A Project-Based Learning Approach to Design Electronic Systems Curricula

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***Abstract*—This paper presents an approach to design Electronic Systems Curricula for making electronics more appealing to students. Since electronics is an important grounding for other disciplines (computer science, signal processing, and communications), this approach proposes the development of multidisciplinary projects using the project-based learning (PBL) strategy for increasing the attractiveness of the curriculum. The proposed curriculum structure consists of eight courses: four theoretical courses and four PBL courses (including a compulsory Master's thesis). In PBL courses, the students, working together in groups, develop multidisciplinary systems, which become progressively more complex. To address this complexity, the Department of Electronic Engineering has invested in the last five years in many resources for developing software tools and a common hardware. This curriculum has been evaluated successfully for the last four academic years: the students have increased their interest in electronics and have given the courses an average grade of more than 71% for all PBL course evaluations (data extracted from students surveys). The students have also acquired new skills and obtained very good academic results: the average grade was more than 74% for all PBL courses. An important result is that all students have developed more complex and sophisticated electronic systems, while considering that the results are worth the effort invested.**

***Index Terms*—Curriculum design, Electronic Systems Curricula, project-based learning, software and hardware tools for education.**

I. Introduction

GIVEN the role of electronics as a fundamental grounding for other disciplines, such as computer science, signal processing, and communications, the design of Electronic Systems Curricula must focus not only on the theoretical basis of electronic systems, but also on the application of electronics in such disciplines. This point of view is especially important in telecommunication engineering studies, a mixture of computer science, signal processing, communications, and electronic engineering. Promoting electronics as a grounding for other disciplines can be done by defining a new curriculum that includes practical courses (laboratories) in which the students develop whole systems involving multidisciplinary knowledge (not just in the areas of electronics).

In a multidisciplinary education context, project-based learning (PBL) [1] appears as one of the most interesting instructional strategies [2]. The PBL strategy [3], [4] tries to engage students in authentic real-world tasks to enhance learning [5]. Students, typically organized in groups, face open multidisciplinary projects with the instructor playing the role of facilitator or coach. Every team designs and implements a whole system with more than one possible approach, in an environment designed to simulate professional situations in which the students have to work with different kinds of knowledge. This practical scenario helps the students to understand the basis of electronics and its relevance as the basis for other disciplines. Thus, the students learn, for example, why the performance of a communication or signal processing system varies significantly depending on its electronic implementation.

PBL is a student-centered strategy that fosters student initiative and focuses the student on real-world, open-ended projects that can increase the motivation for most of them. These projects foster a wide range of abilities, not only those related to content knowledge or technical issues, but also practical skills [6] as follows.

- *Coping with incomplete or imprecise information:* Students must address the system requirements' definition and be better prepared for their professional development.
- *Self-regulation and commitment*: Students get more involved in the learning process because they must define their own specific objectives within the limits imposed by the general trends provided by the instructors of the course.
- *Cooperation and group work*: Students must organize themselves by dividing the workload among themselves and integrating the different parts developed by each student.
- *Interdisciplinary issues*: Complex problems involve several disciplines. In a lecture-centered course, the instructors can focus on a specific subject and minimize the effect of context through abstraction. In PBL, interdisciplinary issues are unavoidable yet beneficial: the student does not need to cope with much discouraging abstraction but with ordinary problems.

These practical skills are an important requirement from companies and industry. The Career Space Consortium states the following [7]:

> It is not sufficient just to learn about technical and other issues and pass exams; the techniques need to be used in real situations. This is particularly important to emphasize the connections between different aspects, to encourage a broad systems view and to illustrate the practical, technological and human constraints of solving real-world problems.

This paper addresses the use of PBL throughout different courses in the curriculum of an electronics engineer and learning

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to adapt the general PBL strategy to cope with the specific characteristics of each course in the curriculum.

In the literature, previous initiatives use PBL as the main learning strategy for curriculum design [8], [9]. In some cases, PBL is enhanced using multiple case studies [10] or using several miniprojects for improving assessment [11]. In the approach proposed in this paper, students must develop a set of multidisciplinary supervised projects, which become progressively more complex throughout several PBL courses that use a common hardware platform. The hypothesis being tested in this educational research is that the interest of students in electronics is increased by the proposed approach.

In the five-year process of designing the curriculum, the instructors from the Department of Electronic Engineering at the School of Telecommunication Engineering have worked consistently to develop better software tools [12]–[14] and hardware equipment [15] that have made the design and implementation of the curriculum possible. In this paper, a complete view of the Electronic Systems Curriculum is presented with a complete evaluation over four consecutive academic years.

The paper is organized as follows: Section II details the academic context and the curriculum structure. The learning resources (software tools and hardware equipment) are presented in Section III. Section IV describes the course-management and student-supervision tools. Finally, Section V discusses the evaluation results, and Section VI summarizes the main conclusions of the paper.

II. Proposal for an Electronic Systems Curriculum Based on PBL

The curriculum proposed in this paper is included in the telecommunication engineering studies. The curriculum is being taught by the Department of Electronic Engineering in the School of Telecommunication Engineering (ETSIT) at the Technical University of Madrid (UPM). The professors and instructors in the department teach both undergraduate and Ph.D. courses in electronics, ranging from simple electronic circuits (both digital and analog) to the specification and design of complex electronic systems. In addition to the educational activities, several Research + Development $(R + D)$ lines are being developed, as follows:

- microprocessor-based systems for a number of applications: controlling, supervision, communications, and multimedia (audio/video decoding/coding);
- signal processing systems: speech technology for advanced human–computer interfaces and medical image processing for helping in diagnosis;
- optoelectronics and microtechnology systems: detection, processing, transmission and recording of information by means of opto- and microelectronics.

The Electronic Systems Curriculum proposed in this paper is made up of four theoretical courses and four PBL courses (including a compulsory Master's thesis). In Fig. 1, these courses are presented within the framework of the five-year telecommunication engineering studies.

The first main characteristic of the proposed curriculum is the application of the multidisciplinary knowledge acquired in

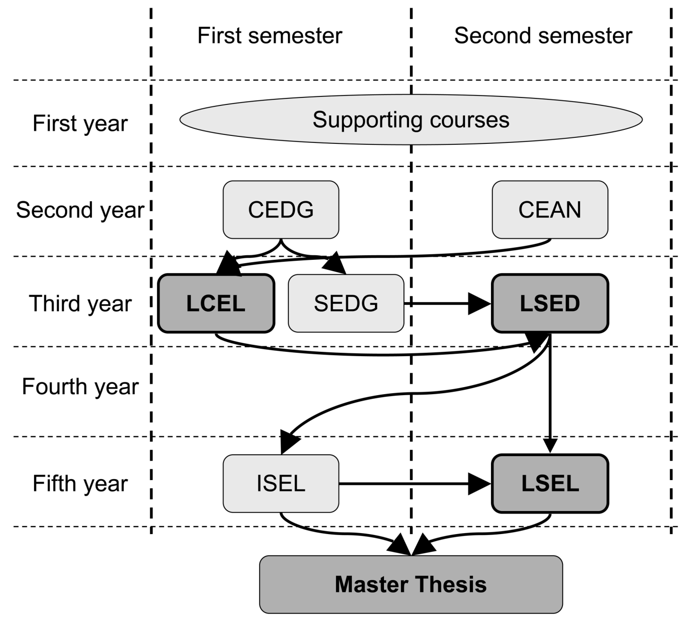

Fig. 1. Layout of the full Electronic Systems Curriculum in the five years of the telecommunication engineering studies.

$R + D$ activities to the design of the academic curriculum and the learning resources developed for its courses. All the systems developed in the department are a convergence point for educational and $R + D$ activities. A very good example of such convergence is the ANTARES board, a microcontroller platform based on the Motorola ColdFire 5272.

The second main characteristic is the use of a common hardware scenario, the ANTARES board, for all PBL courses. This common hardware is used for undergraduate and masters' courses, and research and development projects.

The design of the curriculum has accounted for the following pedagogical objectives:

- to provide solid theoretical foundations in the analysis and design of digital and analog electronic circuits, and microcontroller-based systems;
- to develop complex multidisciplinary systems combining electronic circuits implementation and system programming (microcontroller-based systems);
- to get practical experience in all steps in the life cycle of the development of electronic systems: specification, design, implementation, and testing, with progressive emphasis on the first higher levels;
- to acquire soft skills, such as student initiative, group work, communication, self-regulation, and commitment. Because of this, PBL has been the main learning strategy chosen in the curriculum specification.

A. Theoretical Courses

The four theoretical courses, which address the first objective, are problem-oriented, exam-based courses with a great emphasis on content, but the evaluation is mainly based on the analysis and design of a simplified system. The courses are as follows:

- **CEDG (Digital Electronic Circuits) and CEAN (Analog Electronic Circuits)**. These two courses introduce the fundamentals of both digital and analog circuits. The courses are based on the analysis of a full-hardware system, either digital or analog.
- **SEDG (Digital Systems Based on a Microcontroller)**. In this course, the students acquire the basics for programming a microcontroller system: description of the microcontroller structure, assembly programming and timing resources, or exception handling. The microcontroller is the Motorola ColdFire 5272 with general peripherals such as universal asynchronous receiver/transmitter (UART), analog-to-digital converters (ADCs), and digital-to-analog converters (DACs). The proposed system combines both software (SW) and hardware (HW) but emphasizes the role of low-level system programming.
- **ISEL (Electronics Systems Engineering)**. This course focuses on embedded systems: computer architecture, Microchip PIC microcontrollers, Motorola 68000-series computers, peripherals, interfaces, operating systems for embedded systems: μCLinux, GNU/Linux, real-time systems, and power management problems. In this course, a full design with hardware and software modules is proposed.

The aim of all these courses is to provide solid foundations in electronics and system programming which complement the skills that the PBL courses provide. The theoretical courses do not always have to be passed before the taking the PBL ones. About 60% of students pass the theoretical courses first, but the other 40% pass a PBL course first because PBL courses can provide a good basis for the theoretical ones (they help students to understand some of the theoretical concepts).

B. Project-Based Learning Courses

The design of a full electronic system comprises work on the following two different axes, regarding the pedagogical objectives stated in Section II:

1) the HW versus SW codesign and integration axis, which addresses the second pedagogical objective of the curriculum;
2) the life cycle axis: iterations of analysis, design, implementation, and testing in an evolutionary prototyping process (according to the third objective).

Tackling the whole life cycle of an electronic system in one semester is not possible, considering HW and SW aspects. One must coordinate and organize the PBL courses to define the complementary learning targets covering the whole life cycle and the main HW and SW aspects (both axes). In the curriculum proposed in this paper, the PBL courses are organized in three levels, which are described in Sections II-B-1)–3).

In all cases, the teaching approach is based on multidisciplinary project-based learning; electronics is just the tool to build systems in areas, such as signal processing, communications, control, and user interfacing. In the proposed laboratory courses, the students have to design, build, test, and document a complete HW or SW + HW system with emphasis on the following pedagogical issues:

- the creativity and initiative of the students: encouraging them to arrive at their own solutions;
- realism: limiting the economic cost and development effort;
- professionalism: presenting factors such as the quality of the technical writing and the capabilities for oral communication.

1) Level 1: LCEL and LSED Courses: There are two PBL courses in the first level: Laboratory of Electronics Circuits (LCEL) and Laboratory of Digital Systems Based on a Microcontroller (LSED).

- **LCEL** focuses on the design, assembly, and measurement of several modules comprising an analog and digital electronic circuit. Its main target is to allow students to learn the practical concepts related to analog and digital circuits. The students have to design, build, and measure real circuits with reasonable specifications, taking into account the students' knowledge of electronics. The theoretical support is provided by previous courses, such as CEAN (Analogical Electronic Circuits) and CEDG (Digital Electronic Circuits), both taught the second year.
- **LSED** is closely related to SEDG (they share the same microprocessor and peripherals). The students have to develop a microcontroller-based system with a significant effort made in programming. The system always includes a real-time component (an important part of the functionality is located in periodic interrupt service routines), making the debugging of the system more complex and thus complicating the development of the prototype.

Regarding the HW versus SW axis, LCEL and LSED focus on different areas: LCEL on HW, LSED on SW, although some interaction between HW and SW is also important in LSED. Regarding the life cycle, both courses (LCEL and LSED) focus on low-level module design, implementation, and testing. The instructors provide most of the analysis. Nevertheless, most students are highly motivated by these PBL courses: the students propose new specifications and new objectives that make a certain amount of new analysis and high-level design necessary.

LCEL and LSED are mandatory laboratories with about 400 students attending every year, comprising groups of two students. Because LCEL and LSED are first-level courses; they are partially guided, oriented to showing the students how to organize the different sessions to meet the objectives. To foster creativity in this first level, the students must make optional improvements on the proposed basic system to be able to achieve the maximum grade; these improvements can account for more than 15% of the overall numeric grade.

In the first PBL experience, the students must be given an initial description of the system (of more than 30 pages) that includes the specifications and requirements of the system, part of the analysis (a set of objects or subsystems with their properties), methods and relationships, and some implementation guidelines for the design.

According to the fourth pedagogical objective described in Section II, the evaluation process takes into account soft skills related to teamwork, self-regulation, initiative, and communication.

- Several intermediate electronic deliveries help the instructors to verify the evolution and originality of the work. In this fist level, considerable supervision is crucial.
- The final documentation has the student explain the final analysis, the design, the implementation, and the tests.
- An oral examination is used in which the instructors verify that the prototype follows the specifications and ask individualized questions to determine the capacity of each student to explain the results.

2) Level 2: LSEL Course: In the second level, there is just one course: **LSEL (Laboratory of Electronics Systems Engineering)**. As LSEL is optional within telecommunication engineering studies, fewer students take it. This fact allows the personalization of the learning process for each group of two students.

With regard to the HW versus SW axis, LSEL focuses on the balance between SW and HW. Regarding the life cycle, LSEL puts the emphasis on the whole life cycle, reusing SW and HW modules (not all modules are developed from scratch) and implementing a fully functional prototype.

The main objective of LSEL as an advanced PBL course is to develop a complete electronic system by applying the same methodology as in industrial environments. The instructors emphasize the following pedagogical aspects:

- teach design methodology for developing a full electronic system;
- focus on the higher level phases of the life cycle;
- teach professional documentation and technology transfer issues.

Another important target is to promote the creativity and initiative of the students by using a fully professional approach. The LSEL course is a bridge between the previous PBL courses (more academic) and their professional career. With this approach, assembly programming is not critical; therefore, the emphasis is on high-level programming, module reusability, and student creativity (the students define the whole system including the specifications).

3) Level 3: Master's Thesis: Every student must complete a Master's thesis individually in order to get the Telecommunication Engineering degree. At this third level, the curriculum envisages the students developing their Master's theses in electronics. At this point, students coming from LSEL are very well prepared to take on a Master's thesis involved in one of the research and development lines developed in the Department of Electronic Engineering. The involvement of Master's thesis students in research and development lines is possible because, as will be shown in Section III, a significant overlap exists between the research and development tools and the learning resources developed for the PBL courses. This overlap is one of the main characteristics of the curriculum proposed. Every year, more than 20 new students embark on their Master's theses in electronics.

Similar to LSEL, the Master's thesis focuses on both SW and HW aspects (SW versus HW axis) and considers all the steps in the life cycle (life cycle axis) of developing an electronic system. In this case, the student develops a prototype ready to be transferred to industry.

The main difference with respect to LSEL is that Master's theses are developed individually: The student has to analyze, design, and implement the system architecture, controlling the functionality of all the modules. First of all, the student has to design a detailed testing plan, which is one of the main targets in this level of the curriculum. As a result of the Master's thesis, the student develops a quasi-professional system, generally involved in a research and development project that is being completed by the instructors with a company or a government institution.

III. Learning Resources: Hardware and Software Development Environments

The main effort in learning resource generation has focused on the PBL courses. This effort has been oriented towards creating a new development environment that is complete and flexible enough to be used in all the courses throughout the curriculum. Such flexibility permits students to reuse their knowledge and experience from one course to another. This way, the students can carry out more complex projects, learning the role of electronics as a grounding for other disciplines. This section briefly introduces the hardware equipment and the software development tools that have been designed for the PBL courses. The learning resources have been generated by taking into account the experience acquired by the Department in research and development activities. Additional details on the learning resources can be found in [12]–[15].

A. Common Hardware Platform

One of the main goals when designing the PBL courses in the proposed curriculum was to use the same hardware platform throughout the different curriculum levels. Given this goal, the hardware platform to be used had to fulfill several criteria: robustness (for those students that may not have a high degree of practical skills in electronic systems), flexibility (wide range of capabilities from simple electronic modules to complex hardware and software systems), and professionalism (HW and SW environments closely related to those of industry).

From these considerations, the instructors decided to apply their research and development work in electronic design to their teaching activities. An example of this strategy is the ANTARES board [15], a state-of-the-art industrial electronic platform widely used in the department for both their internal and their external industrial projects. The ANTARES board contains a Motorola 32-bit MCF5272 microprocessor with 16-MB SDRAM memory and 4-MB Flash memory. ANTARES also has an Ethernet Module, two RS-232 serial ports, and one USB slave interface.

The application of the ANTARES platform has different implications depending on the PBL course, especially regarding the software tools provided and the teaching targets to be reached. All the software tools have been developed and designed carefully, keeping in mind which skills must be acquired by the student at each level. The software tools do not include more utilities than necessary to avoid increasing complexity and diverting students from the learning objectives.

Fig. 2 shows an integrated view of the proposed curriculum, including details of the PBL courses (LCEL, LSED, LSEL, and Master's thesis) and the associated theoretical ones (CEAN,

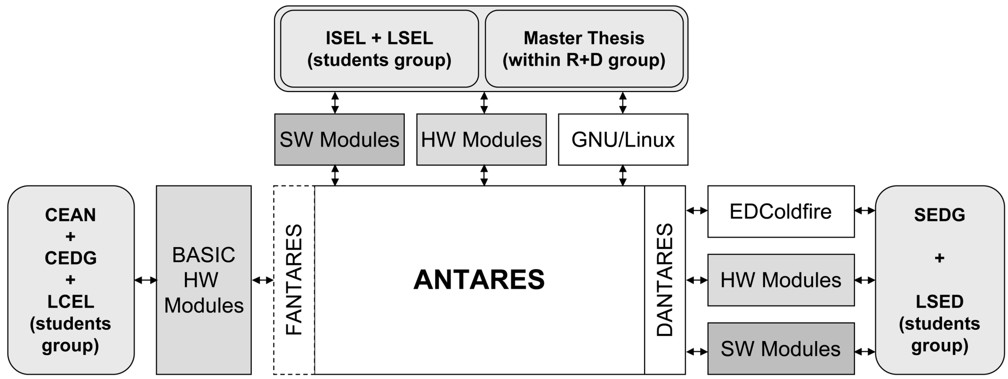

Fig. 2. Integrated view of the proposed curriculum.

CEDG, SEDG, and ISEL). Fig. 2 also includes design items related to each of them (HW and/or SW modules), the supporting software tools (EDColdFire and GNU/Linux operating system), and the common hardware (ANTARES), plus the "adaptation" interfaces DANTARES and FANTARES, which will be described below.

B. LCEL: FANTARES Platform

In LCEL, the students have to design, simulate, build, test, and document a complete system that combines analog and digital electronics (HW-based laboratory), in groups comprising two students. Given this scenario, the software tools consist of circuit simulation environments with visual interfaces, where the student covers the first two steps (design and simulation).

For the building stage, the students use prototyping boards (plastic prototyping breadboards, wire wrapping, perforated boards, or printed circuit boards) with standard analog and digital integrated circuits (ICs), in a fully equipped laboratory (oscilloscope, signal generator, power source, etc.).

Regarding the common hardware support, the instructors are currently working on adding a Xilinx field-programmable gate-array (FPGA) subsystem to the ANTARES platform (FANTARES), in order to fulfill the expectations of basing all the PBL courses in the same common hardware platform.

C. LSED: DANTARES Platform

Just as in LCEL, students enrolled in LSED are still not proficient enough in handling sophisticated hardware systems. Based on previous experience, one must protect the externally available analog and digital inputs and outputs against overvoltages and short-circuits, the most frequent problems in an educational PBL course. A separate protection board is built on which ANTARES is piggy-backed via the DANTARES expansion bus. All the input/output signals are optocoupled and buffered. All connectors have been selected for their high robustness and standardization. Fig. 3 shows the DANTARES platform connected to an external board providing a standard keyboard and a liquid crystal display (LCD), which are given to the students to be used in their designs.

In order to use DANTARES, the instructors provide the students with a Windows environment called EDColdFire. EDColdFire is a visual development environment for the Motorola Microcontroller ColdFire 5272, using the DANTARES platform. EDColdFire has also been entirely developed by instructors, and it allows editing, loading, executing, and debugging source code (both assembler or/and C code).

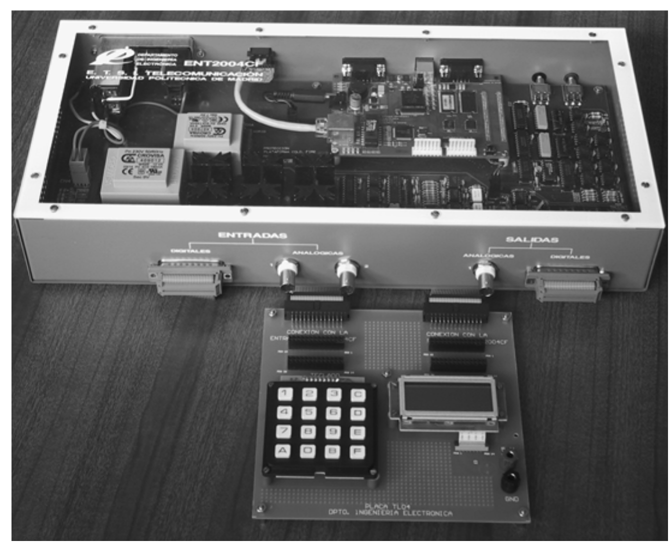

Fig. 3. Photograph of the DANTARES platform.

D. LSEL and Master Thesis: ANTARES Platform Without Protection

Given the elective characteristics of LSEL, its advanced content, and enrolled students who are usually proficient in handling electronic equipment, ANTARES is the standard platform. Neither protection nor additional hardware is used so that the students have full access to all the capabilities of the platform. ANTARES is also used in the Master's theses involved in the department research adn development activities.

In both LSEL and Master's thesis, the students do not have to develop all the system modules; they can obtain several module implementations and integrate them. The instructors provide the student with several modules for electronics, signal processing, and communications. Furthermore, they can obtain numerous open-source implementations from the Internet.

In this scenario, the development tools have to be very flexible and compatible, allowing students to integrate different software modules. The ANTARES board is provided with an open-source operating system, μCLinux, a GNU/Linux adaptation to work on microprocessors without a memory management unit (MMU). This operating system is smaller than the standard GNU/Linux distribution, which makes it very suitable for embedded systems. The μCLinux code is open, allowing complete access and control. Another strong point of μCLinux is that it is based on a GNU/Linux kernel, sharing all its characteristics, such as multitasking operating system, modular architecture, multiple network protocols support, robustness and reliability, availability of the source code, and free GNU license.

The ANTARES board is connected (through a serial RS232 port) to a software development PC running a Debian GNU/Linux distribution. To help the student, the instructors have created a developer toolkit that includes several preprocessors, compilers (C and C++ code), linkers, debuggers, and numerous useful tools to obtain and manage information on different object files.

IV. Administrative, Learning and Teaching Web-Based Tools

When including the PBL philosophy in the curriculum, some difficulties resulting from the combination of the special characteristics of the PBL approach and the student intensive attendance must be tackled. When referring to PBL, a small number of small groups is assumed for the strategy to be successful. Under this scenario, in standard Spanish higher education, PBL could only be addressed in the specialization courses of the final years, not in the compulsory general courses that usually have a high student–teacher ratio. As an example, in the LCEL and LSED courses, instructors have to work with about 400 students every semester. Apart from the administrative overload, additional difficulties are related to the efficient handling of student progress monitoring and feedback, and strategies for the detection of plagiarism and cheating.

To overcome these difficulties, specific Web tools have been implemented for helping the instructors with the important workload generated by the PBL approach. All the tools described below have been implemented using free software supporting technologies because they have proven extremely reliable and versatile, fulfilling all the proposal expectations.

- *Student enrollment tool*: To have full control of the allocation of laboratory equipment and physical resources and take into account restrictions imposed by the university, the students' schedules, and equipment availability, the tool establishes a flexible allocation policy.
- *Management of laboratory slot occupation tool*: This tool allows students to request extra slots in the laboratory, demanded by the open structure of the PBL approach (students seek higher grades through extra creative work). Random delays and the use of a random graphical access key ensure fairness in slot allocation, avoiding the use of Web robots.
- *Examination planning and grading management tool*: To allow for efficient planning of the examination slots for hundreds of students, the task is formulated as a search algorithm that makes intensive use of smart heuristics that ensure the generation of a close-to-optimal allocation policy within a given calendar period and the defined restrictions.
- *Student survey management tool*: This tool fully automates the process from the survey generation stage up to the statistical processing of the results. The process guarantees both student anonymity and system security (to receive only one submission per authorized student).
- *Student progress monitoring tool*: Especially critical in PBL courses with a high student–teacher ratio, this tool uses annotated data related to the stage of development that the students have reached, making possible the estimation of accurate statistics on the students' progress and identifying possible problems in the planned schedule or unforeseeable difficulties in the laboratory assignment. The granularity of the reports is also adjustable so that the user can track the overall progress, specific groups, or even selections of groups.
- *Detection of plagiarism and cheating tools*: In PBL courses with a large number of students developing the same basic prototype, a certain degree of information sharing between students is not only admissible, but also desirable. However, students must achieve the educational objectives on their own; therefore, automated tools to detect copies in the source code developed by students have been developed (standard similarity-detection programs are not useful as they are not fully adapted to dealing with assembly programs cleverly modified by students). These tools have deterred the students from cheating, reducing the number of cheating attempts from 5% to 1%.
- *Automatic software quality analysis and feedback tool*: In the LSED and LSEL courses, the core of the project is the development of an assembly or C program on a Motorola microprocessor. The style of this program is analyzed, and its quality is estimated using an automatic tool which is based on computing a feature vector with up to 48 basic characteristics from a program. The analysis provides the relevance of each parameter regarding the grade and provides an automatic tool for helping both the instructors and students evaluate software quality [12]. The use of such a tool has greatly improved the software quality statistics when compared to the previous academic years (e.g., the average number and length of routines or the use of complex addressing modes). The achieved improvement ranges from 23% to 74% for the most important features.

V. Evaluation Results

The evaluation process over four consecutive academic years takes into account considerations related to both the academic results of students and their impression of the courses, as extracted from their replies to a number of different surveys.

A. Academic Results

Student performance is one of the most widely used quality metrics when evaluating a curriculum. During the past few years, the instructors have been closely monitoring the grades of the students to evaluate their degree of achievement of the courses' objectives. As the detailed evaluation criteria are closely related to the measurement of the fulfillment of the course objectives, the higher the grades, the higher the degree of achievement.

Fig. 4 shows the accumulated grading histogram for LCEL and LSED. To summarize, the main results are as follows.

- Most of the students passed the course: 97.2% for LCEL, and 96.8% for LSED.

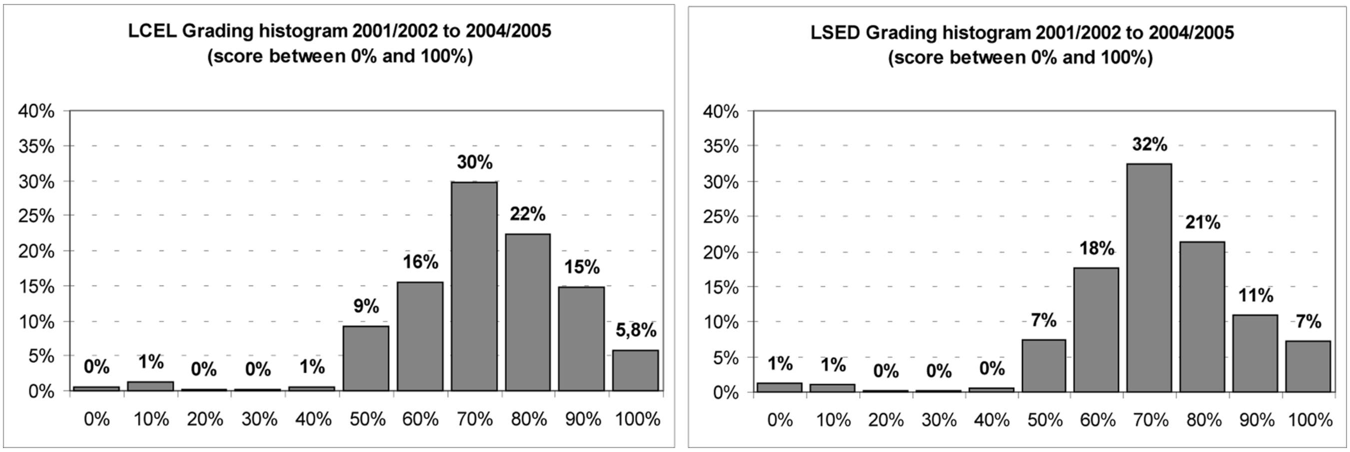

Fig. 4. Academic results for LCEL and LSED.

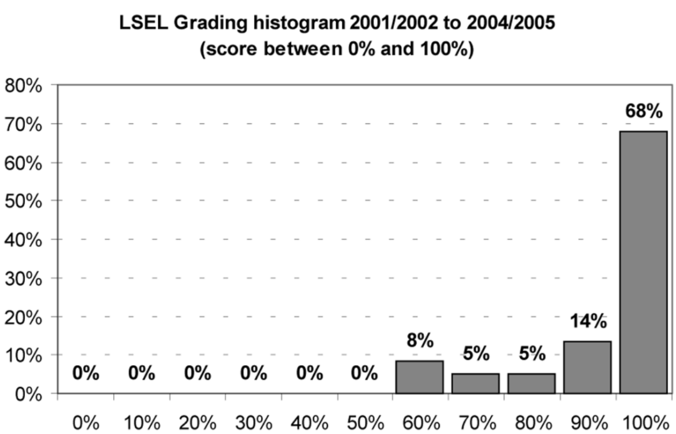

Fig. 5. Academic results for LSEL.

- Of the LCEL students, 42.77% received grades over 80%, while 39.4% of the LSED students received grades over 80%.
- Of the LCEL students, 5.8% received the highest possible grade of 100%, while 7.3% of the LSED students received the highest possible grade of 100%.
- The average grade was 75.2% for the LCEL students and 74.3% for the LSED students, very high in the telecommunication engineering studies in UPM.

All these results show that even though the complexity of the assignments was high, students were very successful in working with them and achieved the course objectives.

On the other hand, Fig. 5 shows the accumulated grading histogram for LSEL.

Clearly, the results are much better in LSEL, which clearly correspond to an elective course in which the students are highly motivated. The additional facilities offered to them actually increase their interest, leading to designs and prototypes of outstanding quality, reflected by an average grade of 88.5%.

B. Student Surveys

When adopting the new curriculum, the instructors started to monitor closely the different performance and quality metrics related to the students' perspective, using student surveys. In the evaluation shown below, among all the possible performance measured metrics, two of them stand out as the most appropriate ones, linked to the following statements presented to the students.

- [Q1] The course has been interesting.
- [Q2] The effort imposed by the course is worthwhile because of abilities and knowledge acquired. This statement roughly measures the ratio between two perceived variables, learning vs. required effort.
- [Q3] The course has increased my affinity to electronics in general.
- [Q4] The students were to rate the course in a 0–100% scale (0 = the worst, 100% = the best). This evaluation measures the overall perception of the course by the students.

To answer the first four questions, every student had to choose between six different answers with a numerical value: I fully agree (5); I agree (4); I partially agree (3); I partially disagree (2); I disagree (1); and I fully disagree (0).

Fig. 6 shows a summary of the student survey results for LCEL and LSED, accumulating data from 2001/2002 to 2004/2005. On the average, 75% of the enrolled students filled in the surveys.

The results for LCEL and LSED are, not surprisingly, very similar.

- Regarding [Q1], most students agree that the course is an interesting one, giving it an average value of 3.9.
- Regarding the balance between learning vs. required effort [Q2], the results also show a positive tendency since the students gave it an average value of 3.2.
- Regarding the increase in their affinity to electronics [Q3], the students show a perceived increment, averaging 3.2.
- Finally, considering the overall grading [Q4], the average value has been 71.7%, very high in comparison with other courses in the same level.

Regarding the results of the student surveys for LSEL, only data from 10 students enrolled in the 2004/2005 academic year is available. In this case, improvements in the appreciation from the students are better, but given the low number of students providing data, the results are statistically very unreliable. The average values are $[Q1] = 3.8$, $[Q2] = 3.6$, $[Q3] = 4.1$, and $[Q4] = 78.9\%$.

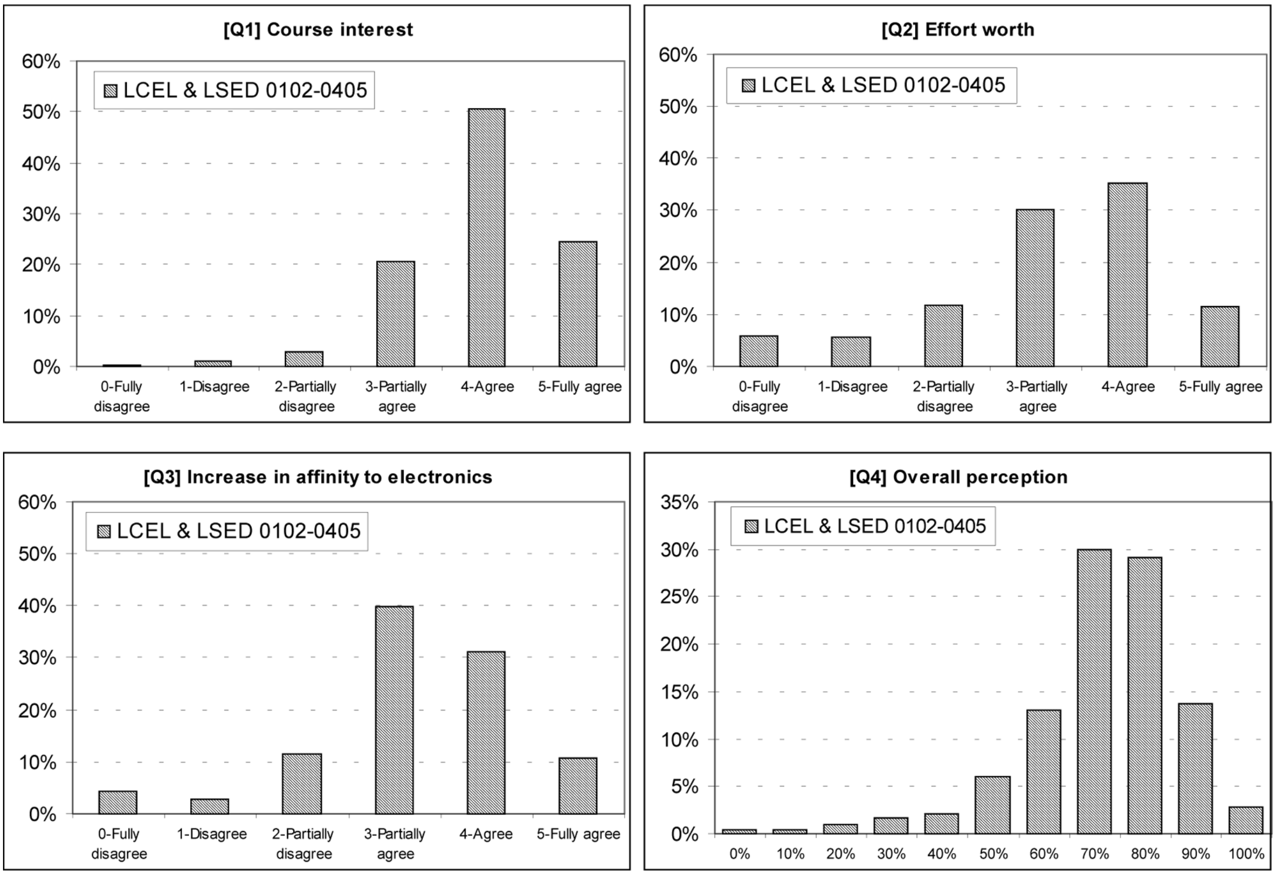

Fig. 6. Student survey results for LCEL and LSED.

[Q2], [Q3], and [Q4] measures are consistently improving over the past few years. This improvement is a reflection of the overall appreciation of the courses among the students, in part as a result of the introduction and refinement of additional tools and utilities using the hardware equipment and learning resources described above.

VI. CONCLUSION

This paper presents an approach to designing Electronic Systems Curricula based on PBL and a common hardware platform, which makes electronics more appealing to students through a set of multidisciplinary projects, according to the proposed hypothesis.

The paper provides a detailed description of the curriculum structure, the resources generated, and the evaluations completed in the last four academic years. This new curriculum has been designed and implemented taking electronics into account as an important grounding for the other core disciplines in telecommunication engineering: computer science, signal processing, and communications. In this context, practical multidisciplinary courses based on project-based learning have been considered as the main strategy in the curriculum implementation.

The curriculum structure consists of eight courses: four theoretical courses and four PBL courses (including a mandatory Master Thesis). The four theoretical courses (CEDG, CEAN, SEDG, and ISEL) are problem-oriented, exam-based courses, with special emphasis on content. They provide the theoretical foundations for the PBL courses. These PBL courses (LCEL, LSED, LSEL, and Master Thesis) are coordinated and organized in three levels of increasing complexity. Each level focuses on different aspects of an electronic system design: HW vs. SW axis, and life cycle axis.

The curriculum design process has taken into account an integrated approach, paying special attention to ease the progressive acquisition of advanced skills based on the use of a common flexible hardware scenario (the ANTARES board, generated by the instructors within the $R+D$ activity of the department) with progressively more sophisticated and industrial-like development tools. The hardware equipment is complete enough to support all the PBL courses involved in the proposed curriculum, while permitting the development of industrial prototypes designed in $R+D$ projects. The development tools complement the learning scenario and have been designed keeping in mind which skills must be acquired by the student at each step in his or her academic life.

The administrative and teaching tools also constitute an important element in the implementation of a curriculum focused on PBL. These Web tools have significantly reduced the workload for instructors allowing the use of PBL in courses with more than 400 students. Tools for supervising and monitoring the students' progress and those related to helping in the evaluation are especially important. The information obtained using them is very useful for helping instructors in planning the advising sessions efficiently.

This proposal has been used and evaluated for the last four academic years and has achieved significant advances. The students have increased their interest in electronics, positively evaluating the PBL courses in the surveys. The students have given an average grade of 71.7% to LCEL and LSED, and 78.9% to LSEL. On the other hand, the students have obtained very good academic results. The average grade for the PBL courses was 75.2% (LCEL), 74.3% (LSED), and 88.5% (LSEL), respectively. Finally, the curriculum characteristics have permitted the students to acquire advanced knowledge and skills to develop more sophisticated and realistic electronic systems.

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