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Virtual Reality Laboratories in Engineering Blended Learning Environments: Challenges and Opportunities

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Abstract

A great number of educational institutions worldwide have had their activities partially or fully interrupted following the outbreak of the COVID-19 pandemic. Consequently, universities have had to take the necessary steps in order to adapt their teaching, including laboratory workshops, to a fully online or mixed mode of delivery while maintaining their academic standards and providing a high-quality student experience. This transition has required, among other efforts, adequate investments in tools, accessibility, content development, and competences as well as appropriate training for both the teaching and administrative staff. In such a complex scenario, Virtual Reality Laboratories (VRLabs), which in the past already proved themselves to be efficient tools supporting the traditional practical activities, could well represent a valid alternative in the hybrid didactic mode of the contemporary educational landscape, rethinking the educational proposal in light of the indications coming from the scientific literature in the pedagogical field. In this context, the present work carries out a critical review of the existent virtual labs developed in the Engineering departments in the last ten years (2010-2020) and includes a pre-pandemic experience of a VRLab tool - StreamFlowVR - within the Hydraulics course of Basilicata University, Italy. This analysis is aimed at highlighting how ready VRLabs are to be exploited not only in emergency but also in ordinary situations, together with valorising an interdisciplinary dialogue between the pedagogical and technological viewpoints, in order to progressively foster a high-quality and evidence-based educational experience.

KEYWORDS: Blended Approach, COVID-19 Pandemic, Engineering Education, Streamflowvr, Virtual Reality Labs.

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1. Introduction

In engineering education, laboratories have always played a key role in understanding theoretical concepts and practising teamwork, observation capability, and communication, as well as in reinforcing important notions related to data analysis, problem solving, testing, and scientific interpretation. For this reason, the lack of laboratory classes during the global COVID-19 emergency phase has negatively influenced the quality of the academic courses, reducing not only the learners' possibility to better understand some real, physical phenomena and processes, but also the chance to obtain the technical skills needed to face future challenges in the labor market (Kapilan et al., 2021; Vasiliadou, 2020). In such a scenario, different European engineering universities have been working hard to improve the teaching curricula and the students' learning experience, trying to circumvent this crisis by moving the essential educational missions into Virtual Learning Environments (VLEs).

To this end, VRLabs could well fill the gap caused by the lack of traditional practical lessons, since students could continue to better understand the theoretical aspects, improve their technical skills and competences, and analyse phenomena in depth through online experiments and training exercises, without the need to physically reach the premises. In addition, well-planned VRLabs could allow social interaction and collaboration among students, reducing feelings of isolation and loneliness at the same time.

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In the last decades only, VRLabs have demonstrated their usefulness in increasing students' knowledge, skills, and performance in examinations, while reducing geographical limitations, health and safety hazards and training costs, thanks to their availability and affordability (Lewis, 2014). When properly planned and executed, VRLabs have been found to provide an equal, and often even enhanced, learning experience, with many benefits that traditional labs cannot offer (Lynch & Ghergulescu, 2017). Cheong and Koh (2018) underlined how VRLabs could increase the active participation of students and allow them to apply their knowledge to simulated real-world scenarios. The enhanced engagement of students in the learning experience using multiple teaching approaches was recognised also by Goudsouzian et al. (2018) and Toth (2016), who confirmed the role of VRLabs and their varied inputs in the form of animation, videos, and other teaching tools in improving students' learning outcomes. In particular, in VRLabs students can carry out experiments that would be too dangerous or impossible to perform in real life and can learn from their mistakes without causing any real damage to themselves, to others or to the equipment/facilities. In fact, they are able to manipulate virtual equipment and materials simply using a keyboard and/or handheld controllers and repeat the same experiment more than once, changing parameters and conditions, without incurring in extra cost or time. These experiences make use of low-immersion technology (desktop/laptop computer), if delivered in 2D, or high-immersion technology (Head-Mounted Display-HMD), if delivered in 3D. The level of immersion is thus an important parameter when evaluating the impact of the VRLab on students and how intuitively they manage to use the technological devices and tools (Cummings & Bailenson, 2016). The actions to be performed in a VRLab can vary from observing a phenomenon to testing theories and/or hypotheses through experiments (de Jong et al., 2014; Potkonjak et al., 2016), not only offering students a first-person experience similar to that of a teaching laboratory (Vrellis et al., 2016) but sometimes involving more complex analyses typical of an actual research laboratory (Makransky et al., 2016, 2019), with student achievements in line with those observed in a physical lab (Darrah et al., 2014; Ekmekci & Gulacar, 2015; Goudsouzian et al., 2018; Koh et al., 2010; Makransky et al., 2016; Ogbuanya & Onele, 2018; Vrellis et al., 2016). In such an environment, reproduced with very high fidelity, the knowledge students acquire in a familiar situation becomes transferrable to other unknown contexts (Kester et al., 2001), boosting their confidence especially in the future professions of engineering (Chemers et al., 2011).

Up until early 2020, VRLabs had been used in support of in-class theoretical lessons in a blended approach to teaching theory and practice. During the pandemic emergency, though, their importance and potential increased. Sometimes they had to completely substitute teachers and not only be of support as a module within a much wider course of studies (Reeves & Crippen, 2021).

It is a fact that the pandemic crisis has enormously changed the entire education model and universities need to reflect on how to establish a sustainable approach to teaching, doing research, and engaging with society. A new and robust system balancing online and physical presence is more and more required. Universities might want to keep using the technological tools they have lately learned to appropriately use to ensure more equality and inclusion, especially among groups of students who would not be able to follow a full-time course in attendance otherwise. Classes have become even more student-centred as learners have experienced a new interaction pattern with the technological content and have become active players in their learning process. They can keep building their ability to manage time, their learning autonomy, and their transversal competences if given the right support to do so. Of course, this revolution in teaching/learning methods requires conspicuous investments in equipment, infrastructures, and content development, thus profoundly transforming the way we teach and learn.

In such context, the present paper describes the limits and opportunities involved in a pre-pandemic experience of a VRLab, the StreamFlowVR, developed within the Hydraulics courses of the master's degree in Civil and Environmental Engineering at the University of Basilicata, in southern Italy (Mirauda et al., 2019, 2020). The StreamFlowVR tool was implemented on the measurement and analysis of water discharges in open-channel cross-sections, having the aim to train students on correctly using the equipment and following the different measuring steps, but also learning how to move within the river, in addition to improving the research methods and analysis techniques explained in class. Designed before the pandemic to fill the existing gap between the theoretical lessons in class and the practical ones in field, which are limited due to weather conditions, long organisational times, and high costs, the StreamflowVR tool is here revisited underlining its useful aspects in the hybrid teaching context and the features that might be improved in the future. At the same time, this work tries to analyse further opportunities of using appropriately designed VRLabs and the current challenges of online/in-class teaching of engineering subjects, starting from a literature recognition on the topic.

The rest of the paper is organised as follows. Section 2 describes the research questions and the methodological approach adopted, while Section 3 provides a review of the VRLabs developed in the last decade in some academic engineering departments, highlighting their potential in improving the practical competences of students in mixed educational environments. To this purpose, a pre-pandemic experience of a VRLab tool supporting engineering education - StreamFlowVR, developed at Basilicata University within the Hydraulics courses, is introduced in Section 4. Section 5 thematises, from a pedagogical viewpoint, how VRLabs can promote meaningful learning in the age of distance learning, suggesting some criteria for their possible future progress in the academic engineering education. From this perspective, rather than showing the results of a work, the present paper questions how VRLabs can be improved starting from the awareness of the educational and technological challenges and processes involved. Based on the scientific evidence produced by the pedagogical literature on blended learning and VRLabs, and reviewing a great amount of existing meta-analyses on the subject, some theoretical indications and methodological criteria useful for the design, implementation, and evaluation of teaching practices have thus been offered. Section 6 proposes the implementation of the StreamFlowVR tool in the near future, taking into account the guidelines extrapolated from the current literature. Finally, Section 7 gives the conclusions of the present work and future perspectives in terms of educational and technological objectives.

2. Methods

From a methodological perspective, the present work develops on two levels, each based on one specific research question.

The first research question investigates the literature on the topic in order to define what instructional guidelines should be considered for the implementation of VRLabs in classroom teaching of engineering subjects. A scoping review (SR) was thus conducted as a second-level study by mapping a reasoned portion of meta-analyses according to their objective, following the PRISMA methodology and guidelines (Tricco et al., 2018). The following keyword strings were used in all searched databases: “virtual reality” or “VRLab” AND “engineering education”, considering sources from 2009 to 2021. Nine databases were used (Virtual Health Library-VHL, PubMed, PsycINFO, Web of Science, Scopus, Scielo, Ebsco, Google Academic, and Embase). The “document type” filter (article, journal article, or conference paper) was employed in all databases. For data selection and eligibility, articles located in the databases were imported into the Rayyan website for screening. Rayyan is a free tool that helps researchers perform systematic or scope reviews through automatic identification of duplicated publications and uses a “blind mode” to reduce the risk of selection bias (Ouzzani et al., 2016). The data extracted included: 1) study identification (i.e., Authors last name, publication date); 2) study design (e.g., case study, quantitative/qualitative); and 3) university courses (e.g., engineering). The inclusion criteria were empirical studies that underwent peer review from 2009 to 2021 on engineering university courses. The exclusion criteria included duplicated articles, studies not in university courses, theoretical studies, and full texts not available online. Initially, 47 records were identified, 12 duplicates were removed, 35 records were screened, 14 were excluded, 21 assessed for eligibility, and 13 studies were finally included in the review.

The second research question explores the effectiveness of blended learning in the design, delivery, and evaluation phases of teaching. The goal for this second level was to examine pedagogical meta-analyses produced internationally and in English on “blended learning” to provide pedagogical criteria for the design, delivery, and evaluation of university courses offered in a “blended learning” mode. This was based on a previous study by one of the Authors (Patera, 2016) from 1994 to 2022.

3. VRLab Applications in Engineering Education

Over the last few years, Information and Communication Technologies (ICTs) have increasingly been integrated into traditional academic teaching by various universities and thus also by Engineering courses, to enhance students’ learning experience and practical skills.

Innovative VLEs have been designed, where interaction between teachers and students occurs through various tools like computer animations, audio and video devices, 3D graphics, and on-line databases, allowing a more immediate communication thanks also to e-Learning systems with Internet-based features such as e-mails, instant messaging, and cyber-platforms.

These VLEs have become more and more efficient recently as collaborative places where students can learn new contents and broaden their knowledge on topics of interest (Hernández-de-Menéndez et al., 2019). Besides, being virtual and not physical classrooms, they help to reduce the costs and times of traditional teaching methods (Manesh & Schaefer, 2010).

More recently, the level of interaction not only with the technological tools but also with the other students and their instructors has greatly increased. Well-designed and up to date VRLabs have been created and are among the most efficient VLEs in engaging students.

Most of the past decades’ research in the field of undergraduate education has been focused on mainly 2D experiences (Reeves & Crippen, 2021) and the area of robotics. Most of the VRLabs in the last ten years were of the non-immersive 2D type and not specifically designed for the course in which they were employed, and a great amount was mainly implemented in undergraduate or introductory courses. Overall, most of the experiences dealt mainly with one specific module of a related course (Reeves & Crippen, 2021).

Therefore, the question is: how much more efficient, in terms of gaining and retaining knowledge and practicing skills, but also of enjoying the experience, is the 3D environment compared to the 2D type? Some Authors have tried to answer this question. Johnson-Glenberg et al. (2021) have very recently come to the conclusion that, although the high immersivity provided by 3D is more presence-inducing, the performance of STEM students is not always comparably higher than the ones working on 2D platforms (e.g., desktop pc), especially due to the possibility of 'overload effects' of the 3D immersive environment. What makes all the difference, they state, is the level of 'embodiment', linked to 'agency' or 'personal empowerment', as they are defined in psychological terms; in other words, learners who can manipulate content via a mouse or other controllers have more chance of faster and better results. Their expectations of higher interaction are also fulfilled and their engagement functions as a motivator for learning. Having highlighted the potential of VR in enhancing kinesthetic interactivity (Johnson-Glenberg et al., 2021), which in turn improves the learning experience if added to the usual visual and auditory input, we move away from discussing the VR platform design itself, giving more space to the VR tools that allow for more body movement and interactivity (e.g., HMDs with tracking and VR hand controllers).

In view of this, VRLabs are very powerful tools that, being more and more affordable in terms of technology cost (Martín-Gutiérrez et al., 2017), can be applied to university education, shaping a new teaching approach by favoring the exchange of knowledge, skills, and technology between individuals (Fogarty et al., 2011). By expanding on the locations where laboratory learning can take place (Bortnik et al., 2017), they can solve most of the problems encountered during practical classes in real laboratories, where some students might not see all the details of an experiment being carried out, for example, or do not manage to listen to the teacher's explanations especially when in large groups. In VRLabs, instead, communication is easier and more immediate, visualisation is of high quality, and all students have the chance to 'virtually' handle and operate otherwise very expensive and not always available tools (Vergara et al., 2019). Learners are empowered through practical tasks, which can also be repeated without incurring in extra costs or even physical risks, aimed at refining their techniques and abilities, and are thus able to advance faster in their studies and meet the labour market needs once graduated (de Jong et al., 2014).

Their student-focused nature is a valid way to improve the learning of the science, and thus engineering, content (Ekmekci & Gulacar, 2015; Goudsouzian et al., 2018) and they make use of immersive technologies which motivate students and increase their enthusiasm for engineering subjects, even when physical resources are limited (Cobb et al., 2009).

Successful VRLabs have been implemented especially in courses of Mechatronics and Industrial Engineering, to provide undergraduate students with basic robotics knowledge and prepare postgraduate ones for more complex tasks, such as the creation of industrial robots which control and monitor manufacturing processes. The VRLab lets students practise automation tasks such as those of a warehouse storage, an elevator, a transport and sorting line, or a manufacturing cell, avoiding the high investment and operating costs the real systems would require if purchased and constantly updated by universities. An example is the virtual laboratory for teaching mobile robotics at the Department of Computer Science at Tecnologico de Monterrey (Mexico). It is based on a 3D simulation, which lets students explore the first concepts in the course (mechanical design, sensors, and control) before they start building a physical robot and includes an intelligent tutoring system that guides the students during their interactions with the virtual lab (Noguez & Sucar, 2006). Another interesting experience, aimed at postgraduate students, is RoboUALab, designed at the University of Alicante, Spain, to simulate and execute a manipulator robot. It allows students to practice movement commands with a simulated industrial robot and to handle a real robot, located in a laboratory of the university, through tele-operation. The latest version is based on Easy Java Simulations, an open-source tool for people who do not have advanced programming skills. The only equipment that the student requires is a computer connected to the Internet, the Java runtime library, and either the VRML software or the Java 3D runtime library, depending on the version of the RoboUALab being used (Jara et al., 2011; Torres et al., 2006).

Recently, Grodotzki et al. (2018) have developed a virtual lab in manufacturing and materials testing in a joint project by three universities in Germany (RWTH Aachen University, Ruhr-Universität Bochum, and TU Dortmund University) called Excellent Teaching and Learning in Engineering Science (ELLI). In detail, the VE-Lab is a web- and app-based environment with access to a library of pre-run virtual experiments based on Computational Fluid Dynamics (CFD) and other numerical simulation methods. The latter, in fact, can reproduce real experiments (material tests, forming and machining processes, product tests, etc.) at a good level of accuracy, supporting problem-based learning courses.

As demonstrated by the above-mentioned experiences, not only are VRLabs able to reduce the daily issues of traditional in-class methodologies, but also to foster a more student-based learning process, where learners are stimulated to take initiative and to reach autonomy while enjoying the process.

In view of this, the VRLab “Ironmaking”, designed at the RWTH Aachen University in Germany, provides a deep understanding of the blast furnace process (Babich & Mavrommatis, 2009). The latter is a complex technological procedure, characterized by a range of phenomena (mechanical, hydraulic, physical, chemical, and physical-chemical ones) and reactions, which occur simultaneously and affect one another. The peculiarities of such a process include: interconditionality, non-linearity of relationships, inertia and transport delays, ambiguity, and loss of information. Similarly, the Department of Chemical Engineering at the Oregon State University created the CVD Virtual Learning Platform, simulating the process of the chemical vapor deposition (CVD), in which students synthesize engineering science and statistics principles (Koretsky et al., 2008). The simulation of the reactor is based on the fundamental concepts of mass transfer and chemical reaction, obscured by added disturbance (noise), using advanced software features (a 3D graphical user interface, an instructor Web interface with integrated assessment tools, and a database server).

More recently, still focused on the engineering control systems, the VRLabs designed at the Slovak University of Technology in Bratislava (Kalúz et al., 2012), at the Universitat Politecnica de Catalunya in Barcelona (Fernández-Cantí et al., 2012), and at the Loughborough University in the UK (Abdulwahed & Nagy, 2013) are worth mentioning. The first virtual laboratory provides for virtual simulations of three technological plants (liquid storage tank system, tube heat exchanger, and continuous stirred-tank reactor), originally using the Adobe Flash programming platform, and later employing Java Server Pages. The experience of Barcelona University allowed implementing a multiplatform virtual laboratory, using a Java language-based tool (Easy Java Simulation) and the Matlab software, to analyze two engineering control phenomena: inverted pendulum cart system and magnetic levitation. The experiments introduced root locus controller design, ITAE (Integral Time Absolute Error) optimal controller design, and PID (Proportional-Integral-Derivative) controllers. The same controllers, together with the main components and instruments of feedback loops and the concepts of open-loop and feedback control, were included in the Process Control Virtual Laboratory (PCVL) designed at the Loughborough University to simulate the Armfield PCT40 tank filling process. This laboratory combines the three access modes (Hands-On, Virtual, and Remote) in one unifying software package (the TriLab), by using LabVIEW. More recently, Hu et al. (2017) implemented a plug-in free online 3-D interactive laboratory based on the networked control system laboratory (NCSLab) framework which, despite being based only on HTML5, supports control engineering experimentation, and provides all services such as monitoring, tuning, configuration, and control algorithm implementation. By replacing the real physical devices with virtual ones, the NCSLab was later extended to the 3D-NCLab, as described by Liang and Liu (2018), which offers an extensible framework for collaborative experiments. Various virtual devices were created by designing accurate mechanical movements using real-time data from hardware-based simulations and the system was efficiently applied to a creative automatic control experiment course in the Harbin Institute of Technology.

Over the years, VRLabs have progressively become more interactive, enabling students to switch from being passive listeners to active participants in their learning process. A good example are VR platforms implemented in the field of architectural and construction engineering as well as in the facility management industry (Whisker et al., 2020), including fully immersive CAVETM or HMD environments and semi-immersive screen display systems to support the design review process of courtrooms, nuclear power plants, patient rooms, and educational buildings. This way, students can understand various planning issues, practice in conditions normally restricted in the real world but without real consequences, and despite their little present knowledge concerning buildings and infrastructures. Therefore, they are also guided towards a more informed and faster decision on the best choice of design, being also able to make any changes to the project in real time. In the same period, in the sector of Hydraulics Engineering, Pieritz et al. (2004) developed an interactive, web-based virtual laboratory with OpenGL technology to simulate and study fluid flow problems, while Pauniaho et al. (2005) introduced a three-dimensional model in a Hydraulics course at Tampere University of Technology (TUT), in Finland, using the virtual reality modelling language (VRML) to teach the structures and functions of fluid power systems and hydraulic components.

Later, the Virtual Electric Machine Laboratory created at Firat University (Turkey), based on HTML (Hypertext Markup Language), ASP (Active Server Pages), and Borland C++ Builder (Tanyildizi & Orhan, 2009), allowed the students to immediately see the effect of loading different synchronous motors by changing all parameters, such as simulation time, sampling frequency, and voltage, and graphically visualize the outputs (e.g., the velocity of the synchronous motor).

Incorporating the students’ real-world interests into the classroom has always been a challenge, satisfyingly met using advanced technology and popular computer games in the educational VRLabs, so that the learning process becomes overall more enjoyable. The Stevens Institute of Technology (USA) developed an innovative online virtual laboratory, enabling students to learn by interacting in a virtual environment very similar to massively multiplayer online games, such as Half-life 2, The Sims, WoW (World of Warcraft), and Second Life (Aziz et al., 2009, 2014). The game-based laboratory environment was created as part of the course “Mechanisms and Machine Dynamics” to introduce the principles of kinematics and dynamics and apply them to linkages, cam systems, gear trains, belt and train drives, couplings, and vibrations. Students, teaching assistants, and professors could design their own avatars and discuss projects through instant messaging, manipulate equipment and machinery to set up their experiments, and visualize data based on the interactions of the parts. The Virtual Engineering Sciences Learning Lab (VESLL), designed at the Loyola Marymount University in California, is also based on the Second Life multiplayer online game, where a private “island” was created specifically for students to explore content, solve puzzles, and participate in activities regarding engineering science, as well as interact with other users (August et al., 2016).

Most research in the field has so far investigated the influence of VRLabs on positive students’ outcome in terms of content knowledge (Chini et al., 2012; Darrah et al., 2014) and retention (Vergara et al., 2019) and on analysing students’ perception and attitude towards the use of virtual labs (Dyrberg et al., 2017) as well as their level of motivation (Koh et al., 2010), while few studies have focused on the improvement of practical and critical-thinking skills. Cheong and Koh (2018), for example, described how students can solve math problems and Ogbuanya and Onele (2018) expressed their idea of VRLabs enhancing students’ learning through engineering practice. Nedeljkovic et al. (2019, 2018) and Sivapragasam et al. (2020) analysed how students build confidence with hydraulics and fluid mechanics issues, using the LabVIEW platform, to test hydraulic pumps tracking the profile of the jet trajectory.

From the same perspective, de Jong et al. (2021) focused their research both on the designing issues of the Go-Lab ecosystem, a STEM-related online laboratory supported by multimedia materials and learning apps, from a teacher’s point of view and on the development of inquiry learning spaces (ILSs) where students can acquire twenty-first century skills while engaging in the process.

Finally, some interesting and recent studies have researched on the importance of the VRLab planning and designing phases, instead, as much as on the teacher’s and, more broadly, the creative team’s perspective, presenting some supporting case studies. Vergara et al. (2020b), for example, has thoroughly discussed the process behind the design and development of these VRLabs together with the teachers’ perception of the VR employment in university education. The same author (Vergara et al., 2020a) extensively analysed the important aspect of technological obsolescence and how it can influence the efficacy of VRLabs.

4. The StreamFlowVR Tool

StreamFlowVR was developed in order to support the theoretical lessons and the in-field activities in the Applied and Fluvial Hydraulics course for the master’s degree in Civil and Environmental Engineering at Basilicata University. These courses are structured to guide learners from the knowledge of basic principles of fluid mechanics to their applications in real-world problems. The expected learning outcomes are represented by the ability to analyse and solve simple and complex hydraulic problems using analytical and numerical models, as well as the technical ability to plan and perform laboratory and in situ experiments. In fact, some problems can be solved in the classroom by applying standard textbook techniques, while other problems require some practical experimental activities to develop the specific skills that cannot be obtained during frontal lessons.

The VRLab implemented and widely described in Capece et al. (2019), Mirauda et al. (2019) and Mirauda et al. (2020) is mainly focused on the measurement of the water discharge in open-channel cross-sections according to the international standards ISO 748/1997 and ISO 1100-2/19 rules. Such data are an important input for the hydraulic sector. The combination among the standard measurement methods explained in the classroom, the use of the VRLab, and the experimental activities in situ allow students to obtain general and specific learning objectives.

The first ones include:

- Improving the understanding of theoretical concepts;
- Preparing the students for forthcoming field activities;
- Increasing the students’ interest in the academic subject;
- Boosting the students’ curiosity, critical thinking, and problem solving, while developing related soft skills and increasing motivation.

The second ones are:

- *Knowledge* - Familiarising students with the classical and advanced equipment employed for the measurement of the water discharge in open-channel flows and memorising the whole sequence of measurement steps through the use of the virtual laboratory;
- *Skills* - Combining the theoretical knowledge with the use of measurement sensors and techniques in a protected fluvial environment through repetitive training;

- *Competence* - Learning to accurately and autonomously apply the standard measurement methods and methodologies in a real fluvial environment, with the possible support of innovative technology.

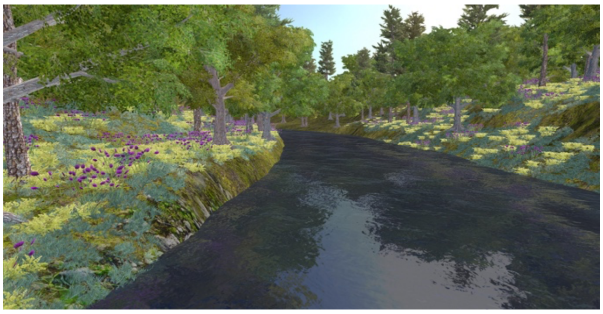

Figure 1 - A reproduced 3D VR scene of a fluvial reach.

This VRLab was designed with high fidelity graphics and immersive content accessible by using HMDs, which allowed students to explore complex subjects in a way that usually teachers and students develop during field activities. It can be used in a classroom setting or at home, in distance learning mode, as there are no significant differences in hardware / software requirements in either environment.

An important development requirement was to devise a VR application that adopted some state-of-the-art user's features but still immediately approachable by both VR experts and non-experts. In the case of non-expert users, in fact, a short training phase (about a quarter of an hour) was considered. Another important aspect to tackle was the motion sickness caused by virtual reality applications, which occurs when our eyes tell us we are moving while our vestibular system is perfectly still. Trying to resolve motion sickness during the development of VR tools is crucial for students to perform long immersive sessions during the lesson in the classroom or at home. Due to the nature of a VR headset, many of the solutions proposed are very difficult or impractical to adopt, e.g., using a fan when wearing a VR headset, taking regular breaks from VR immersion, and so on. Therefore, common strategies were adopted in this VRLab such as: forcing the user to move linearly; keeping the user in control of their movements; avoiding accelerating the camera; and maintaining a steady frame rate at all times.

Figure 1 shows a reproduced 3D VR scene of a fluvial reach generated through the Unity 3D terrain editor, while the free surface waves and light refraction phenomena as well as the water colour, bank fade, bank and depth transparency, flow velocity value and direction were created with the AQUAS Unity 3D asset. Figure 2 shows the different steps to measure the water discharge in an open-channel cross-section, which should be carried out in the field.

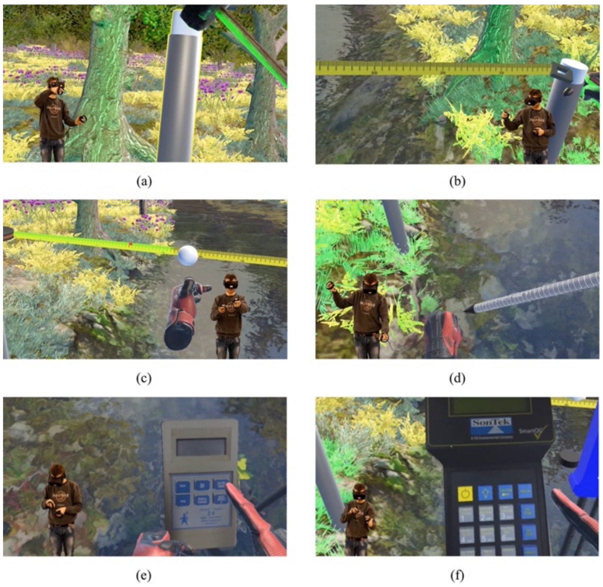

Figure 2 - Steps of water discharge measurement within the VRLab: a) demarcation of the site; b) acquisition of the channel width; c) identification of the verticals; d) evaluation of the flow depth; estimation of velocities with e) current meter and f) acoustic doppler velocimeter.

5. Blended Learning and VRLabs: an Overview of Educational Literature as 'Lesson Learnt' for the Pandemic and Post-pandemic Age

In a historical moment in which the theoretical and methodological discussion on distance learning is still mandatory and urgent, it is necessary to increase opportunities for interdisciplinary work among technologists, engineers, and media education experts, in order to consider the educational experiences of the pandemic not as a temporary misfortune but as a constant terrain of confrontation and dialogue: a 'lesson learnt' useful for facing but also for anticipating the educational challenges brought by contemporaneity. In the case study considered, the 'lesson learnt' consisted in opening a field of dialogue not only between researchers and teachers of the engineering field, but also with media education experts, sharing theoretical and methodological perspectives based on an interdisciplinary reflection and re-elaboration of what was didactically achieved during the pandemic.

Over the last decade, and thus even before the pandemic, the pedagogical literature has offered precious indications for the planning, implementation, and evaluation phases of educational activities that can be considered a great opportunity for the reflection on and redesigning of VRLabs in the engineering field. In this perspective, we intend to avoid falling into easy oppositional reductionisms to the extent that face-to-face and distance learning methods are opposed a priori, taking into consideration blended learning too.

In fact, the most significant meta-analyses both on the effectiveness and the design, teaching, and evaluation of this approach in educational contexts supported by ICT offer some clear indications. In this regard, we critically investigated the main existing meta-analyses to offer a synoptic epistemological and methodological perspective useful for rereading the experience in the case study and providing indications for the subsequent design activities of the VRLab in the next academic years.

The first meta-analyses of the early 2000s (Cavanaugh et al., 2004; Liao, 1999) were characterised by more robust methodological studies. Cheung and Slavin (2011), although referred to K-12, have the merit of dispelling the myth of the beneficial effects of educational technologies *tout court*. Starting from these first results, the milestone works carried out in the last decade by Means et al. (2010), among others, highlight the educational effectiveness of blended learning interventions compared to exclusively traditional or technological ones. Bernard's significant work (Bernard et al., 2004) is based on a meta-analysis published in 2004, and further deepened in 2014, starting also from the evidence provided by the two works of Means et al. (2013). Bernard's first meta-analysis (Bernard et al., 2004), based on 232 studies, states that there is no a priori efficacy of technologies applied to learning and, in fact, he finds an almost zero effect size. Learning technologies are effective due to a more general and coherent planning / evaluation of educational activities in different contexts. Among the many aspects, Bernard highlights: the quality of educational design; the authentic involvement of students; and the active support from the providing organisation. In other words, the effectiveness of ICT on improving the teaching-learning relationship depends on the quality of the pedagogy used, and the inclusion of multiple media in the same educational project does not seem to bring advantages by itself, in terms of greater learning effectiveness. Based on Barnard's work, the milestone meta-analysis carried out by Means et al. (2010) on 51 studies states that "students in online learning conditions performed better than those receiving face-to-face instruction" (Means et al., 2010, p. 5-6), considering the relevance of some pedagogical criteria, such as the fact that effectiveness must be assessed on the basis of a design and formative evaluation model adapted to the contexts and profiles of students as well as to the different levels of education. Later, Castaño-Muñoz et al. (2014) focused on Higher Education and stated that "the principal cause of the improvement is not, in itself, the increase in time spent online for educational purposes. Rather, increasing the time devoted to studying online is only useful when it takes place as some form of interactive learning" (Castaño-Muñoz et al., 2014, p. 149). In this regard, the meta-analysis carried out by Schneider and Preckel (2017) specifies the variables associated with achievement in Higher Education: the stimulation of meaningful learning by presenting information in a clear way or, in other words, the use of conceptually demanding learning tasks. Vo et al. (2017) investigate the impact of blended learning on academic achievement, confirming that it is significantly associated with greater learning performance of STEM-disciplined students than with traditional classroom practice. The latest meta-analyses considered on the topic of blended learning, ~~were~~ published in 2020, ~~and~~ focus mainly on its use during the period of the COVID-19 pandemic. In particular, the work by Camargo et al. (2020) on 38 studies highlights that "the pandemic situation requires a well-integrated trained team to detect students' and teachers' needs and provide prompt answers and support with digital tools" (Camargo et al., 2020, p. 3). In a nutshell, the indications provided by the above-mentioned meta-analyses concern not only how to design blended learning interventions, but also how to improve self / hetero / co-evaluation processes in the framework of formative evaluation.

At the same time, the opportunity given by the pandemic is related to a reflection on how both blended and synchronous hybrid learning environments (on-site and remote) can be designed to promote students' effective and meaningful learning. On the basis of a systematic literature review on hybrid learning, Raes et al. (2020) adopt a rather optimistic view about synchronous hybrid learning as it provides a more flexible and engaging learning environment than a fully online or fully on-site one. They also formulate several design guidelines in order to face the pedagogical and technological challenges of such a new learning context.

The pedagogical-didactic literature on VRLabs, together with that on blended learning just presented, while considering the increase in learning methods related to digital developments, offers some elements for reflection to qualify the adoption of these innovative teaching practices. In the light of the current situation, i.e. the shift from the Information Age to the Experience Age (Wadhera, 2016), large evidence underlines the educational value of VRLabs in the Experience Age (Bailenson et al., 2008; Dalgarno & Lee, 2010; Lau & Lee, 2015), where "the best way to use virtual reality in learning is to create experiences that help students to understand the learning context better" (Lau & Lee, 2015). In line with these preliminary considerations, the meta-analysis by Kaplan et al. (2021) aims to explore, through empirical research, the transferring of training from virtual (VR), augmented (AR), and mixed reality (MR), and to determine whether such extended reality (XR)-based training is as effective as the traditional training methods. The results highlight what has already been reported in the meta-analyses on "blended learning": it is never the technologies themselves to be more effective, but the quality of the pedagogical proposal that guides their use in educational activities. At the same time, the meta-analysis by Howard & Gutworth (2020) focuses on virtual reality training programs as useful tools for the social skill development to determine: (a) whether these programs are effective and (b) the attributes of these programs that lead to success. The main finding is that VR training programs, on average, perform better than alternative training programs for developing social skills, even considering that programs using immersive technologies produce slightly worse outcomes than those using non-immersive displays, also confirmed by Angel-Urdinola et al. (2021). A further suggestion for reflection coming from the pedagogical literature, and useful for re-reading and redesigning the past VRLab experience, is the meta-analysis carried out by Howard and van Zandt (2021) on 149 studies, which discusses individual differences and predicted VR sickness in such immersive environments: motion sickness susceptibility; gender; relevant real-world experience; technological experience; suffering from a neurological disorder; and having a phobia (Howard & van Zandt, 2021, p. 26).

In the light of the reflections and indications offered by the pedagogical-didactic literature on blended learning and on VRLabs, we can state that the future redesign of the VRLab cannot be reduced to a mere technological level but needs to consider: an “aesthetic” dimension, relating to codes and languages; a “critical” dimension, with respect to semantics, social and cultural meaning; and an “ethical” dimension, in reference to values, responsibility, and citizenship. For this reason, the criteria identified in section 5 represent a pedagogical-didactic orientation both to reflect on the experience achieved in the case study presented here and to guide the educational activities that will be carried out in the next academic years.

6. Designing a VRLab in a Blended Learning Environment

Starting from the indications offered by the pedagogical-didactic literature (Section 4), some heuristic criteria are explicitly used both to re-read the experience presented by the StreamFlowVR and to redesign the VRLab tool for the next academic years, in order to carry out an educational planning / evaluation suitable for both face-to-face and blended learning (Castro et al., 2020).

Below are some observations to consider in the future VRLab experience.

Regarding the planning and design phases:

- Besides training the students on the technological aspects involved, it is extremely important to carry out professional training for teachers on: technological skills; digital skills; and active teaching methodologies;
- Additional time for blended learning activities should be taken into consideration;
- Since it is never the technologies themselves that are more effective, the quality of the pedagogical proposal is what guides their use in educational activities;
- Students’ outcomes are strictly connected to their motivation, which should be explored in more depth, and partly by using an initial student profiling (diagnostic evaluation) to discover their disposition to learn, learning style, background, attitudes, etc.;
- There is the need to strengthen students’ support, guidance, and tutoring by defining clear guidelines to be delivered both in the technological environment (e.g., online instructions) and face-to-face, when possible;
- The design of a VR tool promotes opportunities for co-planning between designers in the educational field and technologists;
- HMDs are the most common part of a VR configuration but in the last years several input devices and innovative user interfaces have been developed, which require an in-depth exploration to understand the real benefit from a pedagogical perspective. For example, one of the obstacles highlighted in the literature is motion sickness, which continues to be a problem for some users, although later improvements in the refresh rate of the HMDs and the publication of general guidelines can be adopted to produce minimal VR sickness;
- The application has to be supported by empirical evaluations during the implementation phase, in order to avoid disparate treatment when using VR;
- Attention needs to be paid to the design phase of the intervention (use of systematic instructional design), which is more important than the question of which media to choose or its characteristics. In particular, media should support and promote interaction, as the inclusion of multiple media in the same educational project does not seem to bring further or incremental advantages in terms of greater learning effectiveness;
- Virtual Reality training is more effective than traditional training in developing technical, practical, and socio-emotional skills because the students learning in VR environments are able to make better use of inputs and time, avoiding performance errors;
- Real tasks, connected to their every-day environment, and tasks where problems can be solved with reasoning should be preferred, making students accountable for their learning and aware of the fact that their skills will be employed in future work and social-life related contexts.

Regarding the teaching phase:

- The blended-learning situation requires a well-integrated and trained team able to stimulate meaningful learning, by presenting information in a clear way while promoting the development of technical, social, and emotional skills, and including different types of students, in the same way one would do in traditional learning contexts;
- Small group work and collaborative learning activities, stimulating active - inquiry and problem-based - learning, are even more preferable within online learning environments;
- In blended learning contexts, not only the time of teaching activities but also the time spent on the content and the processing of assignments is greater than the time employed when working only face-to-face; that said, improvement is not measured against the time spent online but rather occurs through interactive learning, which should occur especially in totally online or hybrid situations, avoiding feelings of isolation.
-
- Regarding the evaluation phase:
- It is necessary to develop a valid theoretical and methodological framework for the design and evaluation of blended learning from an evidence-based research perspective;
- Moderator variables influencing the identified effects are to be employed;
- Rigorous research and evaluation models should be used;
- (Fine-grained) Data from the online interactions of the participants in the research should be included;
- Research on effectiveness and efficiency should be carried out with regard to the costs of blended learning;
- Reflective processes should be enhanced, not only on what has been learned but mainly on how it has been learned and on the learning strategies used (formative evaluation);
- Summative evaluation should also be enhanced as triangulation of viewpoints: hetero-evaluation by teacher; self-evaluation by student; peer-evaluation between students; co-evaluation between teacher and students.

7. Discussion and Conclusions

An opinion in the educational community, and society at large, that the 2020 lockdown has reinforced is that online learning could be the future of education. In this case, VRLabs have similar benefits to traditional offline labs with real equipment (Wiesner & Lan, 2004). It could be argued that properly adopted VR-based courses could potentially raise good, qualified specialists all around the globe, not only in local regions, thus democratising education in hands-on skills. A remote course based on a VRLab could be used to transfer knowledge where it is effectively required - to prepare learners to tackle natural disasters or medical interventions, for example. The use cases are innumerable.

However, VR includes complex and expensive technologies. A decision for their use must be based not on technological hype but on scientifically validated outcomes. In addition, VR devices cannot be adopted instantly by teachers and students because they are not yet as intuitive and straightforward as a typical personal computer. To prepare teachers and students to the use of these technologies and to introduce VR smoothly in the classroom, three steps are required:

1. Creating training plans for teachers and lecturers on how to prepare courses for VR;
2. Creating a framework that would allow teachers to easily prepare their material and quickly adapt it to VR;
3. Not overloading students with the need to familiarise with VR in a short time. There should be the possibility for them to still use classical methods, even partially, in order to get through the course.

In recent years, technological advances, coupled with the proliferation of affordable hardware and software, have made VR more commercially feasible than ever. Many investments into these new devices will continue to fuel the market, which will grow in the coming years. VR will impact the world around us in several exciting and beneficial ways, but two are the important aspects to consider for its improved adoption.

The first one is the need for more ways to design efficient and engaging entertainment. Software companies must develop tools which simplify the VR experience-making process for teachers and students. Today, there are several advanced tools to create a hyper-realistic VR environment, but they are for software developers and artists. Creating a new 3D/VR scene authoring tool will allow multiple and different stakeholders to create and manipulate virtual spaces in collaboration, either recreating real-world scenes or constructing new digital environments using their imagination. The objective must be to develop an immersive, collaborative, and open authoring tool software that can assist teachers in building a VR lesson. The tool must feature an intuitive and easy-to-use graphical user interface (GUI) appropriate for non-expert users, allowing them to position 3D contents in the virtual environment and simultaneously view and manipulate scenes of interest. This immersive VR content creation approach must enable teachers and students to reach out, grab, and manipulate objects just as they would do in real life. Working directly in a virtual environment will provide users with a sense of scale necessary to create a realistic scene, while using appropriate tools will enable them to build environments with natural motions and interactions.

The second aspect is the possibility for users to take rich data from various data formats, such as building information models (BIM), and send them to a VR application. The integration of diversified 3D models will enable the integration of dissimilar models from photogrammetry, laser scanning, or 3D modelling software, incorporating heterogeneous formats, scales, and styles into the same VR scene. This feature will emphasise the use and reuse of 3D content. As a result, rather than building 3D content on a 2D screen, teachers could quickly import high-quality contents to better communicate their ideas and intent to students.

Having confirmed their potential through the critically reviewed literature in the field, this paper was aimed at highlighting not only the technological requirements of VRLabs in order for them to be more consciously adopted in the future academic environment, but also the pedagogical criteria to keep in mind when planning a VRLab-supported educational experience or, even, an educational experience occurring completely from the distance, with the VRLab acting not only as a temporary substitute for practical classes or in blended/hybrid learning situations, but as the only available 'virtual classroom'.

Reflecting on the experience carried out with VRLabs in the light of the most recent acquisitions of the scientific literature on the subject was useful to propose some criteria for the design of future VRLabs aimed at encouraging the development of effective learning. In fact, the explanation of the training activities carried out at the University of Basilicata through the StreamFlowVR tool in the pre-pandemic academic year is presented as an opportunity for the improvement of the forthcoming VRLab planning. Unquestionably, despite the fact that the experience presented in Section 3 pertains to the field of hydraulics engineering education, these observations cannot remain in entirely separate epistemological compartments (technologists, engineers, media education experts) but need the interdisciplinary perspective of a laboratory for re-thinking and re-designing the practices implemented.

This paper does not intend to and cannot answer all the questions on the subject nor offer a training model through the VRLab. However, re-reading the experience from different heuristic perspectives can enable both the Authors and the readers to find themselves in the questions, perplexities, and proposals that, starting from a concrete experience, this work has tried to explain.

In the field of media-education, today's challenge concerns: the understanding of teaching and learning methods in large part due to the pervasiveness of new technologies; the emergence of new cultural models that profoundly modify the teaching-learning experience; and the consequent need for teachers to have to adapt their teaching methods (Castro et al., 2020; Griffin & Care, 2015). However, a central theme is the teachers' acknowledgment of the transformation that is taking place in the new generations of students, with reference to the cultural models for which meaning is attributed to learning practices mediated by new technologies (Castro et al., 2020; Fullan & Langworthy, 2011; Martín-Gutiérrez et al., 2017). It is thus essential to explore the cultural changes referring to the modalities of teaching and learning, so as to be able to re-calibrate planning, teaching, and evaluation while promoting digital competence as an indispensable prerequisite for carrying out educational activities based on new technologies.

As Caena and Redecker (2019) and Castro et al. (2020) underline, "Teaching strategies need to change, along with the competence profiles teachers need to develop, so as to deploy innovative pedagogies and empower responsible learners". (Caena & Redecker, 2019, p. 356).

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