Cloud-based virtual labs vs. low-cost physical labs: what engineering students think.

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***Abstract*—The educational courses that fall into Science, Technology, Engineering and Math (STEM) category require an extensive practical training in laboratories, in order to build and strengthen students' skills, thereby preparing them for a future job market. In particular, the significant advancements in computer science and engineering press an urgent need to rethink the core of the existing academic courses, their objectives, and the tools for the practical work, due to the need to maintain the balance between the knowledge that academia provides to the students and the actual requirements for students' future job vacancies. To this end, our educational research includes the design and development of two different types of laboratories, i.e., a low-cost Raspberry Pi-based laboratory, and a laboratory in the cloud, for the practical teaching of the course Distributed systems. In this paper, we present the valuable feedback from our undergraduate students for both types of the aforementioned experimentation approaches, thereby unraveling the pros and cons of both, and analyzing the existing challenges that still need to be properly tackled.**

***Index Terms*—STEM, low-cost laboratories, cloud-based laboratories, Raspberry Pis, students' feedback**

I. Introduction

The practical training of students' skills is a relevant dimension of the overall education process, especially in the case of educational courses that fall into the Science, Technology, Engineering, and Mathematics (STEM) category. In order to build and strengthen students' skills, STEM courses require a corresponding practical work in a laboratory setup, thereby preparing students for a future job market. As stated by McComas [1], the difference between teaching science-related courses and those that belong to other fields is visible, in particular, when considering work in a laboratory, because the science students need to measure, to investigate, to analyze, to question, to hypothesize, and to examine, in order to test their practical knowledge and to prepare themselves for a future working environment.

Given the significant advancements in computer science and engineering in the last ten years (e.g., in Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing), there is a constant need to keep up with the pace of industry and research, and to provide students with the adequate knowledge of cutting-edge technologies [2]. At the same time, the involvement of students throughout the whole learning process needs to be increased in order to familiarize students with different tools and practices, and to create a fair environment for evaluating their skills. There are numerous types of resources that can be used to improve practical education, such as the low-cost devices (e.g., Raspberry Pis (RPis), Arduino boards, etc.), and cloud resources, which are financially more accessible than owning the bare-metal high-processing machines, and high-performance components [3]. Hence, educators need to either redesign the existing courses, or create new ones that will respond to the advancements of technologies in an efficient manner. To this end, our educational research includes the design and development of two different types of laboratories, i.e., a low-cost RPi-based laboratory, and a laboratory in the cloud, for the practical teaching of the course Distributed systems. Firstly, we presented *a low-cost laboratory* based on RPi devices in [4], to improve students' experience of learning distributed systems. Secondly, we leveraged on the virtualization techniques (i.e.,

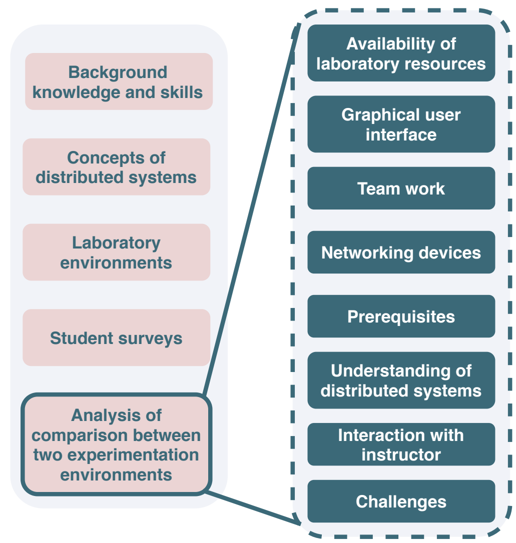

Fig. 1: The topics covered by this paper (left) and the elements of comparison between two distinct hands-on experimentation environments (right).

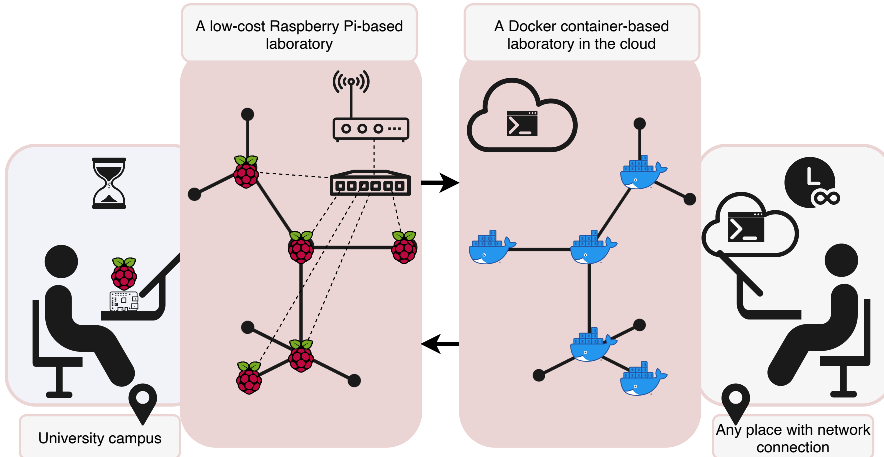

Fig. 2: The types of laboratory environment: A low-cost Raspberry Pi-based laboratory at the University campus, and a Docker container-based laboratory in the cloud.

containerization) to create a *scalable environment* for remote experimentation, and development of distributed systems. In particular, in [3] we presented the results on assessing the social impact of such remote experimentation environment on the students as a target social group, and we inspected the applicability of such experimentation environment in low-income societies.

Therefore, in this paper we study the difference between the two aforementioned approaches, unraveling the pros and cons of both. To do so, we analyze the students' experience in both types of laboratory, thereby recognizing the most efficient teaching practices towards modernizing the existing courses. In Fig. 1, we present the main topics that we cover in the paper: i) discussing the background of students' knowledge and skills they are expected to gain before enrolling the course, ii) studying the concepts of the course Distributed systems for which we designed the two laboratory types, iii) we thoroughly present the two laboratory environments (as illustrated in Fig. 2), iv) we discuss the student surveys that we collected during the past two years, and v) we present the analysis of comparison between a low-cost networking laboratory based on RPi devices and a cloud-based laboratory.

In Fig. 2 we illustrate the two types of networking laboratories for the course of Distributed systems. The Distributed systems is the course at final year of Bachelor of Electronics and ICT Engineering Technology program[1], at Faculty of Applied Engineering, University of Antwerp. During the 2018/2019 academic year, for the purpose of hands-on experimentation on the development of a distributed system we created a low-cost networking laboratory that is based on RPi devices. As illustrated on the left-hand side of Fig. 2, the laboratory consists of 50 RPis that are provided to the students during all 17 laboratory exercises, thereby creating a homogeneous set of five devices for each group. In parallel to the teaching process, we collected a thorough feedback from our students, asking a various set of questions that allowed us to assess the impact of this new learning environment on the learning process and its outcomes [4]. Therefore, we presented our interesting findings about students' experience with work in this low-cost laboratory in [4].

However, due to the lockdown imposed by COVID-19 pandemic that started during the 2019/2020 academic year, there was an urgent need to move all our laboratory activities to the remote mode. To this end, we exploited the remote access nature of cloud computing to design a remote experimentation system for the students, allowing them to access containerized environment on the cloud (as shown in the right-hand side of Fig. 2), and work on their project out of laboratory session hours as well. Thus, in [3] we elaborated on the best practices on remote teaching and experimentation within the course Distributed systems, presenting how the virtual laboratory is designed to meet the same goals that we previously aimed with RPi-based laboratory. Given the valuable feedback from students, where we inspected their experience with the two teaching and experimentation environments, in this paper we study the comparison between these two distinct experiences, and we recognize the pros and cons of both, analyzing the existing challenges that still need to be properly tackled. .

II. Background

Due to the compelling role of hands-on practices in STEM education, a wide range of efforts for modernizing laboratories has been invested by the research community so far. Although highly dependent on the type of the educational course, there are certainly the two main directions in which educational institutions can go towards modernizing their laboratories, i.e., i) the hardware-based modernization, which includes purchase of often highly expensive equipment (e.g., machines, computers, servers, antennas, sensors, etc.) and building the so-called testbeds, ii) the cloud-based approach, which usually means provision of a shared University cloud solutions [5–

[1]Bachelor of Electronics and ICT Engineering Technology program: https://www.uantwerpen.be/en/study/programmes/all-programmes/ba-electronics-ict-engineering/study-programme/

7], or investing in yearly plans for existing widely adopted cloud platforms (e.g., Amazon Web Services (AWS)) [6,8], and iii) providing remote laboratories that consist of physically existing laboratory equipment, which is accessible remotely via the internet[2].

An innovative and yet cost-efficient way to modernize the engineering laboratories is to leverage on the RPi technology. The low-cost RPi-based laboratory solutions as a testbed platform for both hardware and software system exploration, provide a great potential for bringing the learnt concepts into practice [9]. In our previous work [4], we studied the state of the art concepts of involving RPi technology into STEM curriculum [9–13], thereby designing and building our own solution for a low-cost networking laboratory within confines of the undergraduate course Distributed Systems. As a result of this research, we acknowledged that RPi laboratory set-up can be successfully used for a hands-on laboratory approach. One of the major benefits that RPis bring is an opportunity to create a modular and affordable laboratory [9] that can be efficiently upgraded and maintained at a low cost, comparing to the traditional setups with highly expensive computing machines. Some of the examples are presented by Maina [10] and Ioannou [11], who present the incorporation of RPis in the laboratories for signal processing courses, and primary school physics, respectively.

On the other hand, cloud computing is an internet-based technology that offers computational resources via computer networks, delivering flexible, scalable, and on-demand services to the end users, thereby reducing the users' dependency on the specific machines [7]. Thus, the ever-increasing popularity of cloud-based technologies extends the experimenting opportunities to access the laboratory and the study resources in a remote manner [3].

A remote laboratory set-up can be multipurpose, which means that it can be shared between different courses and study years, therein increasing the revenue of the institution that developed the remote laboratories [14]. Although this idea to perform laboratory exercises remotely is not novel, in fact, the potential has been recognized already 20 years ago [14] in many scientific and educational fields (e.g., chemistry, physics, electronics, robotics, etc.), the adoption of cloud computing, and in general the cloud resources, by higher education institutions is getting more popular. In particular, the involvement of cloud computing is gaining a significant status in education, due to the needs for remote teaching and experimentation imposed by potential disasters [8], world pandemic [3], etc. In particular, the rationale behind the design and building remote laboratories is presented by Ionescu et al. [15], and it lays in: i) coping more efficiently, in terms of both cost and time, with the increased need for additional laboratory resources due to the boosted enrolment, and ii) more efficient preparation of educators for performing laboratory exercises, in order not to exceed the time allocated for usual teaching duties. Furthermore, Kawatra et al. [5] study how to preserve the educational resources in disaster situation by exploiting cloud computing for the smooth running of the system. The authors proposed the solution that includes different cloud platforms for different purposes, such as: i) library resources, testing projects, and administration, ii) research activities, evaluations, records, teaching material, for the faculty and staff, and iii) results and curriculum material for the students [5]. Kawatra et al. [5] recognized several advantages of such cloud-based education system, and some of them are: i) real-time learning that enables students to access laboratory resources and study information from any place, ii) energy saving due to the saving of all resources on a remote server instead of using multiple uncoordinated local machines, and iii) cost saving that helps schools and universities to cut down the costs of provisioning and maintaining equipment.

Lascano and Clyde [6] present an interesting concept of using cloud services on the public cloud AWS to improve software engineering education. They present a case study of programming assignments that needed to be done by using cloud services and programming tools that were previously unfamiliar to the students. Although collected from a small group of students, their results show that students expressed positive attitude towards learning new tools and skills, in particular when they brought the theoretical concepts into practice. Furthermore, Vivar and Magna [16] present an approach to cope with the challenge of a limited number of networking devices via creating a remote network lab. Although approach proved to be successful for teaching computer networks, their remote lab system [16] is quite expensive, and allows students to access the system in no more than 16 concurrent sessions at the same time.

Goteng [8] recognizes the importance of employability of engineering students, by studying different career paths that they can take after their formal education, and isolating the competences that refer to the cloud computing, such as administration and management of IT systems, cloud network skills, cloud security, scalability and load. Based on such study, Gotenberg [8] presents their design of curriculum of cloud computing module in collaboration with AWS Academy to include industry-based practical hands-on labs in the curriculum. According to the final results that students obtained, this course modernization resulted in a better performance of students, in comparison to the examination results during the two previous years [8]. Furthermore, in one of our previous works [3], we presented our scalable laboratory for experimentation on-demand, which is designed for development and work on the distributed systems, but presenting the practices that show how the transition from a physical laboratory consisted of personal computers and RPi devices can be transformed to a remote laboratory on the cloud, benefiting from the virtualization technique such as containerization.

However, regardless of the type of laboratory and hands-on work, Ioannou et al. [11] claim that the students' perception about any new laboratory package is crucial for its future educational usage and success. Therefore, we collected the

[2]LabsLand - Remote laboratory concept: https://eeti.uga.edu/online-learning/

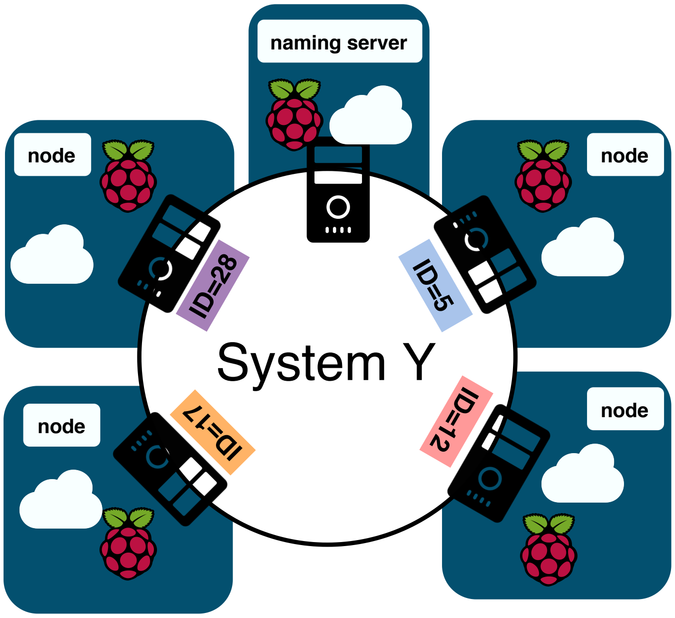

Fig. 3: System Y: The distributed system that students design and develop within the project.

valuable feedback from our undergraduate students for both cloud-based and low-cost networking laboratory, and in this paper we provide a cross-analysis, comparing the students' experience with these two distinct experimentation approaches.

III. Laboratories for Distributed systems

A. Course

The two types of laboratories that we built, belong to the course Distributed systems, which is the course at the final year of Bachelor of Electronics and ICT Engineering Technology program, at Faculty of Applied Engineering, University of Antwerp, Belgium. As presented in our previous work [4], the course is mapped to the IEEE/ACM CS2016 joint curriculum for computer science engineering.

Before enrolling for the course, students are expected to have a general knowledge on using Personal Computers (PCs) and internet, and to have at least basic programming skills in java programming language. All lessons are first taught in the form of theoretical lectures, and then practiced in the laboratory, thereby providing students with the opportunity to improve their programming and networking skills towards creating realistic distributed systems in their future working environment. Therefore, the expected outcomes of the course are summarized as follows:

- to gain a valuable insight into the concepts of distributed systems, and to apply them to the design of medium-sized software projects,
- to be capable of detecting and remedying potential issues and problems within distributed systems,
- to be able to develop a distributed system from a problem definition,
- to be able to combine standard and distributed techniques from a complex problem definition, in order to design and develop a robust software solution.

In this paper we focus on the practical compound of our course, and therefore, here we briefly present the project that students work on in the laboratory during the semester. Regardless of the type of laboratory, the main goal of the student project is to build a comprehensive distributed file system in a ring topology, i.e., a so-called system Y, as illustrated in Fig. 3. In such system, files are being automatically replicated to nodes, and the naming server is created to keep track of all connections of the nodes within the ring. In particular, the naming server is the main node in topology, having two main responsibilities: i) to add and remove nodes from the system, and ii) to map each node to its IP address, thereby resolving the location of the stored files when requested. Besides the naming server, students also need to develop functionalities of other nodes, which are characterized by their life-cycles. The life-cycle spans i) the discovery of all nodes in topology, ii) bootstrap that initializes the local parameters, and updates all parameters of existing nodes, iii) shutdown when a node leaves the network, and iv) failure that occurs when a node stops performing as expected. After students developed the basic functionalities, they also need to design and to develop agents that enable synchronization in a distributed system, which requires enhanced programming skills. Finally, the last project phase refers to the development of a graphical user interface, providing users with a simplified interaction with the implemented distributed system. In the following sections we provide the insight into both types of networking laboratories that we built and used during the two previous academic years, and we describe how these two laboratories are leveraged towards achieving the main goals of the course and the student project.

B. The low-cost physical laboratory

To mitigate the problems of hardware dependency in our course, two years ago we created a fully functional low-cost networking laboratory using RPi devices, and we present it thoroughly in [4]. These low-cost devices are a suitable replacement for expensive and underutilized laboratory equipment, such as PCs with high performances. The whole laboratory setup, which was needed for a single student group to work on a project, previously consisted of five high-performance PCs that were then substituted with a set of five RPis. In particular, one RPi device is used to develop a single node in the system, with the possibility to attach a functionality of a naming server to any of the used RPi nodes. All RPis that belong to one group are connected to the same local network, in order to communicate with each other and share files. Furthermore, additional laboratory equipment, such as network switches, keyboards, mice, and monitors, were needed throughout the whole process of RPi configuration and development of a distributed system. However, due to the strict regulations imposed by Faculty and University, students can work in such laboratory only during the laboratory hours that are allocated in the official agenda.

C. The cloud-based virtual laboratory

Our virtual laboratory, as response to COVID-19 pandemic, is designed and built on top of the cloud resources that are available within the University cloud. Instead of using low-cost RPi devices, as described in previous section, this time we equipped each student group with virtual infrastructure resources in the form of lightweight Docker containers, enabling them to develop the System Y in the cloud. In order to keep the compatibility with our low-cost laboratory, each Docker container that represented one node in the System Y is spawned using a Raspbian Docker image, Including all Raspberry Pi hardware drivers and modules. All five Docker containers share the same IP address, and are being differentiated based on the port. Unlike the physical laboratory, the virtual cloud-based laboratory can be accessed from any suitable place with internet connection, although students need to use University's Virtual Private Network (VPN) to securely retrieve their project resources.

D. Comparison of the laboratories

The analysis of the comparison between the students' experience with these two types of laboratories includes several features, as illustrated in Fig. 1.

a) Lab availability: In particular, if we observe the availability of laboratory resources, i.e., whether laboratory is accessible only during the scheduled laboratory hours or in an unrestricted way, we can spot the clear difference between these two approaches. Namely, the physical laboratory cannot be visited any time as in the case of cloud-based one, due to the aforementioned Faculty regulations. According to the students' experience that we assessed and presented in [4], one of the major issues during the practical implementation of their project was in fact the retricted time students were allowed to spend in a laboratory. On the other hand, the virtual laboratory mitigates these restrictions by providing more flexible working hours, i.e., allowing students to work on their projects even out of the scheduled hours with teaching assistant.

b) Laboratory robustness: In case any node in distributed system Y fails, that means that educators need to provide students with a corresponding backup node. Thus, in physical laboratory it means that additional equipment needs to be bought or borrowed. At the same time, if a Docker container fails in a virtual laboratory, another lightweight instance can be easily created, and set up, as same as in case more machines are needed.

c) Low-cost vs. low-resource consumption: Considering the results we presented in [4], a low-cost laboratory represents a suitable replacement for high-performance machines. However, concerning the resource consumption, a virtual cloud-based lab brings some benefits. This approach saves a significant amount of resources, since a regular Raspbian operating system image for RPi devices takes approximately 4.3GB of storage, which means that a memory card with at least 8GB storage capacity is required. In parallel, the container-based nodes utilize host resources more efficiently, since a single Raspbian Docker container requires around 180MB of storage, and 4.47MB of RAM. Given the lightweight characteristics, a large set of Docker containers can be instantiated when needed, on top of the bare metal machines, private or public cloud, or inside a simple Virtual Machine (VM).

d) Presence of Graphical User Interface (GUI): Although it is expected that students are more in favor of laboratory tools that provide a corresponding user interface, as they are more familiar with simulation tools throughout their education, we learnt that majority of our students did not lack the GUI while working on the distributed system development, as presented in [3]. That is also supported by our experience with the physical laboratory based on RPis, in which students preferred using Raspbian system image with GUI only in the initial phase when they configured RPi devices. Afterwards, accessing the nodes in System Y via command line interface and SSH was comfortable enough. Taking into account that our course belongs to the final year of Bachelor study, such outcome is somewhat expected due to the practical experience that students already gained on working with Linux-based systems, and command line interface in general.

e) Team work: In case of the course of Distributed systems, the team work has an important role, as student projects are performed in groups of five. Regardless of the type of laboratory, students are given the freedom to distribute the tasks and all work in the way they find suitable, aiming to strengthen their team working skills, and to improve the team management techniques. The differences between two lab approaches lays in the physical absence in case of the virtual lab, as students need to use some of the online meeting tools to work together, discuss the issues, and report the progress, as presented in our work [17]. Also, as educators have access to students' remote machines in virtual labs, all work can be monitored, and the progress can be tracked and evaluated accordingly. This is not the case with a physical lab, in which educators can test the developed functionalities and discuss the issues with students only during the scheduled laboratory hours. For all software-related concerns, as well as the progress on the software code, educators can access students' projects on Github in both cases, where they can also check the work provided by a specific student.

IV. Evaluation of students' experience

Since in our two previous works we presented a thorough evaluation of physical and virtual labs separately, here we bring some of the joint topics to discuss and to compare students' experience with both types of laboratories. These topics are listed in Table I, and they are evaluated using a Likert scale [18], starting from *extremely high* with the weight $\omega_1 = 8$, down to the *extremely low* with the weight $\omega_5 = 0$. Furthermore, all the results that we collected from students

TABLE I: Topics and statements to evaluate in order to compare cloud-based virtual labs with low-cost physical labs

	Topics	Scale
T1	The general understanding of distributed systems is improved after laboratory exercises.	extremely high (8)
T2	Programming is one of the major assets for the project realization.	
T3	Previous experience with networking is helpful for connecting machines in a distributed environment.	high (6)
T4	The experience of working with Linux-based systems is helpful for the practical implementation of distributed systems.	average (4)
T5	The traditional setup with physical machines (e.g., laptops/computers) is preferred over new lab. approaches with Raspberry Pis or cloud resources.	
T6	The RPi-based laboratory setup is preferred over the cloud-based one.	low (2)
T7	The cloud-based laboratory setup is preferred over the RPi-based one.	extremely low (0)
T8	The widely adopted cloud platforms (e.g., AWS, Microsoft Azure, Google Cloud Platform, etc.) are a valid approach for building and testing distributed systems.	
T9	The importance of remote access to laboratory resources is highly important for the project realization.	

are processed using the equation (1).

$$G_i = \sum_{j=1}^{N_\omega} \frac{\omega_j N_{ij}}{Ni} \tag{1}$$

In particular, N_T is the overall number of topics, which is 9 in our case ($\forall\, i \in N_T \mid i = \overline{(1,9)}$), while N_ω represents the number of different weights that are given to possible answers that students choose. Furthermore, N_i is the total number of answers on the topic i, and N_{ij} is the total number of answers with the weight ω_j among them. Finally, G_i is the average grade for the topic i, which will be further used to create a fair environment for comparing the results between the two distinct lab approaches. As all student answers are post-processed by utilizing the equation (1), the results are accordingly provided in Table II. In the following sections, we present the results and discuss them per student group. The two student groups presented in this section are designated according to the type of laboratory, i.e., Group RPi-based lab refers to the students who practiced the design and development of a distributed system in the physical low-cost lab, while Group Cloud-based lab refers to those students who experienced working on the project in a remote virtual setup. Therefore, the grades that are calculated according to the aforementioned procedure refer to the average answer for the whole group.

A. Results

Taking into account the overall success students achieved at the end of the teaching process, as well as their feedback on the topic 1 (Table I), we can see how the practical work during the students' involvement in the course impacted their general understanding of the course matter. In particular, in Fig. 4 we can see the average grade of the improvement in students' understanding of the course after performing laboratory exercises. For both types of laboratories, i.e., both students groups, the average grade is close to 6, which is reflected as high on the Likert scale that we used. Therefore, in both types of laboratories majority of students provided a positive feedback, claiming the improvement in their general understanding of distributed systems.

TABLE II: Results

Group	Topic	Student Group RPi-based lab	Student Group Cloud-based lab
Improvement of the general understanding of the course matter	Topic 1	6.071	5.914
Impact of the previous experience	Topic 2	5.507	5.824
	Topic 3	4.613	6.376
	Topic 4	3.627	6.401
Preference among different experimentation environments	Topic 5	5.041	4.443
	Topic 6	4.889	4.054
	Topic 7	4.547	4.533

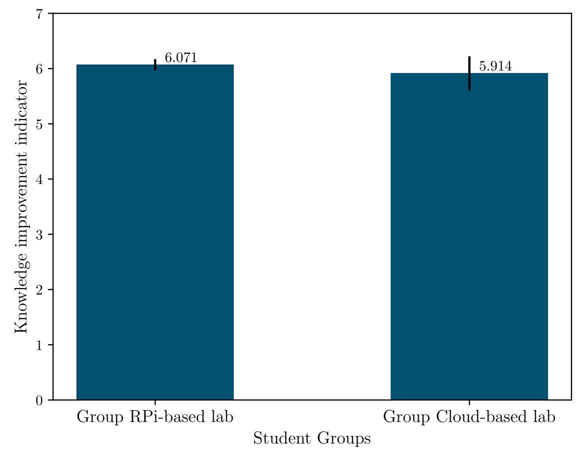

Fig. 4: The evaluation results for the Topic 1.

If we take a look at the topics 2, 3, and 4, from the Table I, all of them refer to the previous experience that students had with programming, networking, and Linux-based system, in particular. We recognized these three fields as a crucial prerequisite for the work on student project, it is important and interesting to assess students' impression of how much this asset facilitated their work. As we can see in Fig. 5, students in RPi-based laboratory evaluated programming with the highest grade, which is slightly below 6 (i.e., high). Due to the lack of experience with RPis, and issues that they experienced with setting-up the network between RPi devices especially in the first stage of the project, students mostly benefited from their programming experience. However, in the case of the cloud-based lab, we can see a different preference trend. In that case, students evaluated their experience with Linux-based systems with an average grade of 6.401, which is between high and extremely high on the Likert scale. Such

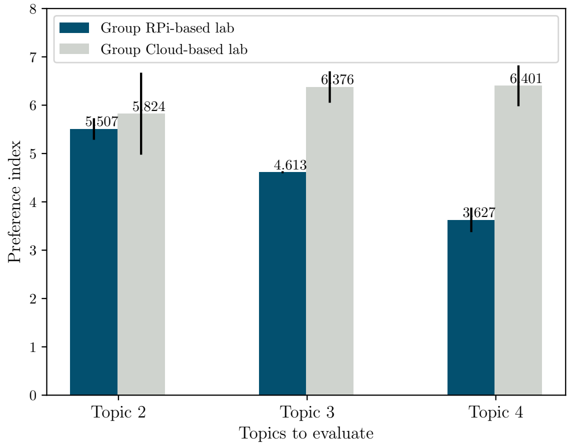

Fig. 5: The evaluation results for the Topics 2, 3, and 4.

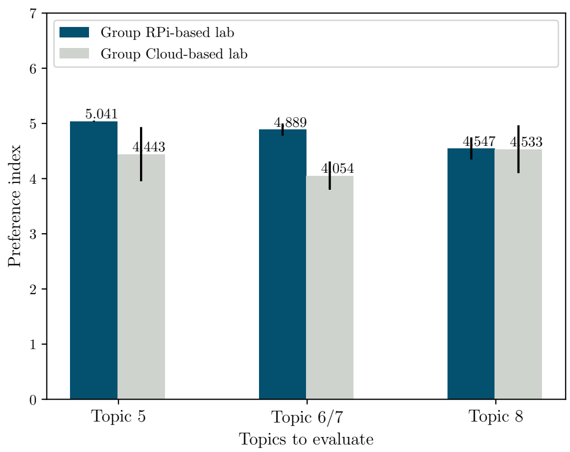

Fig. 6: The evaluation results for the Topics 5, 6, and 7.

evaluation trend from students in virtual lab is understandable, due to the need to efficiently work via command line interface, which is in particular characteristic for Linux-based environment. Although students in RPi-based laboratory also worked on machines with Raspbian Ubuntu operating system, the experience differs because they opted for system version suitable for desktop machines, hence, they used a GUI. The third group of topics, i.e., the topics 5, 6/7, and 8, are tackling students' preference among different experimentation environments. That means that we asked students in RPi-based lab to express their attitude towards cloud-based labs, and vice versa, but we asked both groups of students to also evaluate their preference upon the traditional lab setup with PCs and laptops. In particular, concerning the topic 5 and Fig. 6, we can see that students from RPis-based laboratory express higher resilience towards new experimentation environment, giving the highest preference to the traditional laboratory with PCs/laptops. At the same time, students in cloud-based lab are more neutral towards the traditional environment, evaluating it with an average grade of 4.443 (e.g., average/moderate/neutral is 4). Interestingly, student Group RPi-based lab expressed the preference of RPi-based lab over cloud-based ones, especially due to the experience they gained while working with the RPi devices. On the other hand, given their experience with all different types of laboratories, students from Group Cloud-based lab expressed more openness towards experimenting on the public clouds (such as AWS).

B. Discussion

Here we discuss the main differences between the two lab approaches that we studied in this paper, with regards to the comparison presented in Section III-D, and the students' feedback that is elaborated above.

- The cloud-based labs are more practical in addressing challenges imposed by restrictions in access to laboratory resources, especially in the case of campus closures, such as those in the period of COVID-19 pandemic.
- The cloud-based labs are more robust in terms of the issues with equipment, and failure of nodes in distributed system, which can be addressed more efficiently by assigning more cloud resources via scaling up/in the existing Docker containers. The same principle also applies with under-utilization of resources, which can be released if they are not used, thus they can be provided to some other student group.
- The educators can perform the health check of students' machines, and track their progress remotely in a more efficient way than in a physical lab during the scheduled hours.
- Due to the general resilience towards non-traditional laboratory setup, especially because of the lack of GUI, RPi-based lab is more suitable for the initial phases of the project, when students are setting up the environment and testing simple case scenarios.
- Based on the results presented in the previous section, it is important to recognize the importance of experience with Linux-based systems before moving students' laboratory exercises to the remote virtual lab, in particular due to the extensive work via command line interface. For both types of labs, programming is evaluated as highly important and it is somewhat related to the matter of our course.
- Given the overall success that both groups of students achieved at the end, and the fact that majority claimed that their general understanding is improved after performing laboratory exercises, we emphasize the feasibility of both types of laboratories as solutions for enhancing the learning experience and providing students with the opportunity to highly improve their skills in performing the practical work.

V. Conclusion

Due to the significant importance of improving hands-on work of our students that follow STEM courses, we built the two different types of networking laboratories, i.e., the physical low-cost lab, and the virtual cloud-based lab, and we studied both types of laboratories, as well as the impact they had on students' learning experience. Thus, in this paper, we presented the difference between the two aforementioned approaches, unraveling the pros and cons of both, while analyzing the existing challenges that still need to be properly tackled. With respect to the overall success that both groups of students achieved at the end of semester, as well as the fact that majority of our students claimed that their general understanding of distributed systems is improved after performing laboratory exercises in both types of labs, we emphasize the feasibility of both RPi-based and cloud-based labs for teaching engineering and other STEM courses, thereby enhancing the learning experience and providing students with the opportunity to highly improve their skills in performing the practical work.

VI. Annex

Acronyms

AI Artificial Intelligence
AWS Amazon Web Services
GUI Graphical User Interface
IoT Internet of Things
PC Personal Computer
RPi Raspberry Pi
STEM Science, Technology, Engineering, and Mathematics
VM Virtual Machine
VPN Virtual Private Network

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