Virtual Lab for a Pneumatic Module as a Pre-lab Activity in an Engineering Training Course

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Abstract. Hands-on experience is a fundamental component of engineering and mechatronics education. To enhance student' learning experiences, a growing number of studies have explored virtual and digital environments as preparation tools for laboratory-based instruction. When used as pre-lab activities, virtual laboratories can improve student's self-efficacy and familiarity with experimental procedures before engaging in real-world experiments. However, research on their application within pneumatic and mechatronic training remains limited. In addition, few studies have examined how such pre-lab experiences influence student's engagement and perceptions in technical training contexts. This study evaluates the Virtual Lab for the Pneumatic Module (VL-MN) as a pre-lab tool, focusing on measures of engagement and perceived learning. The findings suggest that VL-MN is an effective pre-lab tool that enhances student motivation, perceived learning, and self-directed engagement, and that integrating virtual and physical labs in a blended approach may further optimize learning efficiency and promote active participation.

Keywords: virtual laboratory, pre-lab preparation, pneumatic training, engineering education

1 Introduction

Hands-on experience has long been recognized as a corner stone of engineering and mechatronics education. Laboratory-based learning enables students to bridge the gap between theoretical knowledge and practical application, fostering a deeper understanding of system behaviour, technical troubleshooting, and design principles [1]. In areas such as pneumatics and control systems, practical training is essential to master circuit configuration, understand the relationship between mechanical and electrical components, and cultivate procedural skills that are critical for professional competence [2].

Despite its importance, providing sufficient access to high-quality laboratory experiences remains a persistent challenge for many technical institutions. Physical laboratories often face constraints such as limited equipment availability, safety concerns, maintenance costs, and large cohorts of students. These challenges were further amplified during the COVID-19 pandemic, forcing educational institutions worldwide to

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adopt hybrid and online learning modalities [3]. Consequently, educators began exploring virtual and remote laboratory environments to preserve experiential learning opportunities under these constraints. Virtual laboratories have since emerged as powerful pedagogical tools that allow students to manipulate parameters, repeat experiments, and visualize theoretical concepts through simulation. They provide safe, scalable, and flexible environments that can enhance both engagement and conceptual understanding [4] [5]. According to De Jong et al. [4], virtual laboratories also promote inquiry-based and exploratory learning.

In engineering education, a large-scale review concluded that virtual labs are a significant predictor of positive engineering education outcomes, particularly to increase learning motivation and engagement. It confirms that virtual labs are an "indispensable auxiliary tool" [6]. An increasing number of studies have explored their role as pre-lab preparation tools. These studies consistently highlight the potential of such tools to improve students' procedural understanding, reduce anxiety, and improve performance in subsequent physical labs. For example, Vahdatikhaki et al. [7] developed a gamified virtual laboratory for civil engineering students and found that pre-lab simulation users required less assistance and time during physical lab sessions, confirming the efficiency of virtual pre-lab experiences in supporting readiness and procedural understanding. Paxinou et al. [8] demonstrated that students who used a 3D virtual lab to prepare for microscopy experiments exhibited higher levels of preparedness and confidence compared to those who used traditional preparation methods. Angelica Vagle [9] reported that a virtual lab as a pre-lab significantly benefits students in the chemistry lab. It was found to reduce unnecessary mental effort and boost germane cognitive load, essentially making preparation more meaningful through a nearly authentic, relatable simulation.

Although these studies collectively affirm the value of virtual labs as pre-lab preparation tools, most of them have focused on disciplines such as biology, chemistry, or civil engineering. Research on their application in pneumatic and mechatronic training contexts remains scarce. In addition, limited work has examined how such pre-lab experiences influence students' engagement, motivation, and perceived learning within technical training modules. This study addresses this gap by evaluating the Virtual Lab for the Pneumatic Module (VL-MN) as a pre-lab activity in an engineering training course.

(a) Real Pneumatic Training Module (MN-Real) (b) Virtual Pneumatic Training Module (VL-MN)

Fig. 1. Electro-pneumatic Training System: Real Pneumatic Training Module (MN-Real) (a), Virtual Lab for the Pneumatic Module (VL-MN) (b)

2 Method

2.1 Real Pneumatic Training Module (MN-Real)

The pneumatic training module used to provide students with hands-on experience is the LQD-DP401 [10], which is a double-sided electro-pneumatic training system designed to meet the requirements of modern pneumatic and automation training environments, as shown in Fig. 1a. In addition to supporting the construction of conventional pneumatic control loops, the system is equipped with both a relay module and a PLC module, enabling the design and implementation of automatic control loops that integrate pneumatic and electro-mechanical components.

This training system is installed in the Process Laboratory at Continental University, Arequipa, Peru. The university houses two double-sided training modules, which are primarily used by undergraduate engineering students in courses related to pneumatics, electro-pneumatics, and PLC-based process control.

2.2 Virtual Lab for the Pneumatic Module (VL-MN)

The VL-MN is a digital replica of the real pneumatic training module LQD-DP401, designed to emulate the real pneumatic and electro-pneumatic experimental environment, as shown in Fig. 1b. The VL-MN includes the same components as Real-MN as follows:

- Pneumatic components: double-acting and single-acting cylinders; mono-stable and bi-stable pneumatic valves with manual, mechanical, and pneumatic actuators.
- Electrical components: inductive, capacitive, and photo electric sensors; mono-stable and bi-stable solenoid valves with electrical actuators.
- Electronic components: Siemens S7-1200 PLC programmable logic controllers.

The VL-MN was developed to provide an authentic and interactive learning experience that closely mirrors the real-world setup. It allows students to practice device identification, circuit assembly, and visualize circuit behaviour in a safe and repeatable virtual environment. The VL-MN has the following features:

(a) Virtual (b) Real (c) Simulated

Fig. 2. 3D Realistic Models of: virtual 3/2 pneumatic valve in VL-MN (a), real 3/2 pneumatic valve in Real-MN (b), and symbol of 3/2 pneumatic valve in FluidSIM (c).

Realistic 3D Models. The VL-MN includes complete sets of pneumatic, electrical, and electronic devices that accurately replicate the components of the real training module. Each component was designed with careful attention to labelling, orientation, and proportional dimensions to ensure visual and functional fidelity. Through realistic 3D modelling, students can recognize and manipulate devices arranged in the same spatial configuration as the physical setup, creating an authentic learning experience.

In contrast, traditional laboratory sessions often rely on simulation software such as FluidSIM, where students design pneumatic and electro-pneumatic circuits using standardized symbols. While effective for testing circuit logic, these symbolic representations differ significantly from the appearance of actual devices, making it difficult for students to identify components during real setup. For example, Fig. 2 illustrates the differences among the virtual, real, and symbolic representations of a 3/2 pneumatic valve. Although each device is labelled, students still spend considerable time locating and matching components, which may reduce the time available to analyse circuit behaviour and system performance. The VL-MN overcomes this limitation by allowing students to design and interact with lifelike 3D components that mirror real-life systems. This immersive approach reinforces spatial understanding, improves component recognition, and allows repeated exploration without time constraints, which may help students build conceptual and practical skills essential for effective circuit design and implementation.

Interactive Operations. Students interact with virtual components in the same manner as they would during an actual laboratory session. These interactions include grabbing components from drawers, placing them on the workbench, and mounting them onto panels. Such tasks form an integral part of the learning process, reinforcing procedural familiarity and spatial reasoning.

The operation also involves connecting components using pneumatic hoses and electrical cables, replicating real laboratory practices. Unlike conventional simulation software that emphasizes schematic representations, the VL-MN prioritizes physical realism in component manipulation and connection. Consequently, the connections are not always perfectly aligned or neatly arranged, which mirrors authentic hands-on conditions and provides students with a more immersive and realistic laboratory experience.

Mistake Tolerance. The VL-MN functions as an open-ended learning environment where students can freely connect components the same way as they would in a physical setup. This flexibility allows them to experiment and even make mistakes, such as incorrect connections. The system does not provide explicit warnings or corrective feedback; instead, it simply reflects the outcomes of students' actions. Through these outcomes, students rely on their own observations to identify errors and refine their understanding.

In summary, these design features aim to create a learning environment that closely mirrors authentic laboratory conditions while providing extended opportunities for experimentation and reflection. By integrating realistic 3D models, interactive operations, and tolerance for mistakes, the VL-MN enables students to explore, construct, and analyse pneumatic and electro-pneumatic systems in a realistic yet flexible virtual setting.

3 Participants and Data Collection

3.1 Participants

This experiment was carried out within the Production Integrated System course during the second semester of 2024 and the first semester of 2025. The participants were fifth-year undergraduate students majoring in Industrial Engineering at Continental University, Arequipa campus, Peru. A total of 16 students completed both the Pneumatic and Electro-pneumatic experiments, as well as the post-experiment survey, across the two semesters—6 students in the 2024 semester and 10 students in the 2025 semester. The course content and structure were consistent throughout both semesters. Of these participants, 10 students provided their informed consent for their survey data to be used in this study, which constitutes the final sample for analysis. However, the interaction data, included all 16 students. The study adhered to the ethical principles outlined in Ethics in Scientific Research: The Basis of All Responsible Practice by Continental University [11].

3.2 Procedures

The experiment followed the same procedure in both semesters, ensuring consistent course settings. It was designed to provide a progressive and integrated learning experience combining virtual, real, and simulation-based activities. It began with a laboratory introduction, followed by two main sessions: a pneumatic session and an electro-pneumatic session.

Each session started with pre-lab activities (Task A) conducted using the VL-MN, which allowed students to familiarize themselves with the components, understand their functions, and explore circuit operations in a virtual environment. Subsequently, students engaged in hands-on in-lab activities, starting with the pneumatic session, which involved implementation using Real-MN (Task B) and circuit simulation with FluidSIM (Task C) to model more complex systems. The same procedure was then repeated for the electro-pneumatic session. After completing all sessions, the participants completed a survey evaluating their learning experience with the VL-MN. In addition, the VL-MN remained accessible throughout the rest of the semester, allowing students to continue their exploration independently.

Each of the two laboratory sessions on pneumatic and electro-pneumatic circuits was organized into two main stages, conducted in separate laboratory environments. The first stage included an introduction (30 minutes) followed by two pre-lab sessions—the Pneumatic session (70 minutes) and the Electro-pneumatic session (70 minutes)—held in the computer laboratory classroom. The second stage took place in the process laboratory classroom and consisted of two in-lab sessions—the Pneumatic session (80 minutes) and the Electro-pneumatic session (80 minutes)—followed by a survey (15 minutes). After that, Students were also given the opportunity for optional further exploration beyond the scheduled sessions. The overall workflow of the procedure is illustrated in Fig. 3, and the detailed activities are described below.

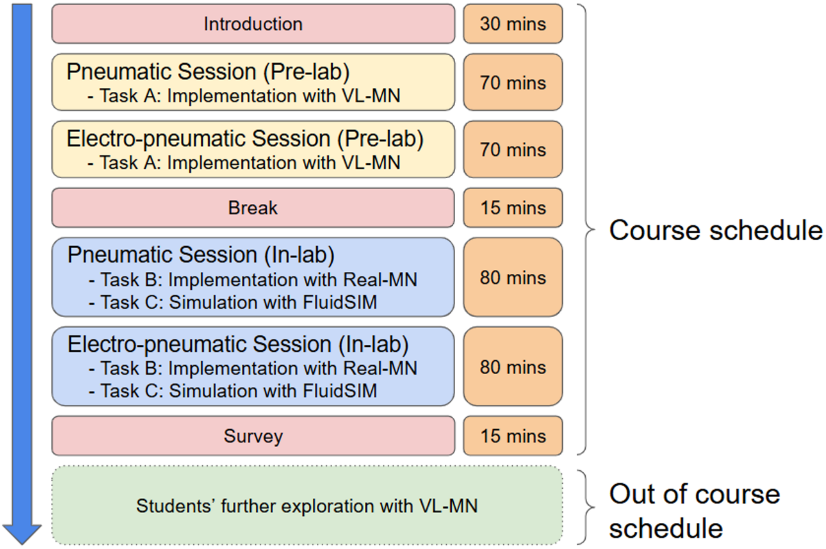
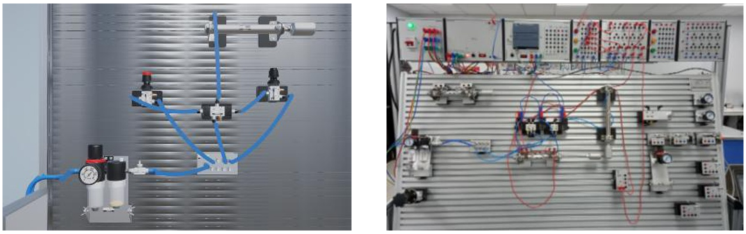


Fig. 3. Laboratory procedure, showing Pneumatic and Electro-pneumatic sessions, each of those performing tasks A, B, and C

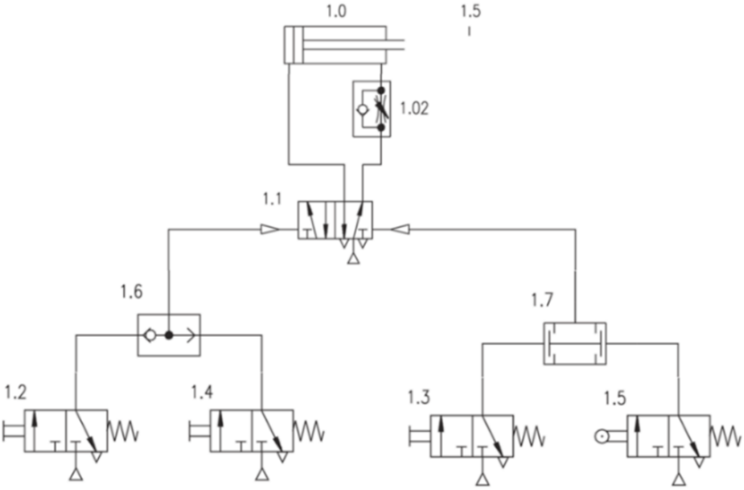
Lab Introduction. In the lab introduction, students were oriented to the general course procedures, the specific tasks they would perform, and the learning objectives for the session. They were also introduced to the VL-MN, Real-MN, and FluidSIM, including their concept, components, and operation. This preparatory brief ensured that the students were familiar with both virtual and physical tools they would use.

Task A - Virtual Laboratory Implementation (Pre-lab). In Task A, the students used the VL-MN to implement and explore the operation of a pneumatic/electro-pneumatic system corresponding to the first stage of a cardboard box assembly machine. This task aimed to familiarize students with the components and basic control logic prior to hands-on work with the real training system. The students were instructed to develop the corresponding circuits, identify the components involved, describe their functions, and analyse the operational sequence of the machine as observed in the virtual simulation. For example, Fig. 4a shows part of Task A in VL-MN.

The pre-lab activity was conducted in a computer laboratory equipped with internet-connected computers. Under these conditions, each student completed the task individually using the VL-MN platform, while receiving continuous guidance and formative feedback from the academic instructor. Upon completion of the task, the students participated in a group discussion to analyse circuit operations and reflect on the difficulties encountered during the task.



(a) Task A (b) Task B



(c) Task C

Fig. 4. Main tasks during lab sessions: Pre-lab activity Task A: Implementation and simulation using VL (a), In-lab activity Task B: Implementation using real training system (b), and In-lab activity Task C: Simulation of complex circuits using FluidSIM (c).

Task B - Real Training System Implementation (In-lab). In Task B, the students implemented the same pneumatic/electro-pneumatic system previously explored in Task A, but this time using the physical training system. This hands-on activity aimed to check the students' understanding of the circuit and reinforce component recognition, procedural, and system-level comprehension. The students developed the corresponding circuits, identified the components, described their functions, and analysed the operational sequence of the cardboard box assembly machine as observed in the real system. For instance, Fig. 4b shows part of Task B in the real system.

Upon completing the pre-lab activity, the students moved to the process laboratory, where the real pneumatic and electro-pneumatic training systems were available. In this stage, they were asked to implement the same circuits previously practiced in the pre-lab, but using actual equipment. The instructor provided formative guidance and group discussions were conducted to evaluate understanding and troubleshoot operational issues. Time was also allocated for group and individual assessments, during which the instructor posed targeted questions to evaluate students' understanding and verify the attainment of the intended learning outcomes.

Task C - Advanced Simulation Using FluidSIM (In-lab). In Task C, the students used the FluidSIM simulation software to implement and analyse a more complex pneumatic/electro-pneumatic system corresponding to the second stage of the cardboard box assembly line. The task required students to identify the components, describe their functions, and examine the operation of the system based on the simulation results. This activity extended the learning experience by introducing additional components that are not available in the physical training system, allowing students to explore advanced circuit design, develop problem-solving strategies, and reinforce the conceptual connections between virtual and real implementations. For example, Fig. 4c shows part of Task C in FluidSim.

As the final task, students were asked to simulate a more complex circuit using FluidSIM software. This step was introduced due to the increased complexity of the circuit and the inclusion of components not available in the physical training system. The activity encouraged students to extend their learning and apply their understanding to more advanced scenarios.

After the lab sessions were completed, the students were encouraged to continue engaging in the virtual lab as an exploration time. This represented an opportunity for them to review the procedure, repeat experiments, or further explore the concepts introduced during the lab session.

3.3 Measures and Data Collection

Survey. An anonymous survey comprised of eight open-ended questions was administered to capture students' experiences with the VL-MN. The questions were structured into four thematic areas: overall perception and motivation, perceived learning effectiveness, perceived usability and improvement, and perceived integration and future application. More specifically, overall Perception and Motivation are to measure student' engagement and interest in the virtual lab, including Q1 "How was your overall experience using the virtual labs?"; Q6 "Did the virtual labs make you more or less interested in the subject? How?". Perceived Learning Effectiveness is to identify how the virtual lab contributed to understanding theory, practicing procedures, and developing skills, including Q2 "Which parts of the virtual labs helped you learn the most?"; Q5 "What skills or knowledge do you think you improved by using the virtual labs?". Perceived Usability and Improvement is to detect operational challenges and suggestions for improvement, including Q3 "What problems or difficulties did you face when using the virtual labs?"; Q7 "If you could change one thing about the virtual labs, what would it be?" Perceived Integration and Future Application is to explore students' preferences for blending virtual and real labs, and perceived long-term benefits, including Q4 "How would you like virtual labs and real labs to be used together?"; Q8 "How do you think virtual labs could help your learning in the future?" The survey was conducted after the virtual lab session. The responses were thematically coded to identify patterns in experiences, challenges, and perceived learning outcomes, providing frequency of themes and illustrative quotes to evaluate the effectiveness of VL-MN as a pre-lab tool.

Interaction Data. The VL-MN platform automatically recorded interaction data for students, including time logs, frequency of actions, and duration of use. These metrics provided valuable insights into students' engagement and interaction behaviours both during the virtual pre-lab sessions and during independent exploration outside of class.

4 Results

4.1 Students' perception of the VL-MN

Overall Perception and Motivation. The survey responses indicate that the virtual lab had a generally positive impact on students' perceptions and motivation. For the question "How was your overall experience with the virtual labs?", eight out of ten students reported a good or excellent experience, suggesting that the majority found the VL-MN engaging and satisfactory. One student rated their experience as average without providing a reason, and one student reported difficulty, describing the system as too complicated to use. This indicates that while most students responded positively, a minority experienced usability or cognitive challenges that affected their overall perception. Regarding motivation, the question "Did the virtual labs make you more or less interested in the subject? How so?" revealed that nine students experienced increased interest in the subject after using the virtual lab. Among these, four students noted that they became more motivated because VL-MN helped them become familiar with a practice in the real lab. Three students valued that they are motivated because it helped them reflect or think differently about the experiment and the knowledge they already learned. Additionally, one student mentioned that the immersive virtual environment itself improves their engagement, while another was motivated by the sense of accomplishment after successfully completing the tasks. Only one student reported decreased interest due to the perceived complexity of the system. In general, these findings suggest that the VL-MN effectively supports not only student satisfaction, but also effective engagement and motivation. Most of the students reported that the virtual lab improved their interest in the subject and facilitated a more active and reflective approach to learning. The small number of students who faced difficulties underscores the importance of providing user guidance and technical support to maximize engagement among all learners.

Perceived Learning Effectiveness. The survey responses indicate that the virtual lab had a substantial impact on students' learning outcomes and practical skills. For the question "What aspects of virtual labs helped you learn the most?", seven out of ten students highlighted interactive simulation and familiarity with equipment as the most helpful features. They noted that practicing with virtual components allowed them to identify and manipulate kits effectively and to rehearse experimental procedures in a manner similar to the physical lab. One student emphasized the benefit of having no time limit, which allowed repeated practice and self-paced learning. These responses suggest that the virtual lab provided a supportive environment for both procedural and conceptual learning. Regarding skill and knowledge improvement, the question "What skills or knowledge do you think you improved by using the virtual labs?" revealed that eight students reported gains in practical skills, including observation, component identification, circuit assembly, electro-pneumatic connections, and pneumatic analysis. In addition, one student reported an improved overall understanding of the course, another noted enhanced critical thinking, and one student indicated better comprehension of theoretical concepts. These findings suggest that the VL-MN contributes not only to technical competence but also to higher-order cognitive skills, preparing students for more effective engagement in the subsequent physical lab sessions. Overall, these results indicate that the virtual lab effectively supports better practical learning, reinforces theoretical knowledge, and fosters skill development. The combination of interactive simulation and unrestricted practice appears particularly valuable to help students gain practical experience.

Perceived Usability and Improvement. The survey responses highlight several operational and usability challenges faced by students when using the virtual lab. For the question "What problems or difficulties did you encounter when using virtual labs?", six students reported issues related to system operation, including difficulties with cable connections and occasional freezing when placing or manipulating components. One student noted that the lack of guidance from the instructor posed a significant challenge, while another student found it difficult to map symbolic representations in the software to the corresponding physical kits. Two students did not report difficulties, indicating that the system was manageable for some users. When asked "If you could change one thing about virtual labs, what would it be?", four students suggested technical improvements, such as adding shortcut commands and clarifying the component selection process. Two students requested additional practice time, and one student expressed a desire to have access to the virtual lab on personal devices outside of the university. One student indicated that no changes were necessary, while another preferred to remove the virtual lab from the course entirely. Overall, these findings suggest that while the virtual lab is generally effective, improvements in operational instructions, technical functionality, and user guidance could improve usability and reduce cognitive load. In particular, providing clearer visual aids to bridge the gap between abstract symbols and real-world components, as well as considering flexible access and additional practice opportunities, may help maximize the learning experience for all students.

Perceived Integration and Future Application. The survey responses indicate that students see strong potential in combining virtual and physical labs to enhance learning. For the question "How would you like to see virtual and physical labs used together?", four students suggested an integrated approach where theoretical designs are first developed in a simulator and then tested in the virtual lab, allowing sequential reinforcement of concepts. One student proposed incorporating industrial examples to practice real-world applications, while another emphasized completing the same exercises in both environments. Additionally, four students requested more time for both physical and virtual labs; one highlighted the importance of guided practice when using both formats, and another suggested having virtual and physical labs available concurrently.

These responses point to the potential of blended learning models, provided that they are carefully structured and supported. Regarding future use, the question “How do you think virtual labs could help you learn in the future?” revealed that seven students saw virtual labs as valuable for design practice and experimental rehearsal, such as creating circuits according to preference, practicing without risking component damage, and preparing for fieldwork or situations where access to in-person labs is limited. One student noted the benefits of virtual labs for large-group learning, while two others emphasized their accessibility and convenience at any time. Overall, these findings suggest that virtual labs not only complement physical labs but also provide flexible, risk-free, and accessible opportunities for skill development and experimental practice, supporting a blended and adaptive learning approach for engineering education.

4.2 Student Engagement from Interaction Data

The interaction data collected from the VL-MN platform provide insight into the patterns of student’ engagement during the pre-lab sessions throughout the two semesters. Table I includes the time that the students spent preparing in the pre-lab sessions. The results show that among 16 students, six students spent less than 30 minutes using the virtual lab, seven students engaged for 30 to 60 minutes, and three students spent more than 60 minutes. The distribution suggests that most students dedicated a moderate amount of time to virtual lab activities, typically ranging from half to an hour, reflecting a balanced level of engagement.

Table 1. Student preparation time using VL-MN in class

Time spent	Student number
Less than 30minutes	6
Between 30 and 60 minutes	7
More than 60 minutes	3

Table 2. Student Exploration time using VL-MN after class

Time spent	Student number
Less than 30minutes	2
Between 30 and 60 minutes	5
More than 60 minutes	2

Table II summarizes the independent use of the virtual lab by students outside of scheduled sessions. Of the 16 students, nine (56%) reported additional engagement. Two students spent less than 30 minutes, five spent 30–60 minutes, and two spent more than 60 minutes exploring the platform. These results indicate that more than half of the cohort participated in voluntary use of the VL-MN, suggesting continued interest and self-directed learning beyond formal instructional activities.

Moreover, the student engagement heatmap (Fig. 5) revealed distinct patterns of engagement with the virtual lab over the two semesters. In addition to the two lab sessions organized as part of the course schedule (red arrow in Fig. 5), the student' exploration was distributed throughout the two semesters. Analysis of time-of-day activity showed that students predominantly accessed the lab during late afternoons and evenings, with peak usage between 20:00 and 23:00, while mornings and early afternoons exhibited lower activity. These patterns align with the survey responses, indicating that the students appreciated the flexibility to practice at their own pace. Overall, the data indicate that the virtual lab effectively supported self-directed learning and enhanced motivation by allowing repeated interaction, additional practice, and further exploration outside of scheduled lab hours.

5 Discussion

The findings of this study suggest that the Virtual Lab for Pneumatic Module (VL-MN) is an effective pre-lab tool that supports student engagement, motivation, and perceived learning. Both survey responses and interaction data indicate that the students were generally motivated by the virtual lab experience and appreciated the opportunity to connect theoretical knowledge with practical applications. The majority of the students reported an increase in interest in the subject after using the VL-MN, with motivation often linked to experiential learning elements, such as interactive simulations and the ability to practice procedures in a risk-free environment.

In terms of perceived learning effectiveness, the students highlighted that the VL-MN helped them develop both procedural and conceptual understanding. Repeated practice with virtual components allowed students to familiarize themselves with experimental setups, circuit assembly, and pneumatic analysis, preparing them for subsequent physical lab sessions. Importantly, some students also reported gains in higher-order skills, such as critical thinking and problem-solving, suggesting that the VL-MN not only reinforces technical competence but also supports broader cognitive development. These results are consistent with previous research that indicates that virtual laboratories can foster meaningful cognitive processing in STEM education [7] [9].

The interaction data further corroborates the survey findings, demonstrating sustained and self-directed engagement over time. Peaks in usage during late afternoons and evenings, combined with consistent interaction throughout the two semesters, indicate that the students leveraged the flexibility of the virtual lab to practice according to their own schedules. Such patterns reinforce the notion that virtual labs can extend learning beyond scheduled class times, allowing continuous self-paced exploration of theoretical concepts. These observations align with experiential and constructivist learning theories, which emphasize active engagement and reflection as key mechanisms for effective learning.

In terms of the challenges students face, only usability challenges were noted. Some students encountered technical difficulties, including system freezes, complicated cable connections, and challenges in mapping symbolic representations to physical components. These challenges can be addressed by improving user guidance, clearer visual aids, and technical refinements.

In addition, students' perspectives on integrating virtual and physical labs underscore the potential for blended learning models. Many suggested the sequential or concurrent use of both types of labs to reinforce concepts and provide real-world context. The virtual lab's capacity to offer risk-free experimentation, design rehearsal, and anytime accessibility supports its role as a complementary tool in engineering education. These findings suggest that careful structuring of blended learning experiences, combining the benefits of virtual labs with hands-on lab exposure, may optimize both engagement and skill acquisition.

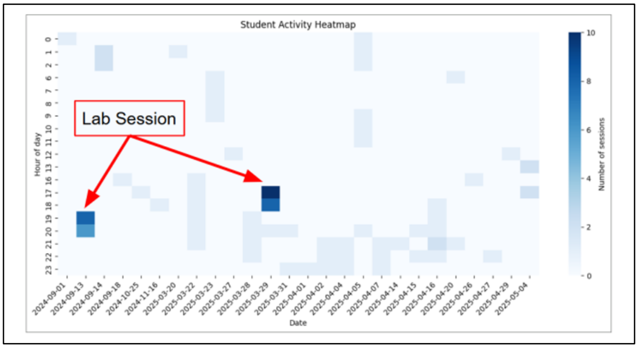


Fig. 5. Student engagement heatmap over two semesters.

6 Conclusion and Future Work

This study demonstrates that the Virtual Lab for the Pneumatic Module (VL-MN) is an effective pre-lab tool that enhances student engagement, motivation, and perceived learning in engineering education. Survey responses and interaction data indicate that students benefited from connecting theoretical knowledge with practical applications through interactive, risk-free simulations. The VL-MN supported the development of both procedural and conceptual understanding, familiarizing students with experimental setups, circuit assembly, and pneumatic analysis. Although minor usability challenges were noted, these can be addressed through improved guidance, clearer visual aids, and technical enhancements. The students also highlighted the advantages of integrating virtual and physical labs within a blended learning model, suggesting that sequential or concurrent use can reinforce concepts and provide practical context.

The findings further show that 56% of the students engaged in the virtual lab in a self-directed and flexible manner, extending learning beyond scheduled class times and reinforcing the value of experiential and constructivist approaches.

Overall, the results suggest that well-designed virtual labs, when combined with hands-on laboratory experiences, may optimize learning outcomes, improve motivation, and support active, self-paced engagement in engineering and mechatronics education.

Future work will focus on expanding the VL-MN to additional modules, improving user guidance and visual aids, implementing technical enhancements, integrating adaptive feedback mechanisms to support individualized learning, and investigating the long-term effects on knowledge retention and the transfer of skills to real-world laboratory tasks.

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