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Enhancing students' learning experience via low-cost network laboratories

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***Abstract*—This paper presents low-cost laboratory which has been designed and developed to enhance learning experience and help students gain skills and knowledge in the field of distributed systems. In order to build a comprehensive distributed file system, we used the laboratory consisted of 40 card-sized Raspberry Pi devices, with the accent on stability, scalability, and its low-cost. Aiming to assess the impact of this new learning environment on the learning process and its outcomes, we surveyed students following the completion of three project stages during the 17 laboratory exercises in one academic year, assuring that we maintained the same subjects of study during the experiments. Supported by interesting answers on various set of questions, we provide a valuable insight into students' experience, obstacles and observations during system's implementation. This particular insight paves the way toward: 1. further laboratory's improvement, 2. adopting this approach in other courses related to ours, 3. encouraging teachers to embrace similar practice regardless of type of education field.**

***Index Terms*—distributed systems, Raspberry Pi, low-cost laboratory, improved learning experience.**

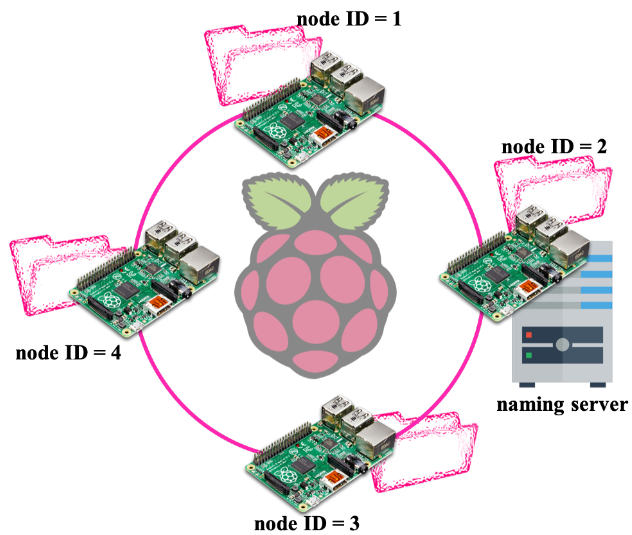

Fig. 1: Distributed File System

I. Introduction and Motivation

The immense importance of laboratory exercises is unquestionable and proven through the most diverse approaches in educational research. First, the well-recognized difference between teaching in science-related and the other fields, is that science students measure, investigate, analyze, question, hypothesize, and examine by using tools during laboratory activities [1]. Second, according to McComas [1], teachers must possess the right tools to appraise students' individual experience. This is crucial, especially because of the impact of teachers' words, and the provided instructional material, on the students' perception of the science. For more than a century, experience in laboratories has been promoted as valuable tool for enhancing students understanding of the subject-related matter, gaining practical skills and problem solving abilities, as well as triggering the students' motivation for further research in the specific field [2]. As stated by Crocker et al. [3], despite the changes of practical content and equipment over time, teaching methods have largely remained the same. It means that teachers usually deliver lectures with demonstration; students emulate teacher's example in small groups, analyzing and discussing the results. Crocker et al. [3] emphasize the importance of moving away from such demonstration-related approach to the significantly larger involvement of students throughout the learning process, enhancing the autonomous learning. Nowadays, having plenty of technology resources available for upgrading laboratories and enhancing students' experience, learning by inquiry has the renewed central status [4]. Motivated by that fact, in this paper we present a low-cost laboratory, designed and developed to improve students' experience of learning Distributed Systems (DSs). The laboratory is consisted of 40 card-sized Raspberry Pi (RPi) devices, providing homogeneous set of four RPis to each group, during 17 laboratory exercises. Importantly, we surveyed students following the completion of three project stages, which will be explained in a greater detail in the Section III-C. The interesting answers on various set of questions allow us to assess the impact of this new learning environment on the learning process and its outcomes. Hence, the benefits of our approach are the following:

- providing a valuable insight into students learning experience, their observations, and obstacles during system's implementation,
- creating a powerful tool for further improvement of the laboratory,
- encouraging teachers to embrace similar practice by presenting a way to adopt this approach in teaching, regardless of type of education field.

In the context of DSs, even highly dedicated work on practical tasks within projects often requires exceedingly strong focus on hardware setup. Work in groups usually means using heterogeneous set of Personal Computers (PCs), which might cause severe problems with updates' synchronization and distracting students from their ultimate goal to learn and gain skills. Thus, we used RPis to realize the general idea of laboratory, which is to build a comprehensive distributed file system shown in Fig. 1. The benefits of this stable framework with no dependencies on the shared hardware are two-fold: it allows students to better understand how particular DS works, and empowers them to be focused on software development and system's deployment. Since our survey results show that prior knowledge about RPi environment is not necessary to meet the final goal of the course and that students mostly preferred this type of environment at the end of semester, our approach can help teachers to build a low-cost and unified set of small computers for the wide variety of experiments that students can conduct. Also, our approach can serve as a common practice to isolate and to identify important feedback from the students, tackling it from a specific set of perspectives, such as:

- students' prior knowledge,
- the complexity of tasks, and
- their preference among different working environments.

Thus, our approach is novel in terms of these perspectives that we embraced to observe the inclusion of RPi devices as a corresponding replacement for traditional laboratory set-up consisted of laptops with features that mostly differ among student groups, thus abstracting heterogeneous hardware issues, and improving the focus on the learning subject.

II. Related Work

Twenty years after their frequently cited critical review of the research on the school science laboratory, Hofstein and Lunetta [4] claim that new methodologies for research and assessment have multiple benefits. Some of them are helping researchers to understand the usage of laboratory resources, how students' work in the laboratory is assessed, and how teachers enhance intended learning outcomes by performing laboratory activities. In accordance with current teaching trends in laboratories, one innovative and frequently utilized approach to modernize the laboratories is to use the RPi environment. Based on a wide range of experiences, Bruce et al. [5] proclaim the RPi as a testbed platform for both hardware and software system exploration, provides a great potential for taking concepts into practice. Inspecting the previous research, we noticed that RPi laboratory set-up can be used for different purposes, such as: remote laboratory prototype [6,7], virtual [8] and hands-on laboratory type [5,9–12]. Since our hands-on approach is related to assessing students' learning experience enhancement, we examine the third category in a more detail. Bruce et al. [5] state that replacing expensive equipment with a modular and affordable laboratory is necessary for increasing accessibility of the laboratory material. The expensive laboratory is mostly consisted of high-performance PCs with subject-specific tools, which are usually underutilized. Despite the fact they recognized drivers for such laboratory kit development (e.g. achieving the same educational objectives as the traditional laboratory equipment, cost, etc.) [5], authors left further assessment of students' experience for future work. However, as Ioannou et al. [10] claim, the students' perception about any new laboratory package is crucial for its future educational usage and success. Several approaches gathered feedback from students, mostly requesting their evaluation of RPi-based laboratory exercises and ability to acquire knowledge in a successful way. For instance, Maina [9] elaborates survey results and specific comments within two different courses related to signal processing. Their results point at students' satisfaction with outcomes, measured by evaluation of their level of understanding. Another similar approach is presented by Ioannou [10], developed within Physics context for primary school students. Authors observed that 42% of the students found out the learning in new environment highly interesting, with another 28% who think of it as very interesting. Whether students consider that they had learned more in RPi-based laboratory than they would learn otherwise was assessed as well. In that case, around 42% of them voted for new laboratory. However, a severe shortcoming of this approach is that no corresponding comparison is actually made, due to exposing the same students to only one laboratory set-up. Although Rao et al. [12] show an interesting way on how to incorporate RPis into embedded systems-related course, their evaluation of students' satisfaction is only purported by what students in general managed to implement during laboratory sessions. Therefore, we think that our approach is beyond recent research scope, since we collected students' feedback not only to upgrade our laboratory, and to improve it for upcoming generations, but also for multiple following reasons. It carefully investigates to what extent students' previous knowledge affects the learning process. It determines students' preferences among different learning environments. Finally, it estimates the complexity of the problems, which occurred during the project implementation. Thus, such approach and results can be recognized and valued broader than our course-related fields.

III. Course Description

Since we address students' learning experience and assess level of its enhancement attained by using low-cost network laboratory in the specific context of DSs, this section provides general information about DSs course.

A. Methodology

DSs is the course at final year of Bachelor of Electronics and ICT Engineering Technology program, at Faculty of Applied Engineering, University of Antwerp. In order to complete the overall program[1], students must obtain the total of 180 ECTS-credits, with 6 ECTS reserved for DSs. The course comprises two different groups of students (i.e. 5-DIST and S1-DIST) designated according to their background education. In particular, 5-DIST students follow the Bachelor program, in order to pursue academic Bachelor degree in Applied Engineering. On the other hand, S1-DIST students already

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

Week	Lecture hours	Lab hours	Experimentation	CS2016 Knowledge area	Project stage
1	2	0	Introduction	Parallel and Distributed Computing	N/A
2	2	2	Characterization of DSs		Introduction
3	2	2	System Models		
4	4	0	Interprocess communication & Remote invocation/REST	Networking and Communications	
5	0	4	Naming	Parallel and Distributed Computing	Naming server
6	2	4			Naming server & Discovery
7	2	4	Indirect communication I & Discovery	Networking and Communications	
8	2	4	Indirect communication II & Discovery		Discovery
9	2	6	Security & Replication	Information Assurance and Security	Replication
10	2	0	Naming server & Discovery	Parallel and Distributed Computing	
11	2	6	Agents & GUI		Agents & GUI
12	3	4			

TABLE I: The content of DSs course

obtained non-academic professional degrees (e.g. applied informatics, mechanics, automotive engineering, etc.), but to be eligible to enroll Master study, they have to bridge the gap in knowledge by attending one extra year. Regardless of their background knowledge, both groups of students attend lessons with the same content and at the same time. This specific diversity enables us to observe how students' previous knowledge impacts the learning process. The prerequisites for the course are the general knowledge of using PC and Internet, and at least basic programming skills in order to be able to create adequate software solutions. The examination is proceeded in two stages: 1. theoretical part - oral with written preparation, 2. practical part - portfolio and project defense. The theoretical part takes 40% of the score, since the remaining 60% are divided to portfolio with 20%, and project defense with 40%. In order to track their step-by-step progress, students have to submit reports after each project stage. The students work on the project in groups of four, mimicking the real working environment practices nowadays. Thus, the defense is supposed to result in a number of points for the whole group, with both theoretical and practical parts being mandatory to pass the exam.

B. Course Content

Throughout the semester, lectures and laboratory sessions are conducted in a synchronized manner, both in time and content. Accordingly, students are supposed to gather satisfactory amount of information to understand practical exercises. In order to map our course to the IEEE/ACM CS2016 joint curriculum for computer science engineering, we followed the instructions given by ACM/IEEE-CS [13], and thus the content of course is presented in Table I. The table shows the course content encompassing theory and experimentation, as well as the project stages mapped to the content of course.

C. Project Description

In order to enable understanding of our survey results, in this section we provide knowledge about the project and the description of project stages. We used RPi devices to build a comprehensive distributed file system in a ring topology, with files being automatically replicated to nodes and the naming server created to keep track of nodes' connections within the ring. The first three laboratories are introductory, aiming to prepare students for the project. The project is performed within three interconnected and dependent stages, briefly presented below.

a) Naming Server and Discovery: Naming server has two main responsibilities: 1. to add and remove nodes from the system, and 2. to map each node to its Internet Protocol (IP) address. In particular, adding node is followed by execution of a *hashing* algorithm, which results in unique *hash* value for each node. Based on the increasing *hash* values, all nodes in the system are placed within the ring topology in the clockwise order. The *hashing* algorithm is beyond the scope of this paper and is not further discussed. The naming server provides access to all files which are locally stored at any node.

b) Replication: Once a node is added, the naming server calculates *hash* values of files which are locally stored at this node. Then, the resulting *hash* values are used to determine the locations to which the local files should be replicated. The same procedure is invoked any time a change (i.e. adding/removing node or file, failure, and shutdown) occurs in the DS.

c) Agents and GUI: The last project phase requires the synchronization within DS, and DS's visualization. In terms of synchronization, students are asked to create two agents: Develop and Failure. The first creates a list of all available files in the network. The second agent is triggered in case of failure, with responsibility to transfer all files from failed node to the new owner. Finally, the Graphical User Interface (GUI) provides users with a simplified interaction with implemented DS.

IV. Raspberry Pi Laboratory

To pave the way toward solving problems of hardware dependencies and to enhance students learning experience, we renovated our laboratory utilizing products from RPi foundation. This section provides an insight to main characteristics of devices we used to replace too expensive and underutilized equipment, such as PCs with high performances. Further, we show how we incorporated these devices into actual laboratory exercises.

a) RPi Environment: RPis are low-cost and tiny computers with Linux-based operating system (so-called Raspbian),

Question		Segments	Answers
1	Is your understanding of DS's basics improved after laboratory exercises?	N/A	Yes (how?)
			No
2	Rate each of the following segments according to the complexity of problems during the implementation.	RPi Setup	Extremely high (8)
		Networking devices	High (6)
		Understanding framework functionalities	Moderate (4)
		Programming	
		Testing	Low (2)
3	Please rate how did your previous knowledge and experience affect the following implementation segment.	RPi	Significantly (8)
		Networking devices	Moderate (4)
		Programming	Non-significantly (0)
4	Do you better understand the non-global issues by using DS RPi framework?	N/A	Yes (how?)
			No
5	Do you think bringing your own laptop and setting the framework with the peers' laptops would be a better approach?	N/A	Yes (how?)
			No
6	Do you think cloud-based systems would be a better approach?	N/A	Yes (how?)
			No

TABLE II: Survey

produced for educational purposes [14]. Some of the advantages of RPis are expandable storage memory with operation speed from 700 MHz to 1000 MHz [12], and importantly, a competence to easily network with other devices, via WiFi, Bluetooth, or Local Area Network (LAN). Due to these capabilities, we found RPi particularly attractive for replacing traditional PCs and students' laptops in developing DS for sharing files. However, the main RPi's limitations are its relatively low working memory in comparison with high-performance PCs nowadays, and its power supply which does not allow any external device to draw more than 100mA [12].

b) Laboratory Exercises: Although we have replaced traditional laboratory set-up with unique set of four bare RPis, we kept the existing content of laboratory exercises from previous academic years. As the main goal of laboratory exercises is to establish DS consisted of the nodes and the naming server, the RPis are used to develop both nodes and naming server, belonging to the same network. Initially, students were instructed to develop all project functionalities directly on the RPi, but they decided to approach the problem by using their laptops as parallel testing set-up, providing us with the opportunity to make a comparison between these two distinct environment experiences.

V. RESULTS

In this section, we present our findings based on the feedback from the students we have surveyed. The questionnaireis presented in Table 2. We conducted three survey cycles, after completion of each project stage (as described in Section III), and asked 40 students to answer the exact same questions each time. Their responses to the questions provide the baseline for our examination of the impact of the innovative low-cost laboratory on students' learning experience. In particular, the question 1 is raised in terms of further improvement of our laboratory. The question 2 helps us to find out which project segment causes the major problems, and whether these problems are linked to our new laboratory or to students' lack of knowledge. The goal of the question 3 is to evaluate whether having prior knowledge about the new environment is required or not, and what are the most useful skills for the students. Finally, questions 4, 5 and 6 are asked to reveal the students' preference among different environments and to check if our approach is justified or not.

In order to evaluate the significance of the difference between results from distinct groups, we conducted one-way ANOVA test with 95% level of significance ($\alpha = 0.05$), with a null hypothesis which indicates that the population means are all equal. In this test, $p\ value$ indicates the probability of getting a result at least as extreme as the one that was actually observed, assuming the null hypothesis is true. Accordingly, if $p\ value$ is lower or equal to α, we reject the null hypothesis.

Gathering answers on the first question, we received the positive feedback which shows that the great majority of students from both groups (more than 92% and 100%, respectively) think that their understanding is improved. The same result was provided in each evaluation, which is proved to be statistically relevant. In particular, $p\ value$ is equal to $7,02e-05$ for 5-DIST, and 0.0002 for S1-DIST group, which indicates that difference between positive and negative answers is statistically significant.

Due to the reduced size of our population, and the nature of our survey, the answers on the rest of the questions are not significantly different between project phases. For instance, observing the difference between project stages in case of evaluation of problem complexity, $p\ values$ for 5-DIST and S1-DIST groups are 0.58 and 0.6, respectively. Such result indicates that we may decrease the level of significance. Despite the fact that $p\ value$ is greater than α, we collected quite interesting objective and subjective results that imply important conclusions related to the impact of the students' previous experience, the evaluation of the complexity of the issues, and the environment preference. Hence, as a future work we aim to increase the size of our population, and thus expect to have statistically more significant results. Finally, for questions 2 and 3 the normalized grade is calculated as an average value of all answers for a particular segment in the question, based on the weights presented in third column of the Table 2

a) Previous Experience Impact: We present herein the answers on the survey question 3. In Fig. 2, we can notice that previous programming experience has the highest impact factor on the students' learning experience, regardless of the project phase. Within the additional comments that students provided, we can see that having JAVA as mandatory programming language for implementation was an advantage, and in line with their previous programming experience. Furthermore,

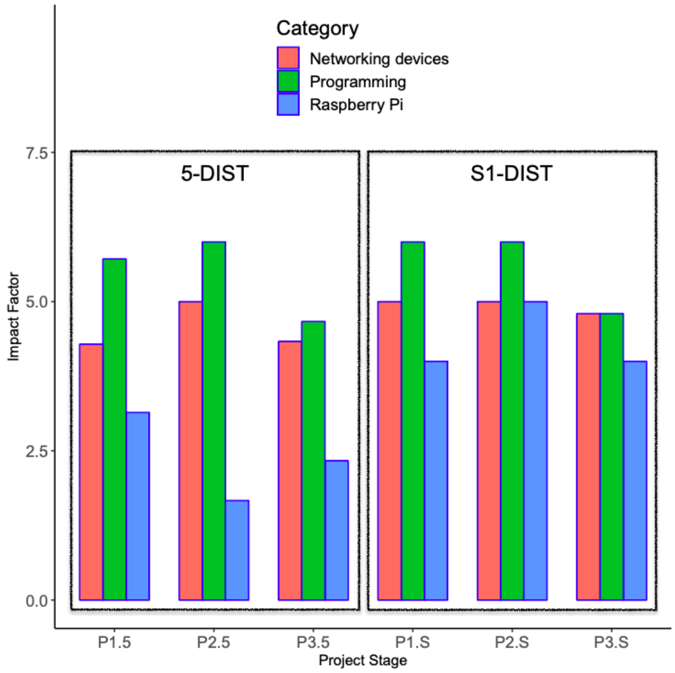

Fig. 2: Previous Experience Impact; $Px.y$ on the x-axis is the project phase, where x stands for the phase number, while y can be either 5 or S, referring to 5-DIST and S1-DIST student group, respectively. The weights for the possible answers are: significantly (8), moderate (4), non-significantly (0).

one important conclusion about RPi setup experience can be drawn.

Due to the lowest score for this type of impact factor in each project stage, previous knowledge about such devices is not required for achieving ultimate goals of the project, and our course in general. According to this interesting result, we refer to a great opportunity in embracing RPi environment in other courses, which are not necessarily related to DS. It makes such innovative laboratory applicable to diverse science fields, such as those presented in [9,10,12].

b) Problem Complexity Evaluation: The answers on the survey question 2 are presented as follows. Fig. 3 shows that for both groups testing phase was evaluated as the most problematic throughout the whole project, except for the slight advantage of networking devices in the first stage (5-DIST only). Based on the additional comments we collected and the fact that students were not allowed to borrow RPi devices, we suspect that the reason for such results originates from limited access to laboratory equipment. During the progress of the project for 5-DIST group, programming complexity was being rated as more difficult. This is somewhat expected since the project tasks have become more complex for both groups as the project was approaching the final stages.

Although students complained about networking devices and University network blocking issues, due to the Information and Communications Technology (ICT) policies and internal regulation, once they managed to establish stable network environment, these types of issues were almost negligible. Despite the decreasing trend of RPi setup problems for S1-DIST, programming kept being quite challenging, followed by slight increase in networking devices' issue complexity. Importantly, both groups of students seem to be satisfied with the understanding of how particular DS works, since its complexity was being evaluated as moderate or lower.

c) Environment Preference: We analyze the answers on questions 4, 5 and 6 (Table II) jointly, in order to assess the students' preference among different environments. If we observe results for 5-DIST students shown in Fig. 4, we can easily notice the increasing trend of RPi environment preference throughout the project stages. S1-DIST students also confirmed increased preference of such environment after the final stage. This phenomena can be implied from becoming more familiar with the new environment. Hence, huge effort in setting up the RPi-based DS can potentially result in students' comfortability with future work in such environment.

Although 5-DIST students preferred their own laptops in the initial phases, they increased the preference for RPi-based environment as the project was progressing, and their preference for RPis was the highest at the end of the project. The different trend of RPi environment preference for S1-DIST students might be the result of being less-experienced and having different background knowledge. Another interesting trend, especially for S1-DIST group, can be recognized if we observe the cloud-based systems. Given the fact that during the lectures students were subsequently acquiring knowledge about different forms of DSs, including cloud environment, we suspect that such increase in preference is related to the content of the lectures. Therefore, the more they learned about other forms of DSs' development the more they were willing to change their opinion and preference.

VI. Discussion

In this section we analyze the results, highlight the main findings, and point at clear articulation of innovative laboratory's role in the learning process.

- Having programming as the most influential factor to the project realization is somewhat strictly related to the matter of course, while being familiar with RPi environment is not mandatory. Thus, we see a great potential in such innovative laboratory set-up, since it can be easily applied to diverse fields, regardless of the background knowledge.
- Expanding on the point stated above, we can clearly see that the previous knowledge about programming and networking devices had a higher impact on the work and success in the laboratory than knowledge and experience with RPis (Fig. 2). Since the course DS is designed considering some prior basic knowledge about programming and networking from engineering students, this result is quite important because it justifies the prerequisites for the course as well as overall course's design.
- Tackling the difference in background of two student groups, we notice that students with previous academic knowledge (i.e. 5-DIST) express smaller resilience to experimenting in new environments. This is somewhat

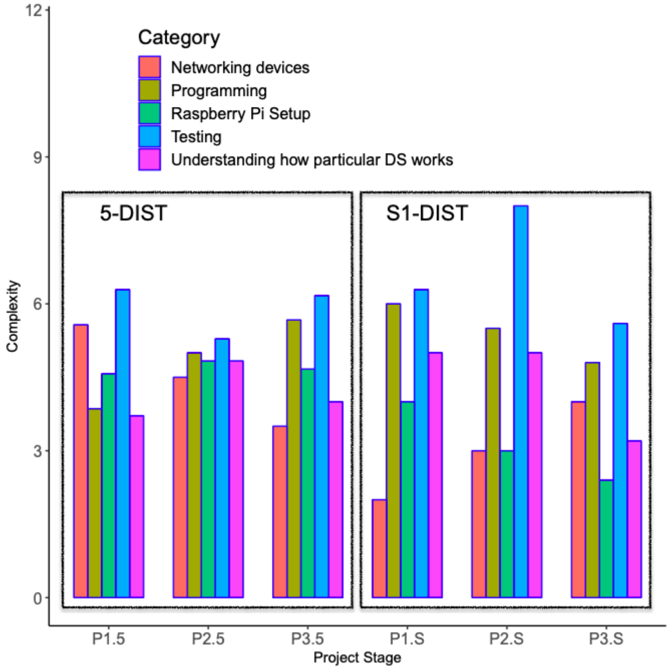

Fig. 3: Problem Complexity Evaluation; $Px.y$ on the x-axis is the project phase, where x stands for the phase number, while y can be either 5 or S, referring to 5-DIST and S1-DIST student group, respectively. The weights for the possible answers are: extremely high (8), high (6), moderate (4), low (2).

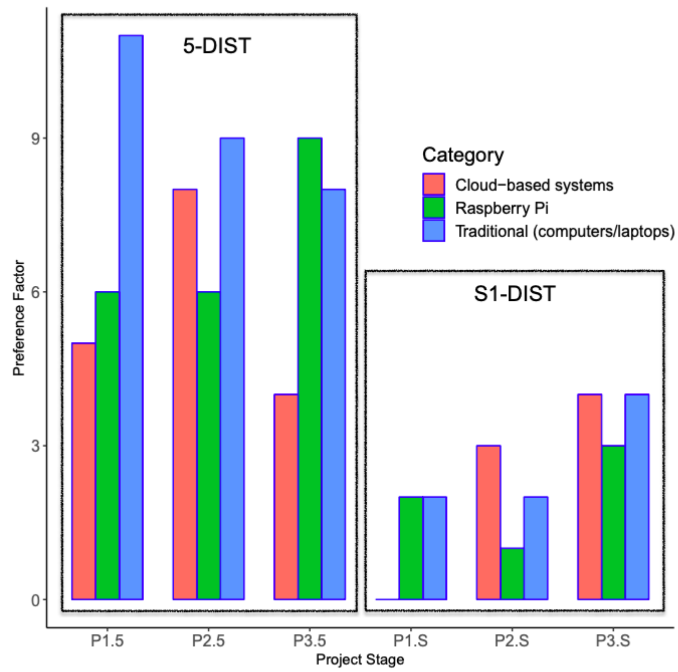

Fig. 4: Environment Preference; $Px.y$ on the x-axis is the project phase, where x stands for the phase number, while y can be either 5 or S, referring to 5-DIST and S1-DIST student group, respectively.

expected, since these students are subjected to broader scope of experimenting tools within various engineering courses, i.e. diverse simulation and testbed solutions, before enrolling the course, as opposed to S1-DIST students.

- We found out that the most severe problems occurred in testing phase. Based on the survey results and students' comments, we suspect that the source of such problems is a limited access to the laboratory equipment. Thus, as part of our future work we plan to investigate enabling mobility of such laboratory, aiming to achieve a flipped laboratory approach [15].
- Students expressed noticeable resilience in leaving their comfort zone, meaning using their traditional PCs/laptops set-up. We also suspect that this phenomena is followed by natural bias towards the Linux Operating System (OS), which is the base for Raspbian OS. That is quite expected due to the fact that students are more familiar with Windows OS. Tackling these problems will be the part of our future work as well.
- Our approach provides a research community with the clear-cut set of perspectives that enable observing the usage of RPi devices as a replacement for traditional heterogeneous laboratory set-up.
- According to the overall success that students achieved at the end of semester, and the fact that great majority claimed that their learning is enhanced after performing laboratory exercises, we emphasize the feasibility of our RPi-based laboratory solution for ultimate learning experience enhancement.

VII. Conclusion

The educational research has proven the immense importance of laboratory exercises, due to the chance to use the right tools to appraise students' individual learning experience. Teaching methodologies with more involvement of students, as well as variety of available technology resources, motivated us to renovate our DS's laboratory. Hence, our low-cost laboratory with 40 RPis is designed and developed to improve students' experience of learning DSs. Our survey collected feedback from students, gathering utterly interesting answers about the impact of their previous experience and knowledge on the work in such innovative laboratory, the complexity of the problems which occurred during the project realization, and their preference among traditional, RPi-based and cloud-based environment. We believe that our valuable results and findings, presented in this paper, can be beneficial to different areas and domains, rather than our course-related research scope.

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