rooms are based on typical room layouts, e.g., school, theater, auditorium, letter U and their various transformations. This was possible since in the traditional form of education, it is not necessary to provide access to areas dedicated to specialized equipment. Traditional equipment in the form of benches, chairs, projectors, blackboards and possibly computers do not have a significant impact on the layout of teaching rooms. These rooms' layouts were usually determined by their shape and by ensuring accessibility for a certain number of students. Therefore, the room layouts mentioned above have been commonly used for many years. However, the implementation of VR technology forces the development of new assumptions for teaching rooms that guarantee the freedom and safety of users' operation in VR. Taking into account the fact that not all content and activities can be fully transferred to the VR environment, the prepared concepts of classrooms must have a universal character ensuring the implementation of classes in a hybrid form, i.e., based on traditional solutions and VR technology. For this purpose, two concepts of universal teaching rooms were developed.

The first concept (Figure 2) allows for free work for laboratory groups (assumed to consist of 12 and 6 persons). In a dedicated workspace, it will then be possible for multiple users to test VR solutions simultaneously, using four base stations dedicated to a given VR solution. Obviously, the proposed solution can be scaled and adapted to work with a smaller or larger group of students. In the presented configuration, users can use both stationary and mobile VR stations. The wireless VR testing area is separated from the design area, where students can analyze the solution on the projection screen together with the instructor. The proposed working area of the VR test zone, as mentioned earlier, can be scalable, but for the specific example, approximately $4 \times 6$ m was assumed. The test area can use a variety of available solutions, including VR glasses connected with wires to the workstations, those connected wirelessly, those connected wirelessly through a dedicated adapter, and glasses using cell phones to display the virtual image. The efficient data communication infrastructure allows for the ongoing transmission, storage and management of various VR projects dedicated to both the entire group and individual users.

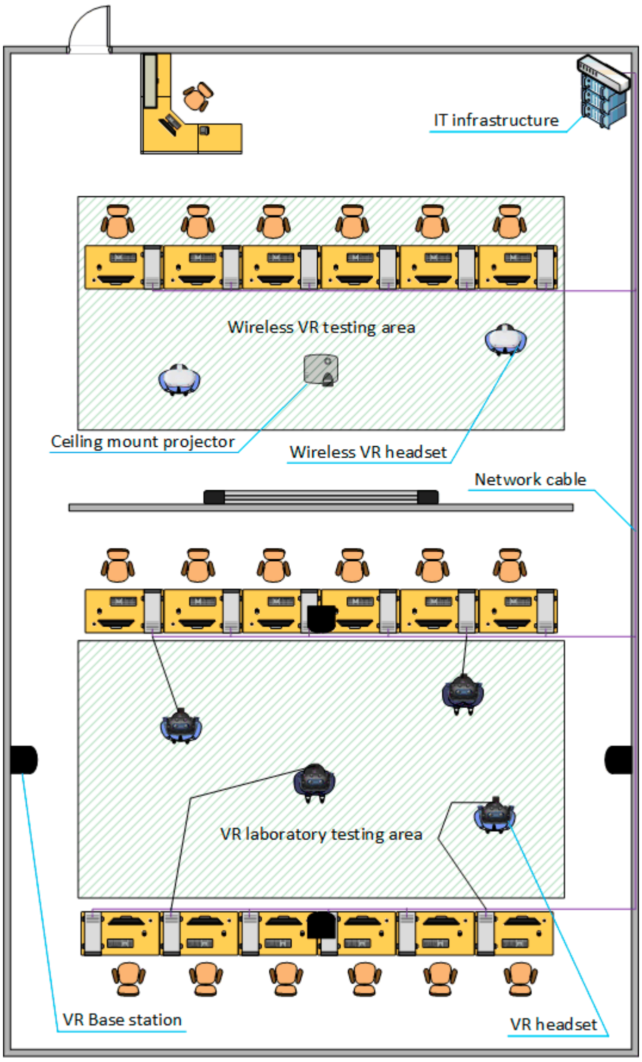



**Figure 2.** Diagram of a room for hybrid classes—proposal no. 1.

For the purpose of the lecture/exercise classes, a different room structure better suited to these forms of classes is suggested based on the auditorium scheme (Figure 3). In this case, both the presenter and the other participants can move to the VR environment at any time. The demonstrator guiding a given VR scenario (e.g., the teacher) can use a mobile zone to which they can invite selected students. The rest of the students use stationary stations equipped with VR goggles. The proposed approach allows for the efficient use of auditoriums and seamless switching between VR and real environments during the classes. It enables one to effectively use the various teaching methods and resources available today. However, it should be remembered that concept no. 2 has an exercise and lecture character—nonetheless, depending on the needs, it can also be applied to laboratory needs. If individual workplaces were equipped with workstations or high-powered mobile computers, it would be possible to perform part of the laboratory tasks on the basis of computer applications, and part in a VR environment—for example, as a final familiarization with the operation of the designed systems.

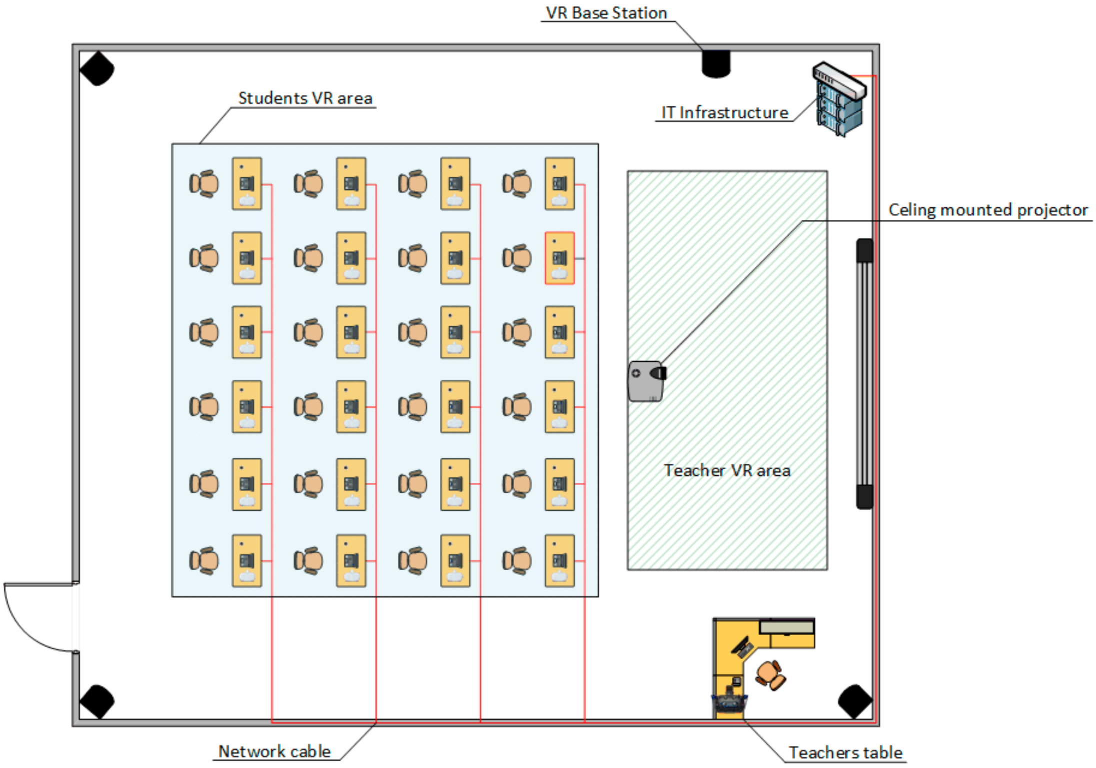



**Figure 3.** Diagram of a hybrid classroom—proposal no. 2.

As a part of the work conducted on the development and implementation of a VR environment dedicated to teaching a selected module in the field of digital circuits, the previously developed methodology for creating VR solutions dedicated to education [28] was used, and then a teaching environment was prepared based on concept 1 (Figure 2). To develop the project, the dedicated graphics engine Unreal Engine version 4.25.4 was used. To build individual scenes as an environment, accessory packages from Epic Marketplace were employed; however, elements directly related to the subject matter of the application were designed using Autodesk 3 ds Max. The project was designed for students of two majors, including students of computer engineering. It was carried out by the staff and students of Rzeszow University of Technology. Through the close cooperation of the academic community, both students and staff, the ELIAKI VR application is tailored to the needs of the university's end users, such as students, with both the knowledge required to pass the course/subject, which the participant will be able to acquire during the exercises, and the simplicity and additional elements developed by the students. Three HTC Vive virtual reality goggles with base stations in SteamVR Tracking 1.0 technology and Oculus Quest 2 64 GB goggles were used for the purpose of analyzing the functioning of the project/application using fully wireless solutions. In a properly prepared teaching room, four students worked in VR at the same time, while 10 students used traditional methods to solve tasks while waiting for their turn. A laboratory room with dimensions of about 7 m × 11 m was used to carry out the activities. The VR work area was 4 m × 6 m. Computers with the components presented in Table 1 were used as workstations. Until now, professional VR headsets have not been common, mostly due to their price. However, this situation is rapidly changing. Currently, very good quality devices are available for approximately EUR 500, making them widely attainable. Within our university, we are constantly expanding our VR laboratory equipment, ensuring accessibility to different technological solutions as mentioned above.

**Table 1.** Configuration and parameters of the computers used for teaching.

| Computer 1–2 Machines | Computer 2–1 Machine | Computer 3–2 Machines |
|---|---|---|
| Intel i7 8700 3.20 GHz<br>16 GB RAM DDR4 3200 MHz<br>MSI GeForce RTX 2070<br>SSD SATA III 256 GB | AMD Ryzen 3400 G<br>32 GB RAM DDR4 3200 MHz<br>MSI GeForce GTX 1070<br>SSD SATA III 256 GB | Intel i7 8700 3.20 GHz<br>16 GB RAM DDR4 3000 MHz<br>MSI GeForce 1070 ITX 8 GB OC<br>SSD SATA M.2 275 GB |

The use of computers with varying configurations allowed us to determine the smoothness of the VR application. The spacing configuration of the base stations was also subjected to modifications in order to determine the optimal placement and tracking of the VR goggles throughout the dedicated space. It is worth noting that the room had windows along the entire length of one wall, which negatively affected the positioning of the goggles in the space through the first generation base stations. The following conclusions were drawn:

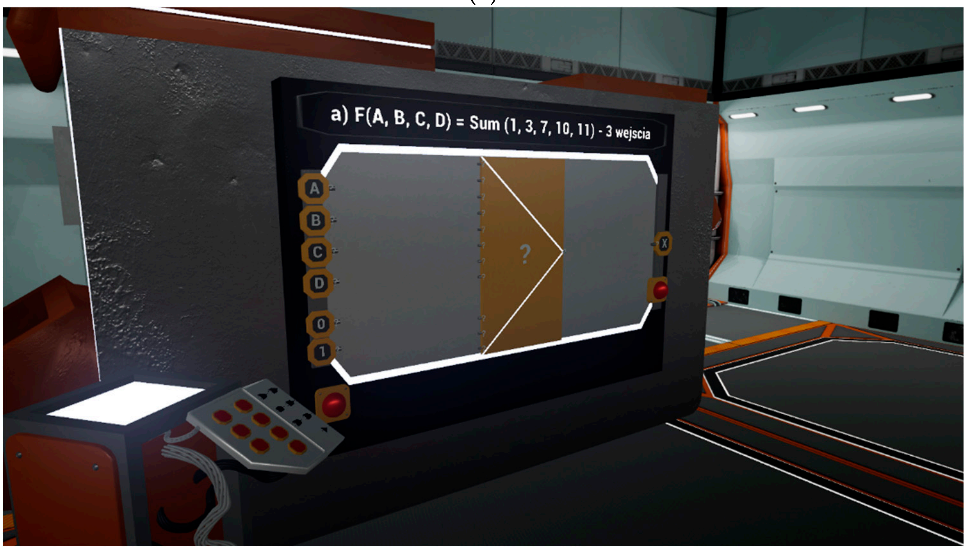
- The application worked smoothly, regardless of the computer configuration, at 90 frames per second. The slight delays that were noticed occurred with PC 2 and Oculus Quest 2 configurations. The key point, however, is that the application was built in full compatibility mode with HTC Vive.
- The highest number of frames per second was achieved with the configuration of computer 1 and HTC Vive. The main element that affected this result was the use of a more powerful graphics card from the 2000 series. For levels where there were significant graphical animations, such as particles on the reactor, or the generation of subsequent stages, the number of frames per second decreased slightly.
- Base station spacing has a significant impact on goggle performance and space mapping. Glass negatively affected positioning, meaning that the goggles could get lost in the space. Covering the windows significantly improved the performance of the base stations, which suggests that the room in which the VR activities are implemented should have as few mirrors/windows as possible.
- With four users, the base stations must be located high up so that participants do not enter the mapping area between each other when using the application. Wireless communication between base stations in the lab room proved more reliable than a wired connection.

Despite the lower performance of computers 2 and 3 compared to computer 1 (older graphics card), the VR application worked well. Students did not experience a significant difference in the performance of the application on the different machines.

## 5. Structure of a VR Application

Studies on various groups of people indicate that the acquisition of new skills and learning with the use of virtual reality is more effective than traditional methods [38,90]. A potential indicator of better learning results may be a full or significant user immersion connected to the prepared application or training course. In order to meet the challenges of the 21st century, as well as to develop a more digestible process of educating participants, the ELIAKI VR project was developed. It is an educational application using elements of computer game mechanics designed to familiarize students with the idea of digital circuits, their construction, logical implementation and application. The task uses virtual reality technology to provide the participant with the opportunity to work in a given environment using virtual simulations of both the environment and the design of logic circuits. An example of the ELIAKI VR application is presented in Figure 4a,b.


(a)




(b)

**Figure 4.** ELIAKI VR project: (**a**) startup room in ELIAKI VR; (**b**) view of multiplexer and industrial machine.

The application responds to the needs of the Industry 4.0 concept and the approach proposed by Education 4.0 by preparing a personalized solution, independent of both time and space, guaranteeing flexibility of learning and the realization of learning based on projects.

The application is divided into three stages. Each stage is one module of the course. A group of two students has 40 min to complete the entire module, 20 min per person. ELIAKI VR is designed in a way where tasks that would have to be solved in class using traditional methods—whether through conversion using traditional sheets of paper or using circuit simulation software—can be fully accomplished in a closed virtual environment. Prior to the first module, each student was familiarized with how to navigate the virtual world and how to use the virtual elements.

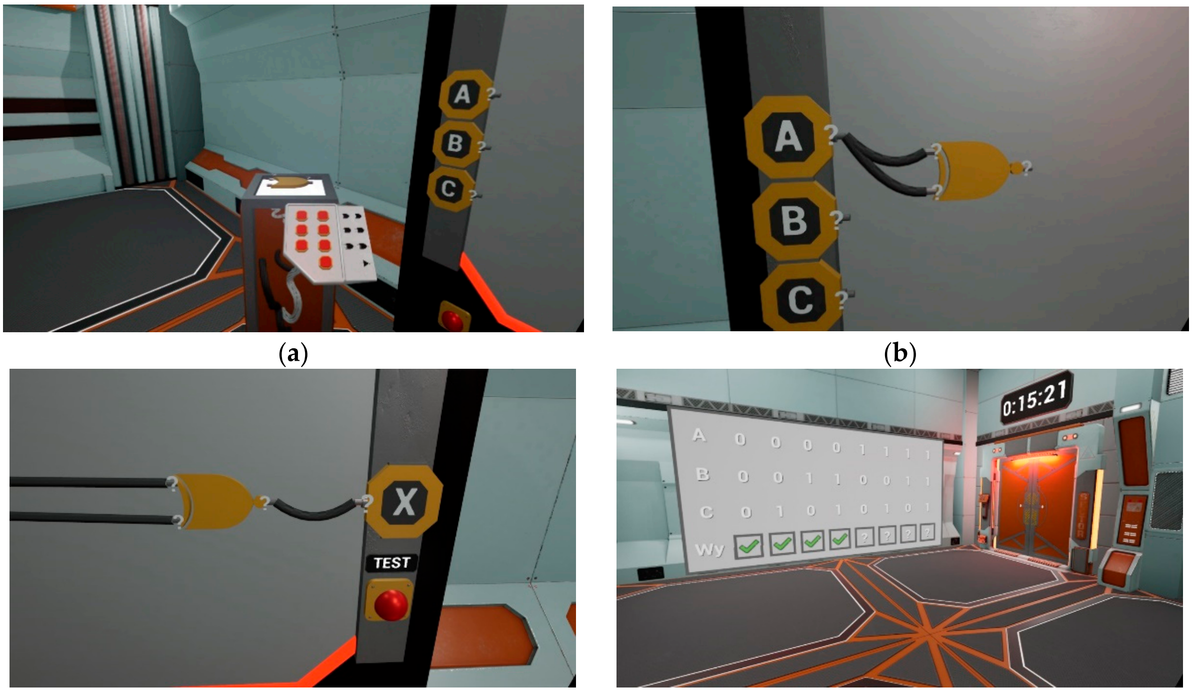
The first module is designed to familiarize the participant/student with the application and use of Boolean algebra laws (Figure 5). The user has to find the right way to the room where a task dedicated to him/her is located. Each student has three sub-items to complete with similar levels of difficulty between them. With each sub-item the task becomes more complex, requiring the student to develop an appropriate layout to pass the room and move on to the next room. Each task must be solved correctly in order to proceed further.


**Figure 5.** View of an assignment on Boolean algebra laws.

The solution to the problem is to build a valid logic circuit using available logic gates that can be called by the logic gate spawner (Figure 6a). The student has AND, NAND, OR, NOR, NOT, XOR, and EX-NOR gates and from four to six input signals. The logic gates are connected via virtual wires using the basic principle that the output of a gate/signal can simultaneously be the input of another logic gate (Figure 6b). The student, using VR controllers, summons a particular logic gate, which they can pick up and then virtually attach to a dedicated board designed for building logic circuits. In order for the logic circuit to work correctly, it must meet the conditions of the task, i.e., perform the given function correctly. The output signal from the last logic gate is connected to the final signal input (Figure 6c). After pressing the red button, the operation of the circuit is simulated and tested for correct operation. The result of each stage is displayed on a separate board located in the same room (Figure 6d). Access to the result board gives the student an opportunity to notice where the error that does not correctly realize the logic circuit prepared by the participant is. The student has the opportunity to verify their solution and then correct it if an error is detected in its implementation. The feedback is very valuable for the participant, because at that moment they are able to find out what kind of error occurs and also to learn how the logic circuit may behave and which element may have a bad influence on its functioning. Having an external contact, the student can at any time ask the teacher for help and explanation of the problem, however, during the course of classes it was noticeable that students were more inclined to solve the problem on their own than using the help of the teacher.

The VR environment allows one to incorporate elements that enable some form of relaxation between tasks. This approach is optional and the user themselves decides whether they want to use it. In this way, the process considers the user's individualism, which can contribute to a better perception of the learning process by users on the one hand, and to their obtaining better results on the other. For example, such an element is the virtual throw of a ball at a target.

The second module was based on the use and application of truth tables known as Karnaugh maps and learning about function formula minimization techniques. The principles of the module were very similar to the first module, which made it possible to bypass the step of training students on how to use VR and navigate the application environment. The participant had to solve three sub-tasks from the main task, working with the same person as in module one at the same time. Each task was divided into two stages. The second stage was based on the solution of the first stage, and therefore it had to be performed correctly in order to complete the next stage. The goal of the exercise in the first stage was to properly complete the Karnaugh map based on the content of the quest (Figure 7).




(**a**) (**b**)

(**c**) (**d**)

**Figure 6.** Module 1—Boolean algebra: (**a**) gate spawner, (**b**) a sample of a virtual logic gate, (**c**) logic gate connection with final input, and (**d**) a view of room with logic helper.

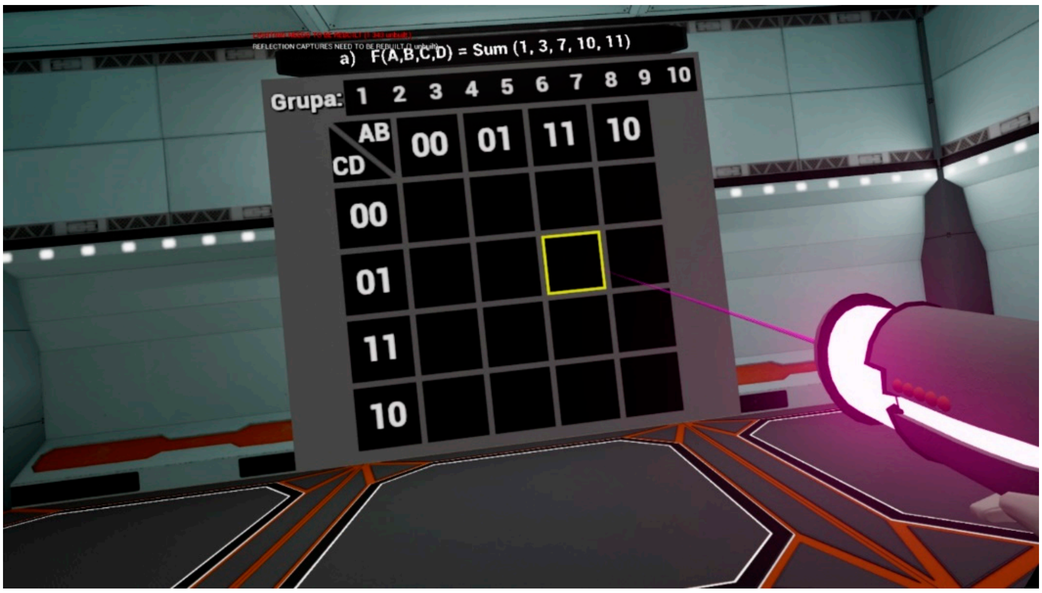
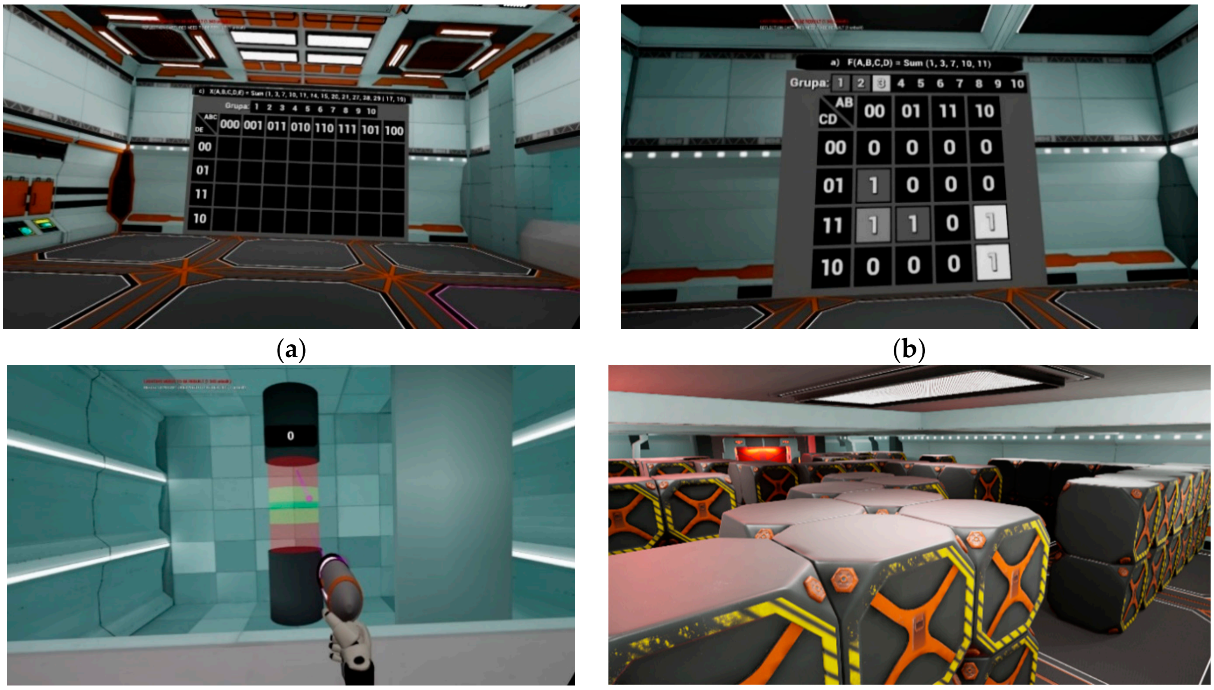



**Figure 7.** A sample of a Karnaugh map.

In the first two cases, the student was asked to complete a 4 × 4 array, and in the last case a 4 × 8 array (Figure 8a). The function of the task was written in canonical form. The participant's task was to correctly enter values into the individual fields of the array. A very important aspect of the task was to pay attention to the type of function. It could be given as a canonical form of the sum or a canonical form of the product. This was conditioned by the idea of solving the task in the process of completing the truth table as well as minimizing the values of the input variables. The second stage was the minimization of Karnaugh maps by means of grouping the elements of the array following the rules determined by the method of Karnaugh maps. Depending on the form of the input function, minimization had to be performed using ones or zeros. In this process, the elements of the array should be properly grouped using an appropriate tool. The participant was able to select up to 10 minimization groups (Figure 8b).




(**a**) (**b**) (c) (**d**)

**Figure 8.** Module 2—Karnaugh maps: (**a**) a view of one of the tasks, (**b**) procedure of grouping minterms, (**c**) relaxation module for students, and (**d**) a virtual labyrinth as part of the in-game obstacles.

Once the appropriate group was selected, the array fields could be selected for grouping. Only after step two could one proceed to verify the completion of the array. The algorithm verified two cases:

- Completion of the truth table: whether the map fields have been completed according to the function given in the task,
- Minimization: whether the array fields were properly grouped with each other and whether the number of groups was minimal.

If both conditions were met, the task was passed. If there was an error in the task, the information on what error might have occurred was given to the user. The message concerned the number of minimization groups (whether their number was appropriate) and whether the fields of the truth table were filled in correctly. After correct completion of the task, the student moved on to the next room, where he or she had to hit the scoring column using a torus (Figure 8c). Depending on accuracy, the number of possible points was variable. An additional element was having to pass through a short maze to reach the door of the next room (Figure 8d).

The third and final module was designed to familiarize the participant with the construction and operation of multiplexers. The final stage contained the solutions that the user learned during modules 1 and 2, including the construction of logic circuits and the use of a laser controller to select/mark the appropriate positions. The principle of module 3's operation inherited the principles from modules 1 and 2. In the case of module 3, the participants, due to the time required to solve the task and the complexity of multiplexers in virtual reality, were familiar with the construction and principle of operation of an 8:1 multiplexer. At each level, the student had to take a dedicated item (Figure 9a), which by solving the task appropriately was produced and then delivered to a dedicated location to open the door to the next room (Figure 9b). The participant had all possible logic gates used in module one to send the appropriate signal to the signal inputs. The address inputs of the multiplexer had to be connected according to the task definition. The output signal from the multiplexer had to be connected to the signal input of the industrial machine (Figure 9c). In order to be able to program the given element, the task had to be solved first in the form of the canonical sum or product.

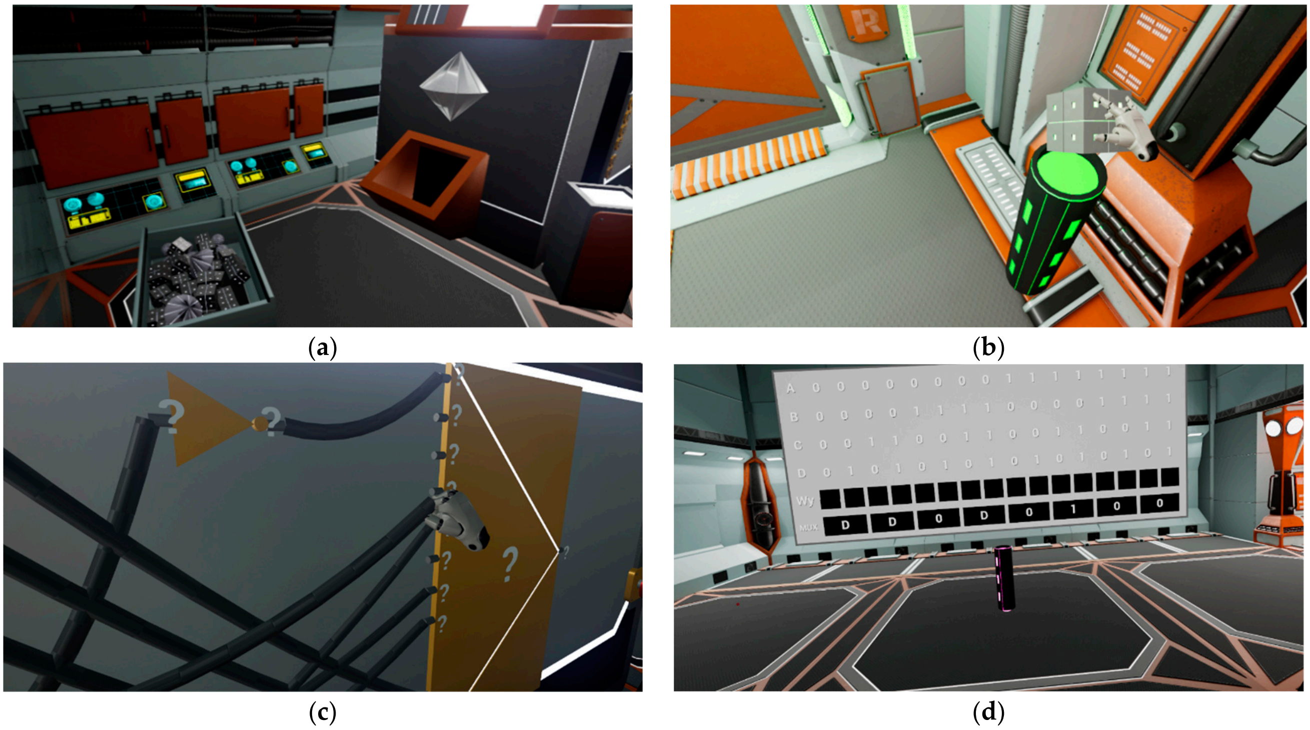



**Figure 9.** Module 3—multiplexers: (**a**) a bay for item for multiplexer machine, (**b**) programmed item used as a key to activate the doors, (**c**) connection of logical gates as input signal for multiplexer, and (**d**) a view of logic helper in case of 8:1 multiplexer.

As an input signal to the 8:1 multiplexer, the user can provide a direct signal or use logic gates to minimize the required number of signals per multiplexer input. There is also an auxiliary table in the room that the student can complete, although it is optional (Figure 9d). The table is intended to help the student solve the task; however, if the student can solve the task independently without the use of the table, the student may do so. The table helps to determine what input signals to the multiplexer should look like in an 8:1 configuration. By grouping the values of the fields, it is possible to determine if 0, 1 or a control signal should be given to the input signal. Before running the simulator, a programmable element must be fed into the machine. If the task is solved correctly, the generating element will be given back to the user. Using the defined interactions, the participant using the manufacturing element will be able to move to the next room.

A virtual jump from a great height was added as a form of relaxation. Each individual experiences their stay in virtual reality differently. In order to allow the student to move on, instead of a virtual jump, the option of teleportation was added, which takes the user directly to the appropriate room. It is up to the user to decide which option they want to choose.

To complete the entire course program, each student must solve assignments related to all three modules. During the course, the student's work in VR is observed and verified by the instructor. In case of problems with the implementation of the task in terms of both technical and substantive aspects, the student could count on the assistance of the instructor. ELIAKI VR, as a modern form of classes, will be introduced as a standard module of a given course in engineering studies.

The aim of the implementation of the educational process based on VR technology is to use modern methods that affect educational outcomes. Solutions in the form of virtual, augmented or mixed reality give the possibility of virtual interaction with any object, including, for example, a virtual production machine, the purchase of which for learning purposes during the study period would significantly exceed the cost of implementing VR technology. Given the wide range of equipment used in industry, it is more beneficial to build a virtual model than to purchase its real counterpart.

## 6. VR Application Methodology for Learning Digital Circuits, Research, and Discussion

### *6.1. Research Methodology*

Before starting the work on VR systems used for education in selected subjects, research was conducted to establish the level of students' interest in the use of VR technology in the teaching process in the fields of computer engineering and automation control and robotics studies at the Faculty of Electrical and Computer Engineering of Rzeszow University of Technology. This was done to determine the effects of learning with the use of digital methods (VR) and traditional methods (a sheet of paper, a simulator of 2D logic circuits). The responses that represented both students' previous experience with VR technology and their attitudes towards it were obtained. The research was conducted between 1 May 2021 and 20 June 2021 and included a group of 40 students. According to the existing regulations in Polish law, because we did not perform any medical tests, we do not need to obtain the permission of a special bio-ethics commission. During our experiment, we did not notice any cases of simulation sickness in the students. All surveys were filled out anonymously and we did not gather any data related to sex, age, and health. The number of gathered surveys was limited by the number of students who attend classes on digital circuits and some limitations caused by the COVID-19 pandemic. No students were forced to take part in the survey and experiment; we based our work purely on volunteers. We are aware that VR is a quite new technology that in some cases can seriously influence people's health, thus all of the participants were informed about possible negative effects resulting from the use of VR. However, our main goal was to indicate whether and how much some solutions related to the use of VR in the didactic process can be used more frequently and whether they guarantee any progress relating to the traditional teaching methods. In our research, we did not focus on possible measurements related to any medical issues, and thus we did not gather any medical data.

The process of students' recruitment was based on a published announcement: we were looking for student volunteers who attend Elements of Logic and Computers Arithmetic classes and were interested in project participation. In the announcement, we described the details of the test activity, and 40 volunteers responded to our request and took a part in the tests. The number of 40 also came from the fact that we sought to test students who so far had not taken part in any classes on digital circuits.

### *6.2. Results of the Surveys*

One of the questions asked about students' prior experience with VR technology (Figure 10a). Overall, 45% of the responses indicated that students had likely only experienced VR technology in a familiarization form: one to two times. In contrast, 16% of the respondents already had more contact with VR solutions, i.e., five times or more. Thus, more than half of the respondents confirmed previous contact with VR technology. However, on the other hand, as many as 39% of the respondents indicated that they had no direct contact with VR.

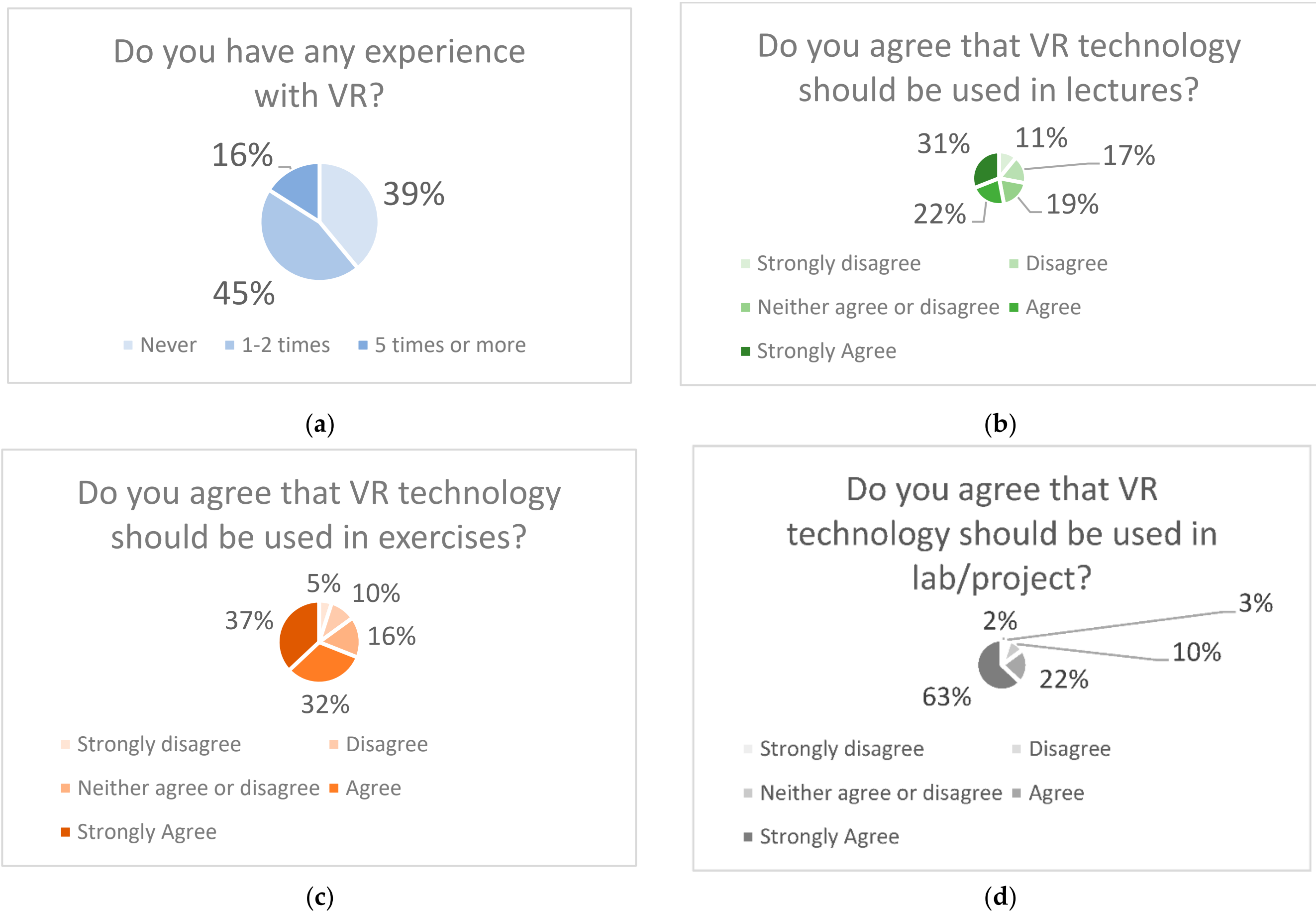



**Figure 10.** Students' survey results on experience with VR technology and its potential for different forms of education: (**a**) Q: Do you have any experience with VR?; (**b**) Q: Do you agree that VR technology should be used in: lectures; (**c**) exercises; (**d**) lab/project.

There were an additional three questions with a five-point Likert scale: 1—Strongly Disagree, 2—Disagree, 3—Neither Agree nor Disagree, 4—Agree, 5—Strongly Agree. As can be seen in Figure 10b—Q: Do you agree that VR technology should be used in lectures—11% of the surveyed students believe that they do not see the possibility of using VR technology in a lecture format. This value is the highest of all three analyzed forms of classes. However, it should be noted that a large part of the respondents, as many as 31%, gave the answer "Strongly Agree", and 22% answered "Agree". This means that these classes also have great potential for using VR technology. In the case of practical classes, which have more practical aspects than lectures, the responses indicate greater potential for VR technology (Figure 10c—Q: Do you agree that VR technology should be used in classes). On the other hand, laboratory/project classes are very popular in terms of using VR technology (Figure 10d—Q: Do you agree that VR technology should be used in labs). In this case, as many as 63% of the respondents indicated the highest value of "Strongly agree" when answering the question regarding the possibility of using VR technology in these forms of classes. The value of "Agree" was selected by 22% of the participating students, representing 85% of all responses. The answer No was strongly expressed by only 10%, and negative by only 5%.

Based on the results presented in Figure 10, necessary steps were taken to develop a special course for selected content within the subject Elements of Logic and Computers Arithmetic. The tasks prepared for students in virtual reality were identical to the tasks that were prepared for classes given in traditional form, as well as using specialized computer applications. During the classes, a hybrid approach was used. Students were asked to solve tasks using traditional methods and using computer software as well as virtual reality. Each student before attending classes had the knowledge necessary to perform the tasks learned during the classes conducted in lecture form. After conducting classes in each of the three forms, a survey was conducted on a group of students participating in the classes. Questions were divided into two categories—see Tables 2 and 3. The first one was solely about working in a VR environment and used a five-point Likert scale: 1—Strongly Disagree, 2—Disagree, 3—Neither Agree nor Disagree, 4—Agree, 5—Strongly Agree.

### 6.3. Discussion about Advantages and Disadvantages of Working in a VR Environment

Analyzing the results presented in Table 2, it can be seen that the students do not have any major problems with the use of the solution based on VR technology. Obviously, the deciding factors were: having previous experience with VR, or the support of the instructor, as well as the openness and positive attitude of young people to new solutions and experiences. At this point, it is also important to note that the responses to question 2 regarding the need for additional training in the use of VR were distributed in such a way that a comparable number of participants believed that such training was required as well as that it was not required. In contrast, a significant number of participants (42.5%-Q.11) had no clear opinion on this topic. Presumably, this was due to similar reasons as mentioned above. Very important from the didactic point of view were the answers to questions 4, 5 and 10. The given answers indicate that the vast majority of students (77.5%-Q.4) believe that VR technology should be used in classes, and 80% (Q.5) are convinced that the VR system contributed to better learning. It is also interesting to note that most of the students (62.5%-Q.10) feel that they achieved better results than they expected. This result may also confirm previous studies suggesting that the use of VR technology has great potential in education. Moreover, the students who participated in the study confirmed that the VR environment did not negatively affect their comfort, and some even confirmed that they felt comfortable. This result may also have been influenced by the visual and graphical legibility of the developed system and the comprehensibility of the defined tasks, as the results obtained in questions 6, 7 and 9 are similar. On the other hand, the prepared color scheme of the developed VR system may have caused a distraction for a certain group of participants (15%-Q.8). Nevertheless, most of the participants (55%-Q.8) do not have a clear opinion on this issue; it did not appear to matter much. Here, future research is needed on the obtained effects of teaching using different (in terms of image quality) VR solutions. It should be also noted that a certain group of students needed additional time to get used to the real environment after their VR work. Obviously, this group was not very large; however, taking this into account, a deeper study of the impact of the VR environment on its users should be considered in the future. Additionally, the authors presented the Cronbach's alpha value for the conducted study in Table 2. The result obtained at the level of 0.734 confirms the reliability of the conducted educational research.

### 6.4. Discussion about Comparison of Different Forms of Education

In the next step, comparisons were made between different forms of education used in the process of teaching digital techniques. The results of the study conducted on the same group of students are presented in Table 3.

**Table 2.** Category I—Working in a VR environment.

| | Questions | Strongly Disagree | Disagree | Neither Agree Nor Disagree | Agree | Strongly Agree | Cronbach's Alpha |
|---|---|---|---|---|---|---|---|
| 1. | Was the VR system easy to use? | 0 [0%] | 1 [2.5%] | 10 [25%] | 18 [45%] | 11 [27.5%] | 0.734 |
| 2. | Do you think that working in VR requires additional training? | 2 [5%] | 10 [25%] | 17 [42.5%] | 8 [20%] | 3 [7.5%] | |
| 3. | Was the time allotted to solve the tasks in VR sufficient? | 0 [0%] | 1 [2.5%] | 10 [25%] | 18 [45%] | 11 [27.5%] | |
| 4. | Should a VR system be used in the classroom for this subject? | 0 [0%] | 2 [5%] | 10 [25%] | 15 [45%] | 13 [32.5%] | |
| 5. | Do you think the VR system has contributed to better learning? | 0 [0%] | 0 [0%] | 8 [20%] | 22 [55%] | 10 [25%] | |
| 6. | Were the tasks defined in the VR system were clear and understandable? | 0 [0%] | 0 [0%] | 8 [20%] | 15 [37.5%] | 17 [42.5%] | |
| 7. | Were the visual and graphic solutions adopted legible? | 0 [0%] | 0 [0%] | 4 [10%] | 21 [52.5%] | 15 [37.5%] | |
| 8. | Did the adopted color scheme of the visualization cause distraction? | 1 [2.5%] | 11 [27.5%] | 22 [55%] | 5 [12.5%] | 1 [2.5%] | |
| 9. | Did you feel comfortable while working in the VR system? | 0 [0%] | 4 [10%] | 18 [45%] | 12 [30%] | 6 [15%] | |
| 10. | Was your experience using the VR system in class better than you expected? | 0 [0%] | 2 [5%] | 13 [32.5%] | 15 [37.5%] | 10 [25%] | |
| 11. | Was the support while working in the VR system at the right level? | 0 [0%] | 0 [0%] | 5 [12.5%] | 17 [42.5%] | 18 [45%] | |
| 12. | Did you need extra time to get used to the real-world environment after completing tasks in the VR system? | 1 [2.5%] | 14 [32.5%] | 17 [42.5%] | 6 [15%] | 3 [7.5%] | |

**Table 3.** Category II—Comparison of different forms of education.

| | Questions | Traditional (Classical) | Information Technology (Computer Applications) | Immersive (VR) | Cronbach's Alpha |
|---|---|---|---|---|---|
| 1. | Which form of education/presenting material is the most suitable for you? | 13 [32.5%] | 23 [57.5%] | 4 [10%] | 0.842 |
| 2. | Which form of education gets you the most involved and active in class? | 6 [15%] | 13 [32.5%] | 21 [52.5%] | |
| 3. | Which form of education can best affect learning? | 7 [17.5%] | 19 [47.5%] | 14 [35%] | |
| 4. | Which form of education provides a better understanding of the practical aspects of the issues discussed in the course? | 1 [2.5%] | 20 [50%] | 19 [47.5%] | |
| 5. | Which form of education allows better understanding of the theoretical aspects of the issues discussed during the course? | 10 [25%] | 22 [55%] | 8 [20%] | |
| 6. | Which form of education seems to be the least time consuming? | 14 [35%] | 26 [65%] | 0 [0%] | |
| 7. | Which form of education would you recommend to your peers? | 3 [7.5%] | 23 [57.5%] | 14 [35%] | |

Analyzing the obtained results presented in Table 3, it can be seen that currently, the most preferred and suitable form of education is a system based on computer tools/applications (Q.1 and Q.3). This is caused by the fact that students have been conditioned to this form of education through many years, meaning that they have become familiar with various software tools that allow them to solve both simple and more complex scenarios and exercise tasks. Additionally, many of these tools indicate possible errors. This is further confirmed—almost half of the students are convinced that a better understanding of the practical (see Q.4) and theoretical (see Q.5) aspects of the issues can be achieved thanks to computer-aided education, and therefore it is currently preferred and will be recommended to peers (see Q.7). However, taking into account students' indications of the effectiveness of acquiring knowledge and skills, as well as their willingness to recommend this form of education to their peers, VR technology maintains great potential: Q.3 and Q.7. In the case of Q.7, some of the answers to VR were probably caused by the students' natural curiosity, but from Q.2, we also expect that VR will require students' involvement and activity during classes, which from the educational point of view is highly desirable. It seems that such collaboration between the traditional educational process and VR technologies can contribute to increased interest in given issues, and a better understanding of them in the context of practical applications.

## 7. Conclusions

This paper presents a number of challenges that are confronting us in the field of didactics in the near future. The revolutionary concept of Industry 4.0 changes our view on many aspects related not only to the production process itself, but also to didactics. New challenges in education require modern methods and techniques of teaching, and VR technology is one of the potential avenues to realize these aspects. In common perception, these types of solutions are rather associated with games and entertainment, but this paper demonstrates that it is possible to prepare an interesting system of teaching support that is positively evaluated by students. Although it is a system that requires improvements, and we will continue to develop it on the basis of the conducted evaluation, it can be seen that it is a unique alternative to traditional methods and learning techniques, especially in the field of practical skills.

In the Introduction, we stated that our solution meets some of the conditions related to Education 4.0. We note that these conditions suggest that education should be, among other things: (i) independent of time and space, (ii) flexible, (iii) involving student participation, (iv) personalized, and (v) not based on a single exam, but rather on continuous improvement. So far, our VR system is stationary, mostly due to the low amount of VR equipment available to students (including at their homes), but this technology is getting cheaper, and some studies [80,81] suggest that the amount of money spent on its development and usage will constantly grow. The proposed system ensures active participation of students, and this activity is also physical. Many exercises have their own teaching scenarios that resemble a kind of game. This solution is also flexible—we can easily change some scenarios and change the visual layout, and passing is not based on a single exam, but rather successive levels need to be passed before the next one is made active, ensuring students' continuous improvement.

The created environment and the conducted research confirm that VR technology can also find applications in the process of educating engineers and specialists in such demanding areas as designing and testing digital circuits. Of course, much more work is required to expand the use of VR in this course. Therefore, based on the obtained results, the VR system should be a complement to computer software-based education. This is similar to the training solutions in the industry: we can see that among traditional training courses, some new solutions are used, and based on the long practical experience, we consider them as a useful extension that is flexible depending on the different external and internal conditions. It should be noted that an large number of students found that the VR system contributed to better learning, but they also attend normal classes. The experiences gathered so far allow for making a very significant contribution in terms of creating coherent exercises covering real industrial processes, e.g., integration, assembly, and testing of digital circuits. This opens up a huge field of application for VR-based education aimed at the needs of Industry 4.0, where flexibility is very important [32,81]. Moreover, this approach reduces costs to a great extent and makes it possible to popularize such courses in the future among other students.

The use of VR has many different imitations including some students' disabilities (e.g., motor skills). However, the same can be said about classical classes when the student is not able to perform exercises requiring his/her physical activity, and at our university we ensure the availability of necessary facilities that help different students. We note that our approach does not exclude classes without VR, but rather represents their expansion. From the gathered data, it can be seen that this solution should be used (see Figure 10b–d) in lectures, exercises, and laboratory/project classes, but the highest rate is in the case of practical classes. Based on obtained results (Table 3), the proposed VR solution will be and should be offered to students as additional but not mandatory, and if someone decides that they are ready to use it, she/he will also take full responsibility for any negative experiences.

According to [91], mental and health disabilities in many cases can be serious contraindications for the use of VR, but on the other hand, a review of recent studies showed that VR is also currently considered as a new medical technology in psychiatry [92], psychiatry disorders [93], and depression [94]. It should be also emphasized that each student before starting technical university education in Poland is required to provide a medical history that does not exclude or limit his/her university activity, especially during technical studies. This is done in order to ensure as much as possible that any mental and physical disabilities that may cause danger to the student are found and accounted for. In the case of computer engineering studies carried out at the Faculty of Electrical and Computer Engineering, there are not many such limitations, but it is obvious that not all persons with mental and physical disabilities can use the proposed solution. Referring to the report [95] presented by the Polish Supreme Audit Office, around 2% of Polish students are persons with some disabilities, and 31% of them have motor skills impairment. In order to ensure that our solution will be more accessible in future work, a voice interface will be incorporated, making the considered solution more accessible. The accessibility of VR can be also raised by different supporting solutions, as mentioned and reviewed, for instance, in [96,97]. There are even some existing systems, such as SeeingVR toolkit [98], which provide the possibility to include metadata analogous to alt text into VR scenes; the objects are described by text to be read aloud to people with vision disabilities. One can also focus on the personalization of VR avatars [99] and additional solutions for blind people to locate some elements in proposed scenes before they attempt to use the system for the first time, as was proposed in [100] which again raises VR accessibility.

An important issue is the inclusion of Universal Design for Learning in the preparation of VR systems [74,75]. VR systems should strive to meet the requirements for adapting teaching to the needs of all students. Moreover, by applying the principles of inclusive design, it is possible to include students who are excluded or have learning difficulties. VR systems allow for the individualization and adaptation of didactic materials [76]. However, these efforts must be underpinned by wider research supported by doctors and specialists in various fields [77]. Therefore, this is a wide field for future research.

Further research also involves developing the range of exercises available, gathering experience over a longer period of time to develop new findings and recommendations, and including augmented reality as a form of digital learning.

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