FPGAS FOR LEARNING DIGITAL ELECTRONICS CONCEPTS

Nuria Novas[1], Rosa M. García[1], Francisco Portillo[1], Manuel Soler[1], Manuel Fernández-Ros[1], José A. Gázquez[1], Francisco Segura[2]

[1]University of Almeria, CIAMBITAL (SPAIN)
[2]University of Almeria (SPAIN)

Abstract

This article discusses the transformation of digital electronics education following the Covid-19 pandemic, highlighting the shift toward technology-based learning methods and active pedagogical approaches. As the pandemic has accelerated the adoption of online teaching systems, universities have invested in upgrading these systems to optimize resources. Digital electronics teaching has evolved to a more interactive and hands-on model, focused on collaborative and project-based learning, combined with simulators and digital design tools. It highlights the importance of preparing students for a technologically advanced working world, especially in the field of the Internet of Things, which has boosted the demand for skilled professionals in digital electronics. The article presents a detailed analysis of the methodology and results of teaching digital electronics in a subject taught in the third year of Industrial Electronics Engineering at the University of Almeria, incorporating sensors, actuators, and FPGA programming. Development projects are proposed using two platforms, one based on embedded systems with microprocessors like Arduino and the other on FPGA. Students select a platform and sensor to work with, allowing them to learn to program on platforms with substantial differences. According to statistics for the last six years, student performance improved with the transition from the traditional to the hybrid teaching mode, with a maximum success rate of 100% observed with the hybrid method in the 2022-23 academic year. The failure rate decreased, while absenteeism rates varied over the years. While there were initial challenges, including the time-consuming nature of converting courses to online formats and the significant efforts instructors require to adapt to available tools, the trend favors distance education to ensure continuity in disaster situations. However, approaches that integrate hands-on learning are needed. Digital electronics students must acquire key skills to become successful engineers, and educators employ interactive methods to enhance their knowledge and future job competitiveness. Despite the challenge, students support systems that reflect real labor market conditions.

Keywords: Digital Laboratory, Electronics, Engineering, FPGA.

1 INTRODUCTION

Since the Covid-19 pandemic, the world has been immersed in a change where technology provided the opportunity to solve many issues affected by social distancing. This paradigm shift reached training centers, where administrations, teachers, workers, and students had to adapt. But this change was not temporary, and many administrations have used it to improve the quality of their services. An example of this is Universities investing in developing online quality training systems. Today, with more time to analyze the advantages and disadvantages of these systems [1], they are being updated to optimize their resources.

All this change was only achieved with the right technology. In the last two decades, technical education in engineering has changed, closing the gap between traditional teaching based on conventional textbooks to the current one where digital laboratories are immersed in the teaching-learning process without sacrificing the basic theories and principles [2]. In the last decade, engineering students have been trained differently, with the increasing use of online digital laboratories [1], online education [3], and attempts to bring teaching closer to the world of work.

In addition, different active teaching-learning methodologies are applied [4]. Traditionally, students were passive listeners in most theoretical classes, where they mostly came to class unprepared and dedicated themselves to listening and taking notes. This teaching system needs more interaction between the teachers and students. Interactions are positive for academic success. Active participation in the classroom makes them more cognitively engaged, and they can better acquire the knowledge and skills specific to their studies [5]. The novel approaches to the teaching process are more focused on the student. The teacher is a guide in their learning process [4].

Digital electronics teaching has benefited from the project-based learning approach, where students apply theoretical concepts in solving practical problems [6]. Together with collaborative learning, where teamwork and collaboration among students foster an active and participatory learning environment, issues related to digital electronics can be discussed and solved [7]. To these methodologies must be added the integration of technology with simulators and design tools [8]. Using simulation software and electronic design tools allows students to experiment and visualize the behavior of digital circuits before implementing them using real hardware. With the help of platforms such as Arduino, Raspberry Pi, or Logic Gate Array (FPGA), the rapid implementation of digital circuits is facilitated, allowing students to develop interactive projects [9]. These considerations mean that teachers continuously update their teaching and implement curricular adaptations. Teaching updates are made for blended or distance learning, permanently adapting the content to a changing and highly technological world that requires constant transformation.

Digital electronics is one of the subjects that have most influenced technological changes, where the integration of electronic devices in everyday life has led to an increase in the demand for professionals trained in digital electronics to develop solutions in the Internet of Things (IoT) field. This technology is based on the ability of embedded devices to process and communicate in groups or autonomously, forming networks. The use of embedded systems in various industries, such as automotive, medical devices, and control systems, has generated the need to educate students on the principles of digital electronics applied to these systems. There is a wide variety of embedded devices, microcontroller-based, microprocessor-based, and FPGA-based, in addition to specific ones. Each has advantages and disadvantages depending on the application, associated with power consumption, memory, and processing capacity.

The acquisition of practical knowledge is essential in engineering. With this purpose, the subject of Digital Electronics taught in the third year of Industrial Electronic Engineering is intended to advance with technology, and students should be immersed in their future work with sufficient practical experience. Students must master correctly all the topics related to digital electronics [10]. This academic course is intended to link the knowledge of digital electronics with IoT using sensors and actuators. This subject is developed based on continuous and formative assessment through short tests, projects, and practical exercises. It provides constant feedback to students and helps them improve their understanding and apply the concepts of digital electronics effectively. Not to mention the assessment of skills and competencies acquired by students in digital electronics, such as circuit design, problem-solving, and teamwork skills, allows for a more comprehensive and performance-oriented evaluation. Digital electronics laboratories enable students to apply theoretical knowledge in practical environments, where they can build and test digital circuits physically and by using simulators. Increasingly integrated design projects are being introduced, allowing students to face digital electronics challenges, from designing simple circuits to implementing complex digital systems.

In a previous study, this research group partially introduced the FPGA application through an independent project based on a Finite State Machine (FSM) with hardware programming and using a determined device to validate the design [11]. The current study's applied methodology and improvements, such as considering incorporating different sensors in the project, are developed in detail. In addition, an exhaustive analysis of the academic results of the students who have studied this and previous methodologies for the same subject has been conducted.

2 METHODOLOGY

This work focuses on developing the practical concepts of the Digital Electronics course, which is compulsory for students in the third year of the Industrial Electronics Engineering degree, and optional for the other specialties of Industrial Engineering at the University of Almeria (UAL). The evolution of the methodology established in the practical part of this subject in the last six years is described in detail in Figure 1.

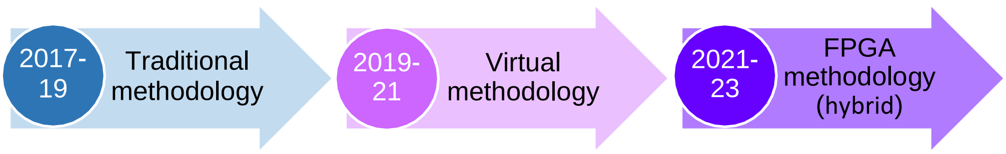

Figure 1. Timeline of the methodology developed in Digital Electronics

Until the 2019/20 academic year, the development of these concepts has had a fully traditional character. In this methodology, the course's practical component was based on dividing students into small groups (2 or 3 students), which were provided with scripts with practical activities. Initially, the students had to develop the solutions of the different activities theoretically according to the concepts acquired in the theoretical sessions. The theoretical resolution of simple exercises based on Boolean Algebra and Karnaugh maps is intended. Subsequently, these theoretical solutions had to be ratified by simulating the problems using a simulation program of digital components, such as logic gates and some basic TTL (Transistor-Transistor Logic) devices. After the correct simulation process, the circuits that met the specifications were implemented in a physical environment in the laboratory using instruments such as oscilloscopes or logic analyzers. The assembly of such circuits allows assessing the functionality of the circuits using discrete components such as logic gates or very low integration devices, such as 4-bit adders, 8-to-1 multiplexers, or sequential circuits. All the theoretical, simulated, and derived results of the assemblies were delivered in paper format or by e-mail to the professor in charge of the practical part of the course.

The 2019/2020 academic year was characterized by the development of a global pandemic, Covid-19, which caused a notable change in the methodology carried out so far in the practical activities to be developed by the students. The conditions of home confinement made it necessary to eliminate the assembly or physical implementation of the circuits in the laboratory. This part was replaced by a virtual performance through virtual environments of greater complexity and precision. The same designs of the classical approach were conducted but transferred to the exclusive use of online software tools. The Blackboard platform was the main means of communication with the students, allowing the consultation of multiple information about the simulation programs, the delivery of reports, the evaluation, and the resolution of doubts, among other applications. The learning of software tools and interactive simulation capabilities offer students another approach to consolidate the contents explained in the theoretical sessions, so this methodology was maintained during the 2020/21 course. These tools favor autonomous learning, which is fundamental in the university stage, so after the pandemic, we tried to integrate these tools to develop the subject.

During the 2021/2022 academic year and thanks to the development of the teaching innovation project, "Relevant Methodology for Comprehensive Learning of Digital Electronics at a Commercial Level," the methodology of the practical part of the course was modified again. The graphical circuit simulation tools used in the course allow their translation into models that can be incorporated into programmable hardware such as FPGA systems. An FPGA system is a complex programmable integrated digital circuit composed of input/output ports and configurable logic blocks whose functionality and interconnectivity can be programmed (Figure 2).

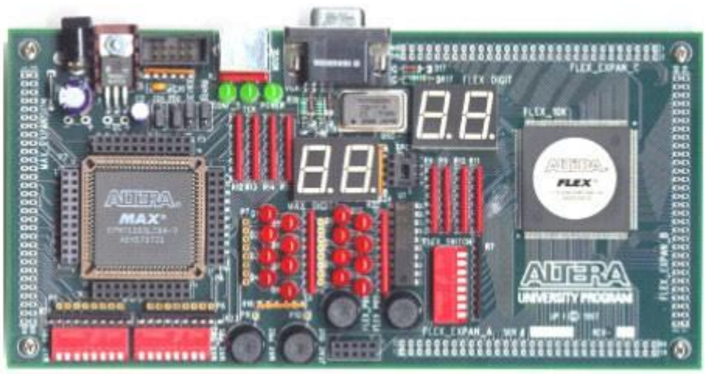

Figure 2. Altera UP2 Hardware Board.

The methodological innovation developed lies in letting students know that virtual tools are not only important for the simulation of problems. Still, it can also be used as physical implementation, thus establishing the last facet of current digital design. It is intended to evolve in complexity by incorporating hardware programming languages that differ from what students have analyzed in the programming subjects of the curriculums. This approach places the student in a position close to the labor market and introduces them to the advanced development of microelectronic systems.

To include these modifications, the practical sessions of the course were restructured, leaving half of the sessions for the simulation of the circuits and their assembly as in previous years. For the rest, a new methodology was introduced that can be subdivided into two stages:

1 In the first stage, emphasis will be placed on becoming familiar with the devices and hardware description languages of the designs made with the previous approaches. Initially, the characteristics and specifications of the device to be used must be known. Considerations related to the type of unit for signal processing, the additional hardware present (sensors, actuators, etc.), or the interconnection and operating characteristics are determined. These include power supply, input, and output ports or communication modes. A process of information search should be established regarding the software used for programming the system, as well as examples or demonstrations that allow the operation of the different sensors that it presents or the use of the appropriate libraries. It is helpful to establish small modifications in the examples to determine the variations in the system and if enough has been learned about the system to determine its functionality.

2 In the second stage, it is intended to establish the design of an own example where different sensors or utilities of the provided system are used. The errors that arise during operation must be set, trying to correct them with the learning acquired so far and reprogramming the system until their complete elimination.

After completing this stage, we move on to assemblies that combine the two parts of digital design, the combinational and the sequential. The practical sessions are focused on a collaborative and meaningful learning methodology formed by two students. The finalization of the sessions has significant importance, and it unites all the knowledge of the subject in a single design favoring holistic expertise and implementing these systems in the commercial world today.

Regarding the evaluation, a continuous system is proposed where the students present the results of their work in groups of 2, scaling up in difficulty. The final grade is not cumulative. If the student has been solving the mistakes they have been making, the grade of the deliverables will be fine. This allows the student not to focus on the grade but to learn from the mistakes they may have made. A final practical exercise is also proposed as an individual evaluation test, consisting of a modification of the project presented by each group. Due to the experience obtained during the pandemic, this working group considers it fundamental to individualize the final grades. Finally, there is a practical exam in which the students must demonstrate what they have learned, answering some theoretical and other questions about what they have done in the practical sessions.

The current academic year 2022/23, the established practice methodology has been continued and improved to optimize student learning. As a new initiative and using the previous years' experience, different sensors and actuators have been introduced, as well as more advanced examples, to understand their operation on the board more visually as part of the FPGA. This allows the student to experiment with IoT technology, where sensors and actuators are managed from FPGA-based systems as an alternative to microcontroller or microprocessor-based systems.

3 RESULTS AND DISCUSSION

Students' performance has been depicted in Figure 3 to analyze the correlation between the different methodologies. The data spans six academic years and captures a transition in learning modes from traditional to virtual and hybrid. This reflects the adaptation of educational strategies due to the COVID-19 pandemic.

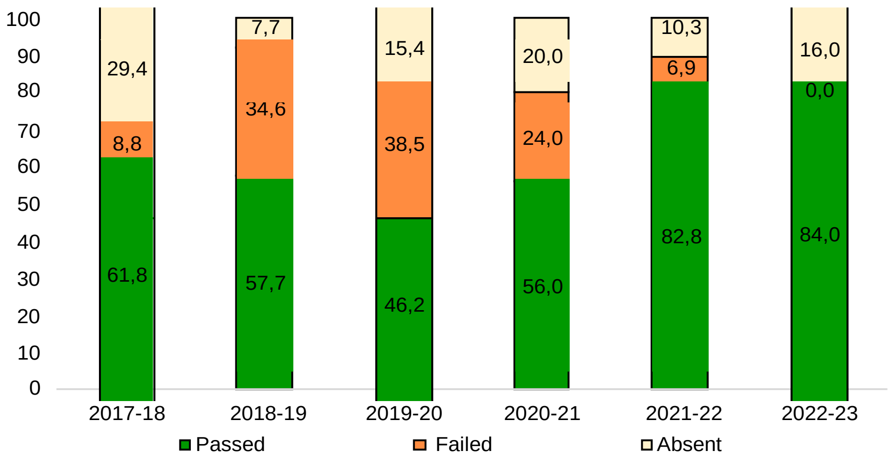

Figure 3. Academic results of practices (in percentage) in the last six years.

It can observe several trends and key points:

- Improvement in performance with hybrid mode: the hybrid learning mode significantly improves student performance. The pass rate is the highest in the last two years (82.8% and 84.0%), and the success rate reaches its peak at 100% in the 2022-23 academic year. This suggests the hybrid model may be more effective in this learning context.
- Decrease in failure rate: the failure rate declined over the years, especially in the hybrid mode, where it dropped dramatically to 6.9% in the 2021-22 academic year and to 0.0% in the 2022-23 academic year. This suggests that students might benefit from the flexibility and resources the hybrid mode provides.
- Variable absenteeism rates: the absenteeism rates fluctuate. In the classic mode, there was a high absenteeism rate in the 2017-18 academic year, which dramatically reducing in the 2018-19 academic year. In the virtual mode, absenteeism increased in the second year of the pandemic. In the hybrid mode, there is a slight increase in absenteeism in the second year. Several factors, including engagement levels or the convenience of the learning mode, could influence this.
- Virtual mode analysis: When the learning mode switched to virtual in the 2019-20 academic year due to the pandemic, the pass rate decreased compared to the previous year. However, in the next year, there was an improvement in the pass rate (56.0%). This could suggest an adaptation period required for students and teachers to adjust to the virtual learning mode. The shift to virtual learning brought hurdles educators and students had to overcome. While virtual learning can offer flexibility and make education more accessible for some, it is essential to address these challenges to ensure that students can benefit from this learning mode. Institutions and educators should work towards developing strategies and support systems that help mitigate these challenges and facilitate effective learning in a virtual environment.

Table 1 presents data from the last six academic years on the success rate of practices (percentage of students who passed compared to those that took the exam). Data shows a clear upward trend in the success rate when the teaching methodology transitioned from classic to hybrid.

The transition from classic to virtual methodology in the 2019-20 academic year shows a dip in the success rate, which could be attributed to the sudden shift and the challenges associated with adapting to online learning. However, in the 2020-21 academic year, there was a notable improvement in the success rate in the virtual mode. This may indicate that students and educators adapted by developing new skills, finding effective tools, or adjusting their strategies to suit online learning better.

The hybrid methodology, particularly, is highly effective in ensuring student success. The success rate reaching 100% in the 2022-23 academic year is exceptional. This could be an indicator of an extremely effective hybrid methodology.

The number of students is stable but slightly decreases throughout the years. It needs to be clarified if this impacts the success rates, but smaller class sizes can allow for more personalized attention, which could contribute to higher success rates.

Table 1. The success rate of the past five years.

Academic year	***Methodology***	***Students***	***Success rate (%)***
2017-18	Classic	34	87.5
2018-19	Classic	26	62.5
2019-20	Virtual	26	54.5
2020-21	Virtual	25	70.0
2021-22	Hybrid	29	92.3
2022-23	Hybrid	25	100.0

Table 2 displays the students’ grades. The data suggest improved grades in the later years, particularly in the hybrid methodology years. This correlates with the success rates discussed earlier and suggests that the teaching methodologies or other factors positively impact student performance.

Table 2. Percentage of students that achieved each grade.

Grades	2017-18 (%)	2018-19 (%)	2019-20 (%)	2020-21 (%)	2021-22 (%)	2022-23 (%)
A+ (10)	0.0	0.0	0.0	0.0	0.0	0.0
A (9-9.99)	2.9	0.0	0.0	0.0	20.7	20.0
B (7-8.99)	11.8	19.2	34.6	32.0	34.5	24.0
C (5-6.99)	47.1	38.5	11.5	24.0	27.6	40.0
F (0-4.99)	8.8	34.6	38.5	24.0	6.9	0.0
Absent	29.4	7.7	15.4	20.0	10.3	16.0

There is a widespread tendency to prefer distance education methods to ensure the sustainability of educational tasks in natural disasters, where formal education cannot occur (pandemics, floods, earthquakes, snowfalls, and storms, among others). Effective transfer of theoretical knowledge can be accomplished in these activities. However, practical teaching activities can be interrupted, so it is interesting to establish projects in which the acquired knowledge is integrated into the labor market requirements.

4 CONCLUSIONS

Students in the digital electronics course need to acquire some essential skills that will make them successful engineers. Teachers continuously try to improve students' knowledge using active methods and make them competitive in their future work. New interactive learning methodologies allow students to acquire extraordinarily complex knowledge without the effort associated with rote learning. The essence is to relate new knowledge to existing expertise in their cognitive structure. Through practical development, the consolidation of fundamental concepts is enhanced.

In this work, we have described and analyzed the implementation of three methodologies, the traditional, the virtual, and the hybrid model between both. It has been found that the second years of the methodology change have a higher success rate. In the virtual model, the success rate has gone from 54.5% to 70%; in the hybrid model, the change has been from 92.3% to 100%. The evolution of this rate from the traditional model (54.5%) to the hybrid model (100%) can also be observed gradually. Since a methodological change is not successful if applied directly, it requires time for correct implementation and analysis of improvements and adaptations.

The percentage of students who have passed the practices has improved notably since the implementation of the virtual model, developed during the year of the Covid-19 pandemic (46.2%), to the current course where the hybrid model has been perfected (84%). The percentage of students who have yet to pass the course has also decreased from 38.5% to 0%.

All the data analyzed confirm that despite the challenge posed in recent years by the hybrid learning model, with the inclusion of projects with the FPGA and face-to-face support classes, students opt for the inclusion of systems that bring them closer to the real specifications of the labor market. It can be concluded that although the virtual model allows distance learning, which guarantees the continuity of the learning process during exceptional situations, engineering students need practical face-to-face support to acquire their skills and competencies properly.

The teaching staff must constantly strive to find alternative learning methods to the traditional ones, although such a change requires time and effort from all members involved. To this end, it is proposed to establish another initiative of development projects in subsequent courses where another platform is provided based on embedded systems with microprocessors (from the Arduino family). Students must select a proposal with a microcontroller or FPGA and are supplied with a sensor to interact with it. This initiative arises from adapting to the technology and assuming the need to learn to program on different platforms with substantial differences since microcontroller-based technologies are oriented to programming for device control. FPGA-based ones are introduced to hardware configuration. It is important to remember that trends, methodologies, technology integration, evaluation, and practical experiences applied to digital electronics content are continuously evolving today.

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