DEVELOPMENT OF THE DIGITAL SYSTEMS UNIT IN AN ELECTRONICS ENGINEERING CDIO CURRICULUM

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ABSTRACT

The electronics engineering program at Javeriana University has been renovated following the guidelines of the CDIO philosophy. As a result of this process, a new curriculum is being implemented based on the guidelines of the twelve CDIO standards. The new curricular structure is organized by learning units (physics, mathematics, signals, analog systems, digital systems and CDIO projects), which are articulated and focused on the development of general competencies for the professional development of electronics engineering. This paper describes the Digital Systems Unit, aiming to train students in the construction of electronic systems that solve context problems using digital devices. The challenge of the unit is to emphasize the methodology beyond the devices, in such a way that in the future the engineers can provide solutions adapted to the accelerated changes of the technology. Our proposal begins with a description of the technological advancement of digital devices as a challenge in the teaching-learning processes of electronics engineering. Then we present the general competencies and the skills of the construction of systems that are integrated into the unit. Subsequently, the proposed courses, the integrated competencies and their thematic contents are described. At the end, a special emphasis is placed on the systemic vision of the courses and their alignment with other units of the new curriculum.

KEYWORDS

CDIO implementation, systemic thinking, Standards: 2

INTRODUCTION

In this document, we present the pedagogical proposal for the development of the Digital Systems Unit in the electronics engineering CDIO curriculum at Javeriana University in Bogotá, Colombia. In order to develop this field of knowledge and its corresponding courses, we have considered not only the modern technological tools, but more importantly the development of the necessary skills that the students require to solve engineering problems through the usage of digital devices, such as FPGAs, microcontrollers and processors. This perspective in the design of the unit aims to decouple the courses from the constant evolution of the technological tools, achieving a stable curriculum that does not depend on a specific set of tools, and remains applicable and valid for future students.

With that in mind, the fundamental element in the design and implementation of the Digital Systems Unit is the pedagogical methodology (the philosophy) that the professors and students follow to solve the problems, and the technological tool lies in the background as a support component to make feasible the final implementations. It becomes natural for this kind of courses to integrate two specific CDIO skills: formulation and identification of problems, and systemic thinking. These CDIO skills are aligned with the disciplinary skills across all of the digital systems courses (Crawley et al. 2007).

The Digital Systems Unit includes three courses as part of the core component of the curriculum and more than ten courses within a shared emphasis with the Signals Unit, where the students develop a holistic thinking towards the solution of problems, and also learn to use the right elements (block, flow and state diagrams, network of events, etc.) to describe the solution to a system (SLD – System Level Description) considering functional and non-functional requirements. This shared emphasis is the result of a common effort to build not only the concepts and skills on digital systems, but also to have an attractive context of implementation (signal processing) and to stay close to the industry requirements.

Although the design and implementation of the proposed Digital Systems Unit considers the aforementioned CDIO skills as the fundamental building blocks, the courses also integrate the usage of state-of-the-art technological tools (development boards, software development kits, integrated development environments, etc.) to implement hardware based (FPGA) and software based (microcontrollers and processors) solutions. With this philosophy, the students learn a way to come up with a solution to a problem, not just which button they must click to compile a project, and moreover, these students become engineers that can easily adapt to the fast-evolving technologies that the market provides (Al-Atabi, M. 2013).

In this paper, we first present the set of skills that an electronics engineers must develop to solve problems based on digital systems devices. Later, we describe the proposed (and implemented) core courses, focusing on the concepts and skills that are developed across the Digital Systems Unit. We finish the document showing how the proposed unit aligns with other units from the electronics engineering curriculum, and also presenting the implementation results achieved so far.

The rest of the paper is organized as follows: Section 2 defines the problem; Section 3 presents the engineering skills to be developed in the Digital Systems Unit; Section 4 details the proposed Digital Systems Unit; Section 5 explains how all units in the curriculum are aligned; Section 6 presents our preliminary results; and Section 7 concludes the paper.

PROBLEM STATEMENT

The Digital Systems Unit has a particular difference from other areas of knowledge related to electronics engineering: while some areas, such as controls, analog electronics and signal processing, have a large theoretical component that does not change much from one year to another, the design and implementation of a solution based on a digital system depend strongly on the development tools and the particular architecture (microcontroller, processor, FPGA, etc.) of the selected device (United Nations, 2016). The work by Bruce et al. (2013) presented a methodology to teach programming concepts while using low-cost embedded devices, but when the authors compiled different courses with this approach, they realized that most of them were oriented to simply teach and use a set of technological tools, for instance an integrated development environment (IDE) to generate code for a microcontroller. As seen in Table 1, there is a large variety of architectures and IDEs that could be used for a digital systems courses (both software- and hardware-oriented), but which one would you pick?

Table 1. Commonly Used Architectures and IDE for Digital Devices.

Manufacturer	Architectures	IDEs
Microchip	8-bit PIC, PIC24, dsPIC, PIC32	MPLAB-X
Atmel *(owned by Microchip)*	AVR, ARM, SAM	Atmel Studio
Texas Instruments	MSP430, C28x, ARM	Code Composer Studio
NXP-Freescale	S08, S12, HC12, HC16, ARM, i.MX, PowerPC	MCUXpresso
Xilinx	Spartan, Virtex, Kintex, Artix, CoolRunner-II	Vivado, ISE, XPS
Altera	Stratix, Arria, Cyclone, MAX10	SDK-OpenCL, Nios II ES, SoC EDS

Unfortunately, this configures a scenario where some curriculums are designed around the technologies and not the methodology to design and implement a solution from a systemic point of view, training engineers that will not be able to tackle a problem if they are not accustomed to the available technology. Considering this, it is necessary to decouple the courses from the constant evolution of the technological tools, achieving a stable curriculum that remains applicable and valid for future students (Crawley et al. 2014).

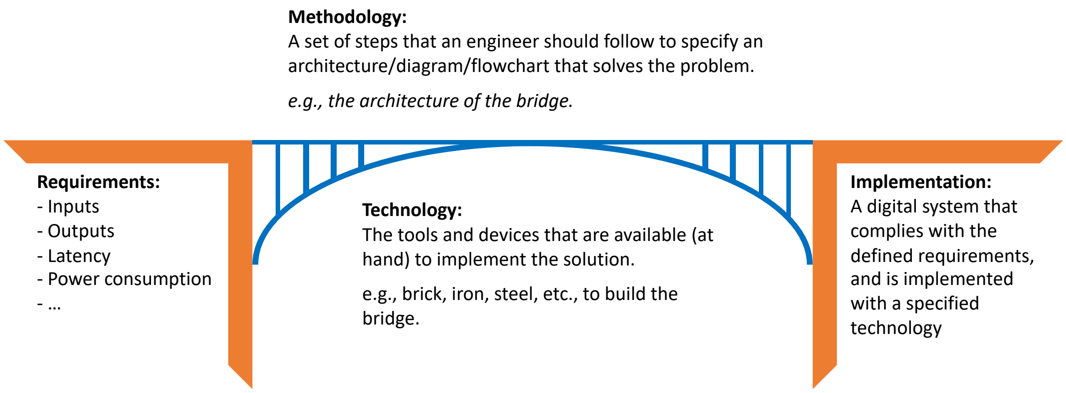

Figure 1. A bridge as a solution for an engineering problem.

As it has already been presented, the fundamental component of this approach is the pedagogical methodology that the professors and students follow to solve a problem, considering a set of requirements to propose a solution (architecture) based on the devices at hand. We could exemplify this through the metaphor presented in Figure 1, which considers 4 main components:

- **Requirements:** the set of desired characteristics that will define the specifications of the final implementation. This is the initial enter point for our students (and future engineers). For the case of a digital system, we normally take into account number/type of inputs/outputs, latency (speed), power consumption, among others
- **Methodology:** a set of steps that an engineer should follow to specify an architecture/diagram/flowchart that its implementation would solve the problem, fulfilling the defined requirements. In this metaphor, the output of this component would be the kind of bridge (architecture) that, depending on the specific landscape (requirements), could be constructed (implementation). Let us state again that at this point the way we will *build* the bridge (technology) is not relevant.
- **Technology:** the materials at hand to implement the solution (IDEs and devices). Depending on other considerations, such as availability and cost, we could decide to build our bridge using bricks, iron, concrete, steel, etc. Whichever the material is, in general, the defined architecture will remain the same.
- **Implementation:** the final digital-based system that complies with the desired requirements and is implemented following the defined architecture and available materials.

DESIRED SKILLS FOR DIGITAL ELECTRONICS ENGINEERS

The technological advances produced by the industry, such as microprocessors and FPGAs, are used in different applications, e.g., automotive, communications, military, medical, and aerospace, and since each of these applications has very diverse requirements, the solution normally requires a heterogeneous integration of technologies. Hence, the digital electronics engineers of the future require not only the fundamental concepts, but a set of skills to be flexible enough to adapt themselves to these fast-evolving markets.

The new CDIO curriculum of the electronics engineering program at Javeriana University is based on the CDIO Syllabus (Crawley et al., 2011), and for our particular case, the Digital Systems Unit courses are responsible for working and evaluating: *the current state knowledge skills of the world of engineering* (2.5.4), *social and external context* (4.1), *conception and application of engineering to systems* (4.3), *design* (4.4), *implementation* (4.5), *written, graphic and oral communication* (3.2). These three courses work all these competences, and its intensity is increased as the student progresses through the curriculum. Each course analyzes the current state of the world of engineering, and later on, identifies several problems from real scenarios. The Electronics Engineering Department invites different stakeholders to help identify these problems: companies from diverse economical markets in Colombia, research institutions, and social-oriented non-governmental organizations. The study of these problems not only takes into consideration the technical requirements, but also the social impact of the developed solution and the legal regulations of the country.

The electronics engineering program at Javeriana University implemented the ABET Student Outcomes in order to integrate and simplify skills and attitudes from CDIO Syllabus. In that sense, each CDIO competence is mapped with the following student outcomes:

a) an ability to apply knowledge of mathematics, science, and engineering
b) an ability to design and conduct experiments, as well as to analyze and interpret data
c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
d) an ability to function on multidisciplinary teams
e) an ability to identify, formulate, and solve engineering problems
f) an understanding of professional and ethical responsibility
g) an ability to communicate effectively
h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
i) a recognition of the need for, and an ability to engage in life-long learning
j) a knowledge of contemporary issues
k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

During the design and implementation, different stages must be considered depending on the selected approach (hardware, software or hybrid). The students tackle this process in a concurrent fashion, considering the functional and non-functional requirements, the building blocks (and their interconnections), time-diagrams and events, the software development kits, the development boards, among others. In this way, after conceiving, designing and implementing solutions using digital-based devices, the student develops the necessary skills to tackle and solve problems from diverse contexts. The students also develop oral, graphical and written communication skills, necessary to present the problem and the solution, according to the audience.

DIGITAL SYSTEMS UNIT PROPOSAL

The electronics engineering curriculum was conceived to incrementally build skills, but always considering the product-oriented development of projects, even from the first year at the university. However, this goal raises new challenges in order to align the disciplinary contents worked in each course of the curriculum.

During their first year, the students have been exposed to a problem-oriented methodology from a systemic perspective, through the CDIO methodology of product construction, while initially utilizing basic technologies that are selected because of their short learning curve. At this point the students are not asked to fully understand how the devices operate but just to learn how to use them correctly (e.g., Arduino-based development boards).

Since the beginning, our study program offers mathematical modeling tools and the understanding of real physical phenomena, and the interaction with these phenomena occurs through the acquisition and processing cycle of the related signals (STEM). At the same time, the curriculum develops the knowledge and tools that are specific to the electronics engineering career, and in particular, we pay special attention to the development of the Digital Systems Unit since it is considered a transversal area for the design and implementation of engineering solutions.

Proposed Methodology

The skills associated with the Digital Systems Unit are defined from analysing a context, in which the student states the problem and proposes solutions based on the utilization of digital devices. This solution proposal implies a first dimensioning of the system and its functionalities, as well as the generation of recommendations for the implementation stage, hardware-, software- or hybrid-based (Fai, 2011). The courses that are part of the Digital Systems Unit are focused on the conceiving, designing and implementing cycle. During the conceiving stage, the student fixes the requirements and goals of the solution, defining the architecture and its specification. It is here where the students develop a holistic thinking towards the solution of problems, and also learn to use the right elements (block, flow and state diagrams, network of events, etc.) to represent the solution (generic).

Depending on a set of performance metrics (latency, power consumption, area, etc.), design time, implementation costs and some predefined priorities, the student selects the technology (HW, SW or hybrid) that better fulfils these metrics. After selecting the technology, the students move into the dimensioning (memory, interfaces, peripherals, etc.) and implementation of the solution (flow diagram), considering the particular details of the selected technology.

Although the design and implementation of the proposed Digital Systems Unit considers the aforementioned CDIO skills as the fundamental building blocks, the courses also integrate the usage of state-of-the-art technological tools (development boards, software development kits, IDEs, etc.). With this philosophy, the students learn a way to come up with a solution to a problem, not just which button they must click to compile a project, and moreover, these students become engineers that can easily adapt to the fast-evolving technologies that the market provides. Table 2 summarizes how the desired CDIO skills are developed through the Digital Systems Unit (Jamison et al. 2014).

Courses Implementation

We propose a systemic perspective for the Digital Systems Unit, including an innovative organization of the courses, with respect to the traditional curricula in which the teaching of disciplinary concepts of the field begins with an introduction to the logical circuits, followed by courses related to the architecture of a processor and the solutions based on such a device. The above-mentioned organization of the courses can be explained by the fact that in the traditional curricula the student first learns about the devices and then proposes solutions using them as tools. The contents of the courses are aligned with the current technology and change according to the advances of the same technologies. In addition, the courses are offered in the last years of the programs.

Table 2. Development of the Desired Skills throughout the Digital Systems Unit

Analytic Reasoning and Problem Solving	The courses of the area focus on working on *Problem Identification and Formulation* in the context of the application of digital systems. Problem analysis includes modeling using functional behaviors and quantitative considerations related with performance metrics (speed, consumption, area). At the end of each course, students are able to develop generalizations of analytical solutions and to propose recommendations about technology, and improvements in the problem-solving process.
	(2.1.1), (2.1.2), (2.1.3) (2.1.5)
Ethics, Equity and other Responsibilities	The digital systems area promotes the awareness about the world of engineering, technology advances and innovations, and their social and technical impact. This goal is achieved by allowing students to acquire familiarity with current practices/technology in engineering. The courses use the link between engineering theory and practice to develop those skills.
	(2.5.4)
Communications	These skills are developed from the perspective of a product development context. Technical writing skills, formal technical drawings and oral presentations are required to link different components in the stages of conception, design and implementation of a digital system.
	(3.2.3), (3.2.5), (3.2.6)
External, Societal and Environmental Context	The role and responsibility of engineers are developed using real contextual problems from a global perspective. These problems highlight the objective of the engineering profession as the achievement of a society and a sustainable future. A real context analysis involves students to understand the impact of engineering on environmental, social, knowledge and economic systems in a modern culture.
	(4.1.1), (4.1.2), (4.1.6)
Conceiving, System Engineering and Management	Based on system goals and requirements of a solution, the courses of the digital systems area aim to analyze the system performance metrics, requirement completeness and their consistency. Functions and behavioral specifications allow to incorporate appropriate levels of technology to fill all the functional characteristics stablish by high-level architectural structures. Simulation tools and design methodologies are given to the students to select appropriate technologies according to the requirements.
	(4.3.1), (4.3.2), (4.3.3)
Designing	The courses are oriented to engage students into proposing alternatives in the design to achieve the desired specifications for each component derived from system level goals. The course methodology includes the phases of conceptual, preliminary and detailed design and some experimental prototypes are developed. Students are expected to strengthen problem solving, inquiry, system thinking, creative and critical thinking.
	(4.4.1), (4.4.2), (4.4.3)
Implementing	The implementing process is focused on breaking down of high-level components into sub-modules (including algorithms, data structures and hardware elements). The courses include different hardware description and programming languages, and specific methodologies for the integration of software, hardware, sensor, actuators. Finally, test, verification, validation and certification concepts are included.
	(4.5.2), (4.5.3), (4.5.4), (4.5.5)

Our proposal is characterized by three approaches that contrast with the traditional curricula. First of all, training in the field of digital electronics begins in the second year of the curriculum.

Second, the unit is designed to introduce the student into methodological concepts for problem solving through a CDIO cycle, even before understanding the particular characteristics of the devices. Thirdly, our courses are based on training in the area that is independent of technology and allows adapting to changes and evolutions of the same. Figure 2 shows the new digital systems courses and compares them to the old curriculum.

Semester 1	Semester 2	Semester 3	Semester 4	Semester 5	Semester 6	Semester 7	Semester 8	Semester 9	Semester 10 10
Old Curriculum									
					Logic Circuits	Digital Design		Computer Architecture	
New CDIO-based Curriculum									
		System Design with Processors	Digital Systems Design	Computer Organization					

Figure 2. A comparison between our old and new CDIO-based curriculum.

The curricular structure of the Digital Systems Unit has three compulsory courses that belong to the fundamental training core: Systems Design with Processors, Digital Systems Design, and Computer Organization. The course System Design with Processors course is based on the CDIO cycle emphasizing the design methodology with processors and microcontrollers. Learning outcomes of this course include, among other concepts, requirements in engineering, specification definition and "top-down" methodologies at different levels of abstraction. Students learn about the general architecture of microcontrollers to be able to define solutions.

In the second course, Digital Systems Design, the students continue to develop in the methodology CDIO, however the requirements of the systems to develop imply that the solutions are custom-made using dedicated hardware on programmable logical devices (FPGA). The use of these tools implies that the student understands the organization of these devices from logical gates, registers, and state machines. Learning outcomes include all concepts of logical, combinatorial, and sequential design.

Finally, the third course Computer Organization, allows the students to develop the criterion of selection of devices, so they can choose between the processed solutions and the custom-made solutions. Students could also define a hybrid system that includes a combination of these devices. The learning outcomes are focused on understanding the processor architecture, and the different levels of abstraction related to the programming. These three courses include learning outcomes that integrate the competencies mentioned in Table 2. For example, communication skills are developed in the context of the generation of reports and design documents. Problem solving includes identification in a real context, the formulation by means of quantitative and qualitative analysis of variables that generate functional requirements. These requirements are the starting point in the process of building the system that gives solution to the problem using the CDIO methodology.

DIGITAL SYSTEMS UNIT ALIGNMENT WITH THE ELECTRONICS ENGINEERING CURRICULUM

From the perspective of the curricular structure, the Digital Systems Unit is integrated with the other units that are part of the program. To understand this alignment, we will describe the general organization of the electronics engineering curriculum. The curriculum has 160 academic credits and a duration of 5 years, organized in semi-annual periods. The fundamental core of training has 109 credits and the remaining credits include free-elective subjects and the emphasis of the program, developing 6 training units as shown in Figure 3.

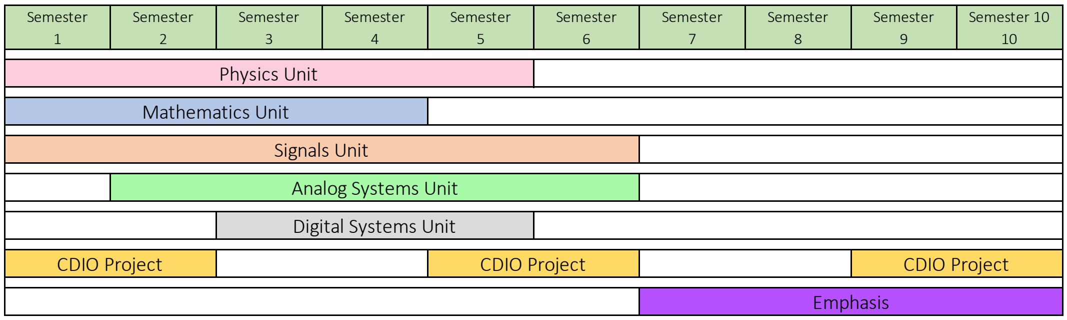

Figure 3. A representation of our 6 training units planned in the new curriculum.

The Physics Unit is in charge of developing the concepts, knowledge and competencies related to the phenomena of the world. These physical phenomena are those that the electronics engineer will sense, process and control. The most important general skill of this unit is the search and construction of knowledge. An electronics engineer “reads” the physical phenomena from signals, the same that adapts, processes and sends back to the world. The nature of these signals is diverse and complex. This complexity is modeled, simplified and adapted by means of mathematical tools, so that these phenomena can be understood and processed. Here lies the importance of the Mathematics Unit, which has the central competence of the formulation of problems. The Signals Unit is responsible for introducing the student to the concepts related to the characteristics of the signals, their complexity and the tools to transform them into other representations for processing.

With the skills and knowledge developed by the three units described, the student has knowledge of the world, can read it (sense), transform the signals into information and use it to take decisions that modify it. The tools used to make these processes belong to the Analog Systems Unit and the Digital Systems Unit. The Analog Systems Unit promotes the learning of circuit analysis tools and develops the entire line of work with analog devices in the context of systemic thinking and the holistic vision of solutions. At this point, the Digital Systems Unit is integrated as a field that develops the knowledge in the tools of digital electronics, but the basic skills are the design and implementation in the CDIO context.

As an integrating element, the program has a CDIO project unit, which articulates, in a design and construction experience, the knowledge, skills and competencies that the other five units develop. The program has three CDIO projects, in the first, third and fifth year. These projects seek to solve real contextual problems and to achieve this particular objective, the program has as allies different companies of the industry and research groups. The unit integrates general skills such as teamwork, communication, project management, and again, exposes the student to the CDIO cycle. Additionally, the project unit is in charge of developing competences related to techniques, disciplinary concepts, and advanced engineering tools that allow students to solve problems with requirements, constrains and standards from the real world. Programming is one of the most important disciplinary skills developed in the projects, beginning with the development of algorithmic and logical thinking, to later achieve a structured thinking.

As mentioned earlier, the electronics engineering curriculum includes emphases on different fields of the discipline. The program offers three lines of deepening: emphasis on Communications, Control and Energy, and Signals and Digital Processing. The latter is articulated between the Digital Systems and Signals Unit and aims to provide tools for signal processing in advanced contexts of application.

PRELIMINARY RESULTS

Due to its novelty, the alignment of the Digital Systems Unit with the rest of the curriculum has not yet been studied. During the first semester of 2018, the whole unit will be offered just for the second time. However, during the design of this new CDIO curriculum, we have had the chance to offer the three courses of the Digital Systems Unit, as part of the old curriculum, in order to test and validate the proposed methodologies.

Prematurely offering these courses allowed us to redesign some of our pedagogical strategies, since we were able to identify that the active participation of the students was key for achieving satisfactory results. We moved from a methodology based on contents transmission where the professor is the center of the classroom, to one focused on active learning, using strategies, such as, problem- and project-based learning, integrating experiences and collaboration. Some of the activities to achieve this were: role-playing, peer learning, oral presentations, lab practices, and comparison of designs (Forero et al., 2011).

The proposed methodology was positively accepted by the students, who stated that it is more interesting to tackle the theory by considering a context, since it is easier to remember when, how and why they applied them. These results constituted the guidelines to define the learning outcomes and the evaluation rubrics (Brodeur et al., 2005) for our three courses. Taking into consideration the length limitation of this paper, next we will only show the learning outcomes for the Digital Systems Design course:

Digital Systems Design Outcomes:

- Formulate a problem through logical description based on a requirement.
- Build a system model by using logical functions to describe inputs, outputs and their behavior in time.
- Interpret the instantaneous behavior of logical and arithmetic blocks.
- Describe the functional behavior of each of the components of the proposed architecture of a digital system.
- Use combinatorial and/or sequential circuits in the design of each of the architectural blocks.
- Determine a complete set of input/output combinations for the verification of the system.

And as an example, the rubric of the first learning outcome of the Digital Systems Design course is shown in Table 3.

From the CDIO Student Outcomes selected by the program, Outcome Performance Indicators were defined. These Indicators are more specific descriptions of CDIO Skills and for each Indicator, Performance Levels were defined as specific disciplinary abilities that the students are expected to attain. Between two and three levels of performance are attributed to each Outcome Indicator. To cover different levels, courses from different units and semesters were selected to carry out the assessment process.

Table 3. Rubric of the first learning outcome of the Digital Systems Design course

Formulate a problem through logical description based on a requirement			
Performance Indicator	*Less Acceptable Rating*	*Average Rating*	*Excellent rating*
Use logical connectors (conjunction, disjunction and negation).	Does not use logical connectors.	Use logical connectors, but the connectors are not consistent with the intension.	In sentences, use the connectors consistently with the intension.
Include variables in statements describing the system.	The variables used in the sentences do not correspond to the requirement.	The sentences used for the description include some of the variables that are part of the requirement.	The variables included in the description are related to the functionality of the system
Propose a description of the problem using the connectors and the variables.	It does not describe the problem using the connectors and variables for its formulation.	It describes a problem based on a requirement, but it does not relate the variables to the functionality of the system.	It describes the problem from a requirement and describes the functionality of the system.

CONCLUSIONS

A revision of the electronics engineering curriculum let us structure a Digital Systems Unit, focusing on promoting the development of abilities to conceive-design-implement systems in the context of digital electronic solutions. One of the main challenges of the construction of the unit is the effective alignment with other units (physics, mathematics, signals, analog systems and CDIO projects). The first implementations of the courses, have taught us in this respect, that for the validation of the integration of skills it is important to establish program evaluation models based on the measures of the student outcomes.

Currently, the evaluation model of the new curriculum is under construction and have as reference the quality assurance model based on ABET criteria of the old curriculum. This model facilitates the continuity in the development of competencies, allows to maintain the quality of the courses and guarantees the systemic perspective, that strengthens a methodological approach more than one adhered to the technology.

The evaluation and the assessment in the courses shows us evidence of the best pedagogical practices that engage students in the learning of unit. In this sense, special preference is given to active learning, project-based learning, laboratory practice, among other activities. Finally, the systemic perspective of unit has allowed students to recognize sufficient criteria and to manage a robust methodology to opt out for a technological solution, no matter how fast the digital electronic devices evolve. At this point, self-confidence and knowledge of the global and technological context is vital for the training processes.

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BIOGRAPHICAL INFORMATION

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