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Industry 4.0 Paradigm on Teaching and Learning Engineering*

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This paper evaluates the impact of the early adoption of Industry 4.0 tools and methods (industrial systems that enable many innovative functionalities through their networking and their access to the cyber world) on engineering education. The proposed analysis considers two points of view: professors (teaching) and students (learning). In this context, two experiences were conducted: an advanced correction and validation system with real-time feedback and a virtual learning environment supported by a remote laboratory. In this paper two objectives are addressed: first the paper describes the proposed Industry 4.0 education tools, based on e-learning and cyber-physical technologies; second the performance of these tools is evaluated in a real context, where more than one hundred students were involved. The experience was deployed in subjects related to microcontroller programming in Telecommunication Engineering and Bioengineering degree programs. Results were evaluated using statistical methods. First evidences of the improvement in the students' motivation, their academic results and their acquisition of Industry 4.0 competencies were obtained.

Keywords: Industry 4.0; engineering education; educational technologies; virtual learning environment; automatic feedback

1. Introduction

Defined in 2014, the term Industry 4.0 refers to industrial systems that enable many innovative functionalities through their networking and their access to the cyber world (cloud computing, Big Data, etc.) [1]. Technically, Industry 4.0 [2] is a new and very promising application scenario of Cyber-Physical Systems (CPS) [3], unions of cybernetic and physical processes where feedback control loops are employed to make both worlds to evolve together. Socially, this seamless, pervasive and global integration between physical elements, people and cyber components (both, hardware devices and software services) is creating a new kind of citizen. Prosumers [4] (users acting as both, content producers and consumers) [5] are nowadays a relevant social group; digital native people are getting the biggest social stratum; and technological constructions such as virtual identity, remote actions, real-time services or personalization have turn into key characteristics of our reality. These facts affect all social aspects, including economy, work market and education.

These three areas (economy, work market and education) are not, in fact, totally independent, and sometimes must be considered together to really understand educational phenomena. With this wide view, at least two very negative impacts in learning can be nowadays understood as a consequence of this discoordination between students 4.0 and the use of tools 2.0 (wikis, forums, etc.) and 3.0 (gamification, Flipped Classroom, etc.) in Information Technologies (IT) engineering education.

First, engineering students' employability is reducing. Economy is transforming into a high-efficiency process [6], where technology and engineering must support a minimum resource consumption. Agile development methodologies have crossed the borders of software engineering and are now applied to most fields where fast customer-centered products and solutions are preferred to general, heavy and/or slow approaches. This new paradigm requires from engineering students a large practical experience in real application scenarios (as aeronautical experts currently do) but IT degree programs are mostly focused on modeling, mathematical frameworks, etc. Therefore, while traditional positions are completely over demanded, other new and innovative jobs and companies' needs get uncovered because new professionals lack the proper Industry 4.0 competencies [22]. At log-term, this fact causes the number of students in engineering degree programs to be decreasing each year [8].

And second, IT engineering students report low motivation levels and problems to acquire certain competencies; especially those related to abstract modeling and algorithmic designs [9]. In fact, in an Industry 4.0 social context which encourages creative behaviors and empowers proactive people, teaching methodologies cannot be mostly based on passive learning and a limited access to physical

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experiments and devices. Besides, in a society characterized by a permanent and fast feedback between creators and consumers, the lifecycle of standard or blended homework (although supported or enhanced by e-learning tools) is unacceptable and causes the students' despair; either because of the great feedback delays (usually more than forty-eight hours) or because of the low number of interactions between professors and students (typically less than five feedback activities per subject).

These problems have been quickly noted by students and companies, but higher education institutions are reacting in a very disorganized manner. In fact, although education has totally changed in the last ten years [7] with the introduction of e-learning and blended learning methodologies [33] and tools [34] (such as Kahoot!, Moodle, Flipped Classroom, etc.), the upcoming Industry 4.0 and its new citizens are a pending challenge for most universities.

We argue these problems may be addressed by introducing Industry 4.0 tools and methodologies in education. In this paper we describe two different, but complementary, experiences focused on addressing these challenges in the IT area, specifically in microcontroller programming. During several consecutive courses, two new Industry 4.0 learning tools were employed (by an experimental group of students, different each year) in two subjects where surveys showed a very low motivation level among students, a great failure rate and a decreasing students' working time. Contact office between Industry and University received different complains about students' competencies in these areas (subjects) too. The first tool consisted of an advanced correction and validation system with real-time feedback; and the second one of a virtual learning environment emulating a real Industry 4.0 scenario and supported by a remote laboratory. We will describe these two new Industry 4.0 e-learning tools, and the use of these platforms in Programming courses in Telecommunication Engineering and Bioengineering degree programs. Results from 2015 to 2018 will be considered.

The rest of the paper is organized as follows: Section 2 describes the state of the art on Industry 4.0 tools and methodologies in Higher Education; Section 3 describes technically how both proposed new tool were developed. Section 4 describes the experimental methodology, the context of the proposed experience and the experimental results. Section 5 concludes the paper.

2. State of the art on industry 4.0 education

The relevance of previously described problems has made several authors to study tools and methodologies for Industry 4.0 education. However, commonly, the reported experiences are limited and only some few students (around ten) are involved during a very short time period (some weeks at most) [14]. Thus, results and conclusions are usually only partial and deeper studies are required. This work fills this gap. Nevertheless, in this section, those initial studies in the state of the art are reviewed.

The most typical educational proposal for Industry 4.0 is focused on preparing students to future jobs and to fulfill the uncovered companies' needs in relation to Industry 4.0. Different methodologies to enable students to acquire those competencies have been reported. Some of them consist of demonstration scenarios where students work as in Industrial companies (an approach named as scenario-based learning or work-based learning) [12]; but other introduce some innovative Industry 4.0 technological solutions (such as augmented reality industrial systems) into the teaching process to make students more comfortable and familiar with them [13]. Most basic proposals reorganize contents in traditional subjects to teach IT competencies using a holistic approach [17], essential in Industry 4.0 to implement optimum and efficient products and solutions. Results of these experiences prove the students' learning becomes more efficient using Industry 4.0 tools, but not significant conclusions about other fields such as the teaching procedures or the students' motivation are reported.

Furthermore, some simple strategies have been also reported to advance to Industry 4.0 education. For example, experiences where collective intelligence and collaborative learning is supported through virtual environments have been described [11]. However, these approaches have a very limited life, as they (actually) employ web 2.0 tools [32]; and are only adequate for students in the border between society 3.0 and the fourth industrial revolution. Native Industry 4.0 students are not completely motivated or future technological competencies totally worked with this approach.

The use of Virtual Learning Environments (VLE) [10] has been considered to evaluate how learning and teaching processes have changed by the use of avatars and virtual mechanisms. These works are defined as "preparatory" for Industry 4.0 education, as they evaluate the current state of education in relation to the fourth industrial revolution. Initial obtained results show current virtual team work is inefficient as industry experts and IT-related scenarios should be integrated into the teaching procedure. Other relevant works analyze current education problem and challenges to be addressed through Industry 4.0 solutions [14]. The previously cited problems, as well as talent management, are some of those key challenges [15]. Moreover, and considering these reports, first experiences in designing Industry 4.0 education programs have been reported [19, 20]. As these proposals are being now published, no data about their performance are still available.

In a more technical sense, other e-learning instruments have been developed and studied as Industry 4.0 education tools. In particular, mobile learning applications for working personal and social abilities have been proposed [16]. These applications are designed to support the ubiquitous and lifelong learning; working competencies such as security, resource efficiency or work organization. Finally, the most advanced institutions (such as TU Wien) have created Industry 4.0 pilot factories [21, 24] where students can learn using scenario-based methodologies, but with the help of tangible objects, devices and real situations [18, 23]. Personal, social interpersonal and action-related competencies are worked with these innovative tools. Nevertheless, no scientific results about the performance of any of these tools in real education scenarios have been reported.

3. Proposed industry 4.0 education tools

To improve the education quality in the IT engineering field and courses, particularly in microcontroller programming courses, we have created two different educational Industry 4.0 tools. The first tool consisted of an advanced correction and validation system with real-time feedback; and the second one of a virtual learning environment emulating a real Industry 4.0 scenario and supported by a remote laboratory. Both tools have been integrated in a more general blended learning methodology described in Section 4. In this section, both proposed Industry 4.0 tools are technically described.

3.1 An advanced correction and validation system with real-time feedback

Educational solutions to provide automatic feedback to students have been studied for many years in areas such as Mathematics [25]. However, this random-generated-problem-based approach has been barely studied in the context of programming subjects, and more sparsely in microcontroller programming. The main cause is the difficulty to create generic base problems, and the corresponding validation and feedback provision schemes, to later enable the definition of coherent specific random programming problems to be solved by students.

Besides, microcontroller programming faces some specific challenges. Programs to be uploaded into resource constrained devices are concise and non-exhaustive (contrary to high-level programming). No errors or exceptions are generated, and the same program is indefinitely executed regardless if it works or not. Furthermore, errors are sometimes assumed to create lighter or faster programs, contrary to user application which must exhaustively consider all possibilities and include a managing policy for each one.

In order to address this situation we propose a technological scheme where microcontroller programs are executed and controlled by a supervisory process, in the same way as a professor observes the real execution during a laboratory class. This approach is similar to current proposals of Industry 4.0 process execution systems [26]. Results and observations made by this process are used to create feedback.

3.1.1 Tool's architecture

Fig. 1 shows the proposed architecture for this first Industry 4.0 educational tool. As can be seen it includes two different user interfaces: one for students to solve programming problems and obtain feedback, and other for professors to create base problems and follow the students' performance. Both interfaces are connected to a problem-generation engine, which creates specific programming problems in a random way from patterns described in base problems. Once the student submits his solution to the proposed problem, it is sent to an evaluation engine where the code is executed in a sandbox supervised by an orchestration process. Results returned at real time to the student as feedback. After a certain execution time (microcontroller programs are basically indefinite loops), the supervisory process cancels the execution an generates a final report which is sent to the student and the professors.

In this tool, the sandbox simulates the most popular microcontroller architecture nowadays in education: Arduino. Using any of the existing open-source projects to simulate Arduino boards using software tools we can easily create this sandbox. Students will see at real-time the behavior of their code and, contrary to local simulators, professor will be informed about the performed activities. Supervisory process will allow the code execution for enough time to execute, at least, ten times the main loop in the program (Fig. 2 shows the typical structure of a microcontroller program).

The supervisory process evaluates, after each instruction in the code, the state of the pinout in the Arduino board, and the content in the serial terminal. These data will be sent to students at real-time. The final report indicates if the code behaves in the expected way, considering not only a correct execution, but also time constraints, the use of memory, etc. It also offers information about pos-

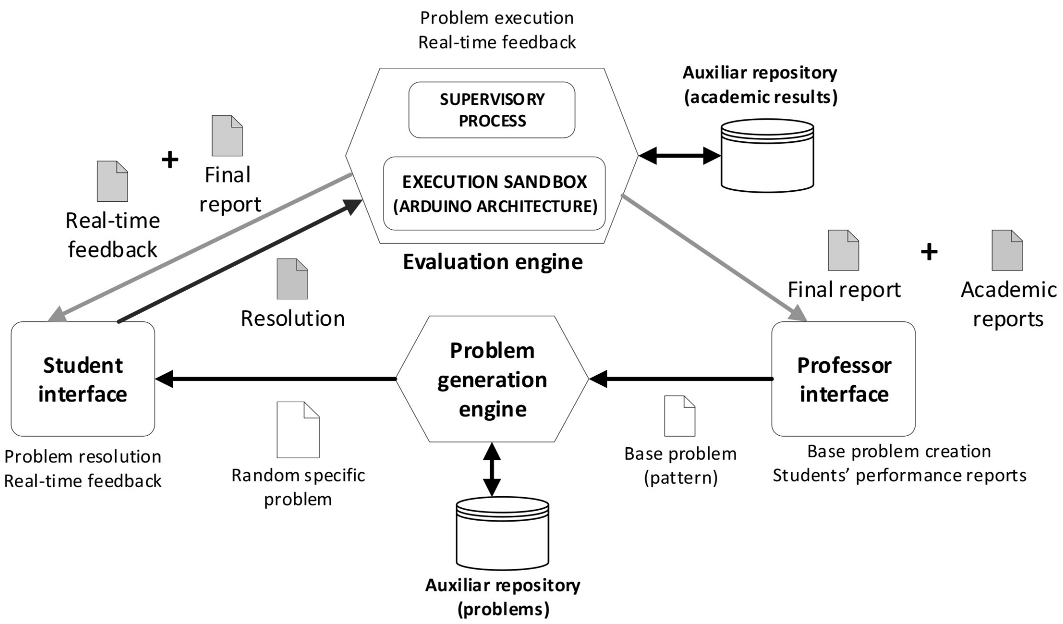


Fig. 1. Architecture of the proposed correction system.

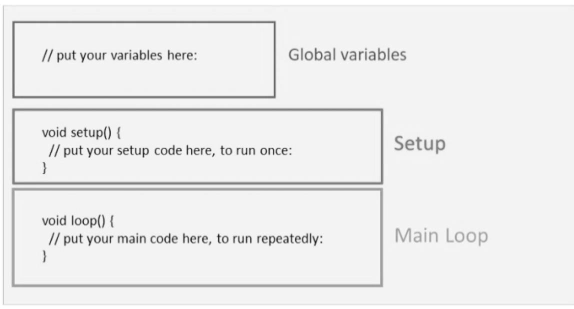


Fig. 2. Structure of a microcontroller program.

sible errors and non-coherent code blocks. All this information is showed in different frames in the student interface, where students can also see the problem description and the proposed initial configuration (see Fig. 3): additional devices connected to the Arduino board, information sources, etc. As this experience was carried out in subjects where programming was the focus, no request or evaluation about the electronic implementation was considered.

3.1.2 Base problem (pattern) definition

In the context of microcontroller programming, we have identified two different problem types: objective-centered and procedure-centered.

Objective-centered programming problems are those that are focused on creating an algorithm to perform a certain action. No requirements about what mechanisms (instructions, libraries, etc.) should be employed are included. Students are free to create any solution being able to perform the proposed action. However, in an Industry 4.0 context, students should investigate different options to be familiar with different approaches and select the most efficient, fastest or lightest. In these objective-centered problems, the boundary conditions may be considered as key variable parameters to create totally different problems. For example, "creating an algorithm to sample a certain input analog signal" is a problem generating an entire family of totally different solutions depending on the proposed signal (peak value, waveform, bandwidth, etc.). However, from the validation point of view, the same scheme and correction algorithm may be employed for all instances of the same base problem (as all of them have the same solution). Some problems of this type are: (i) *calculating the mean power of an electrical device* (as the solution depends on the selected current sensor); (ii) *decoding messages received from infrared modules* (many different libraries are available depending on the infrared module); or (iii) *obtaining the GPS position* (many different libraries are available depending on the module).

Procedure-centered programming problems are those that are focused on the use or certain microcontroller mechanisms (usually instructions). To enforce students to use a certain mechanism, the boundary conditions must be very rigid and cannot be modified. In order to create different specific problems from a base problem, the internal configuration parameters in the program must be requested to be different. For example, "write a digital HIGH signal in a pin" must indicate different pin numbers in different problem to enforce the solutions to be different (and avoid plagiarism or memorization). From the validation point of view,

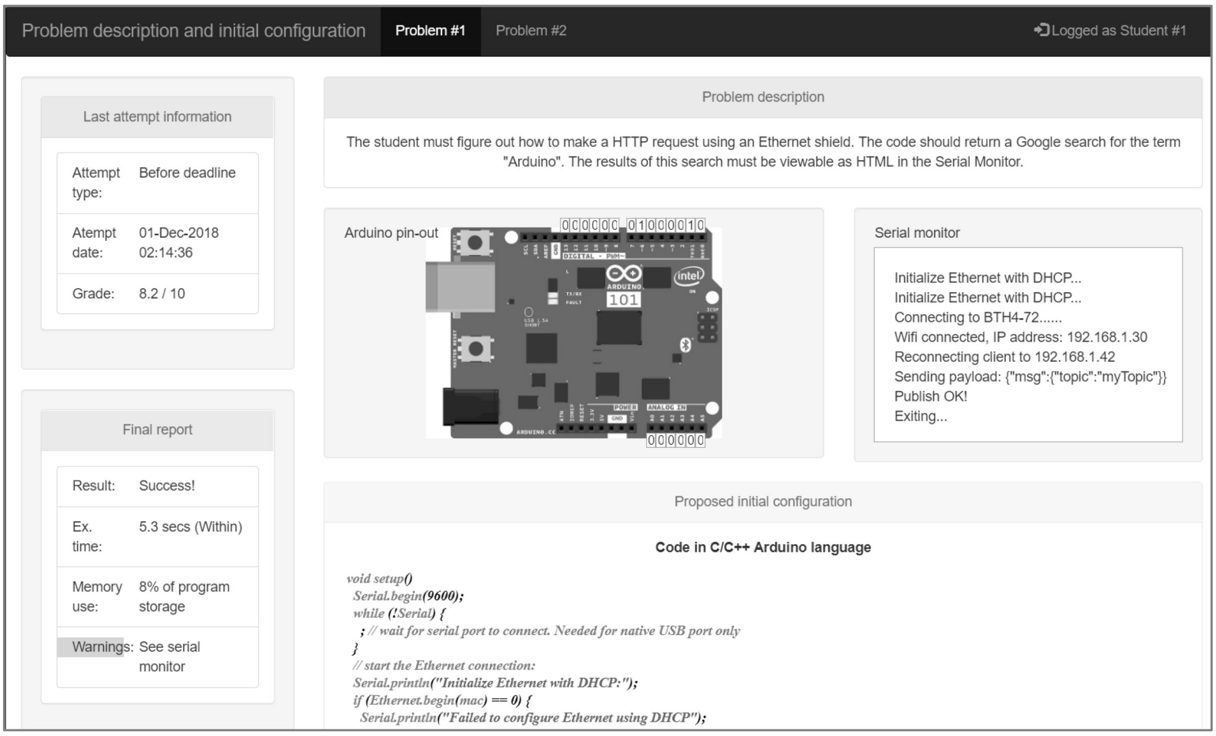


Fig. 3. Proposed advanced correction and validation system with real time feedback: student interface, employed to solve problems and obtain real-time feedback.

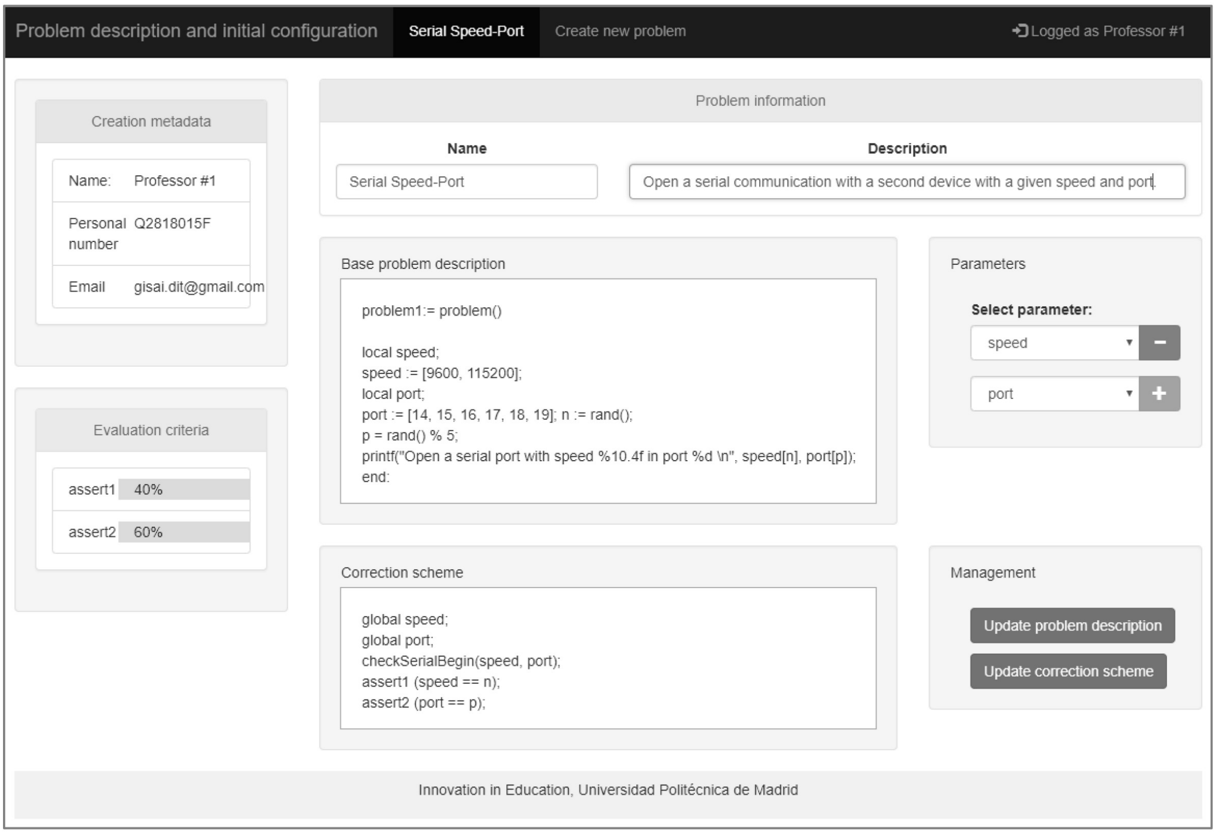


Fig. 4. Proposed advanced correction and validation system with real time feedback: professor interface, employed to create problems, automatic feedback and control the students' learning.

each one of these specific problems executes a different action and requires a different correction scheme. The generation of different specific solution from the base solution is necessary. Some problems of this type are: (i) *opening a serial communication with a second device* (the speed, port number, etc. are variable); or (ii) *configuring a PWM (Pulse Width Modulation) signal* (where the duty cycle, frequency, etc. are variable).

To codify problems, both types, professors are provided with a specific interface (see Fig. 4). In this interface, professors may create base problems which are later instanced by the problem-generation engine. A base problem is a general template representing an entire problem family. These patterns include three different elements:

- The base problem descriptor. This is the static part of the base problem. It includes all elements and descriptions common to all problems belonging to the same family. The problem-generation engine does not modify this part.
- Variable parameters. The problem descriptor has embedded symbols which are substituted by specific values from a set to create specific problems from the pattern. Possible values for each parameter must be also indicated by professors. Values for variable parameters may be selected randomly and independently among the set of possible values, or some additional rule may be defined. The problem-generation engine will create instances of the base problem substituting symbols by specific values.
- Correction scheme. It refers the correction strategy. In objective-centered problems, each problem family has a unique validation strategy, as all solutions should perform the same action. In procedure-centered problems, the validation scheme must be also defined as a pattern with variation points (symbols). The problem-generation engine, in that case, creates both at the same time: the problem and the corresponding solution. Global evaluation criteria are also configured at this point, considering parameter validation and qualification weights.

The proposed Industry 4.0 tool includes an editor to enable the base problem definition. Each pattern gets identified by its creator's identity (name, personal number, etc.) a title, and the topic or unit it belongs to. As all professors involved in this experience had programming skills, the editor did not have graphical instruments. All elements (problem descriptor, parameters and correction scheme) were defined using a symbolic language (see Fig. 5).

3.1.3 *Real-time validation scheme*

Once a student submits a solution, it is sent to the evaluation engine. The engine executes the solution in a sandbox which publicly offers two information pieces: the state of each pin in the microcontroller board, and the content written in the monitor serial port.

At the same time, the correction pattern is loaded into a supervisory process. This control process constantly monitors the execution in the sandbox and creates a feedback loop with the student to provide him with real-time information about his solution's performance. In particular, in procedure-centered problems, the state after each instruction is compared with the expected one (obtained from the corresponding solution) and students are informed at real-time about the results. On the contrary, in objective-centered problems, where only the final result must be evaluated, both information pieces offered by the sandbox are directly sent to the students (no comparison step-by-step is done). Besides, in this case, the supervisory process evaluates some relevant performance parameters. Three indicators are considered: the memory usage, the number of code malfunctions and the required execution time. Parameters are represented at real-time in graphics, so students can identify the most efficient parts of their code as well as the least efficient ones. The supervisory process in objective-centered problems compares the final result to the expected one to inform students and professors about the validity of the proposed solution.

After executing the main loop in the solution the number of times indicated by professor in the system configuration, the supervisory process cancels the execution and generates a final report. This report shows a global evaluation of the proposed solution according to evaluation criteria proposed by professor during the base problem definition.

```
problem1:= problem()
       local speed;
       speed := [9600, 115200];
       n := rand();
       printf(`Open a serial port with an speed %10.4f\n`, speed[n]);
end:
```

Fig. 5. Example, a base problem.

3.2 An industry 4.0 virtual learning environment

The first proposed tool is a very promising solution to accelerate the exercises' lifecycle, according to Industry 4.0 students' profile, needs and requirements. However, Industry 4.0 is characterized by the high and seamless integration between hardware and software and how they influence each other. Thus, many Industry 4.0 competencies cannot be developed but using real devices and environments. In this context, the previously proposed tool is not complete and requires an additional complementary instrument.

In large engineering courses, laboratory infrastructures must be shared among a great number of students, which cannot access to real devices as much as they want. In order to address this problem, we propose a Virtual Learning Environment (VLE) [27] based on e-learning technologies to provide students with a free access to real devices and infrastructures. Most virtual laboratories are only virtual constructions [28, 29]; thus, real hardware-related problems (such as electrical noise, numerical errors, etc.) and competencies (critical in Industry 4.0) cannot be developed. In our proposal, the VLE is finally supported by a real infrastructure so students must face real problems and situations.

Fig. 6 shows the architecture of the proposed VLE. This new tool does not require an automatic problem generation and correction system, as underlying hardware introduces all needed randomness and variations. Thus, the proposed VLE only includes a problem repository where professors may introduce exercises through a specific interface. In order to exploit all synergies between both proposed tools, problems in this repository may be extracted from an objective-centered problem collection in the real-time correction system. Students must login in the official e-learning platform to get into the VLE. Then, the system proposes a problem and students, in the same interface but in a different frame, must create a solution (see Fig. 7).

The solution (code) is then executed in a remote real hardware platform whose state is constantly monitored. Using remote communication procedures, students can control the hardware infrastructure at real-time. The system cancels the execution of each program after some time (as microcontroller programs are infinite). Then, an evaluation module offers a report, analyzing some practical indicators usually not evaluated in only-virtual tools, such as the measurement error. Finally, when students request for a new problem or log out, the system (through the evaluation module) creates a final report describing the student performance and learning.

The real hardware platform supporting the final solution execution is composed by several different Arduino microcontroller boards. These boards are interconnected to enable the creation of programs involving several different microcontrollers. Besides, signals around the physical devices are monitored and controlled through a Digital Signal Processing instrument. This instrument, as well as the microcontrollers, are connected to a computer acting as remote server and platform manager for the VLE. Up to ten different identical infrastructures were deployed to guarantee all students can work with the VLE. Fig. 8 shows one of those infrastructures. It must be noticed that the proposed

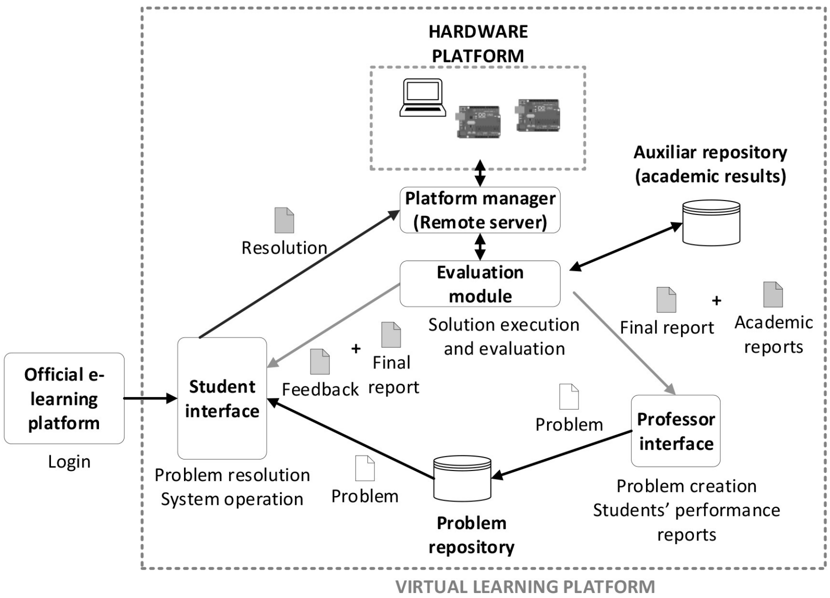


Fig. 6. Architecture of the proposed VLE.

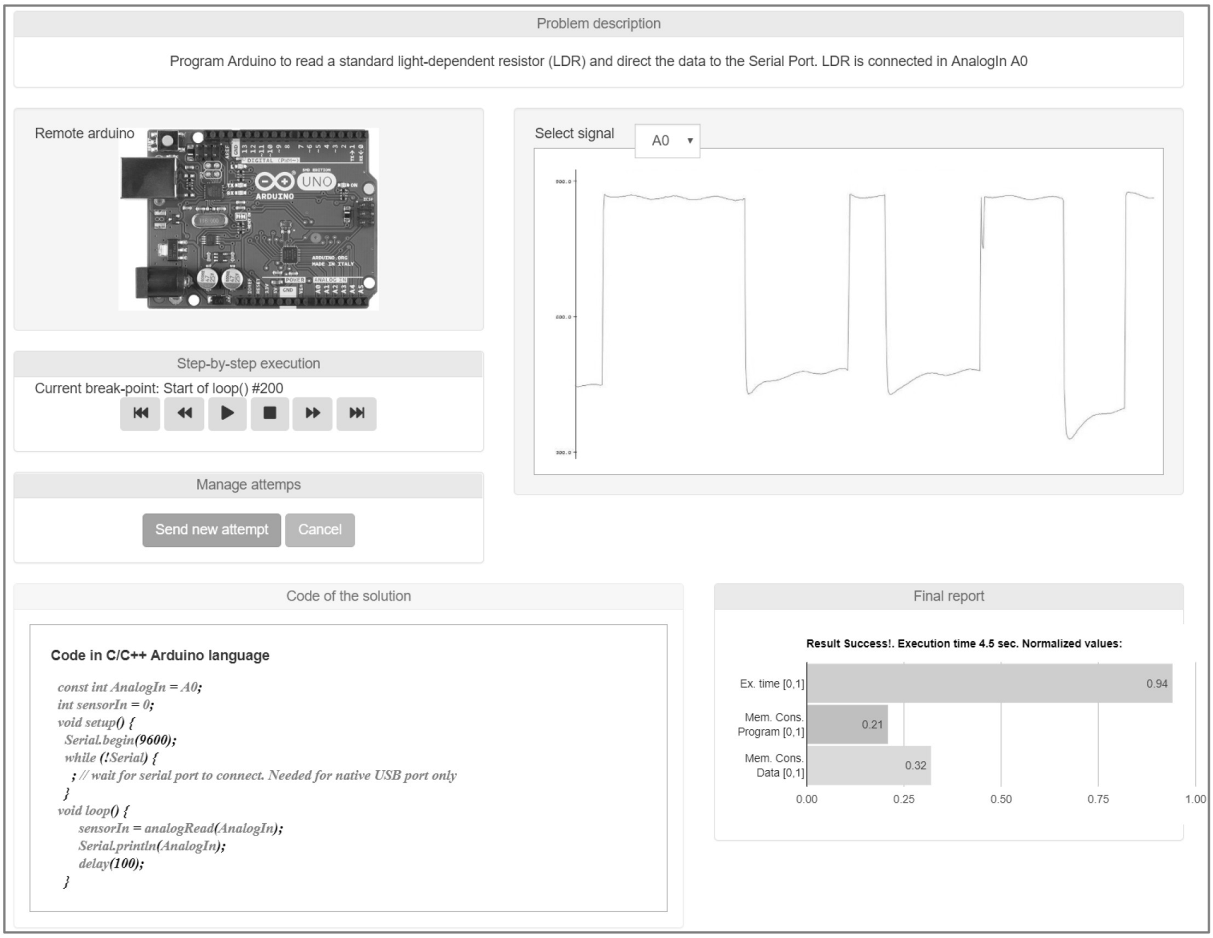


Fig. 7. Student interface in the proposed VLE.

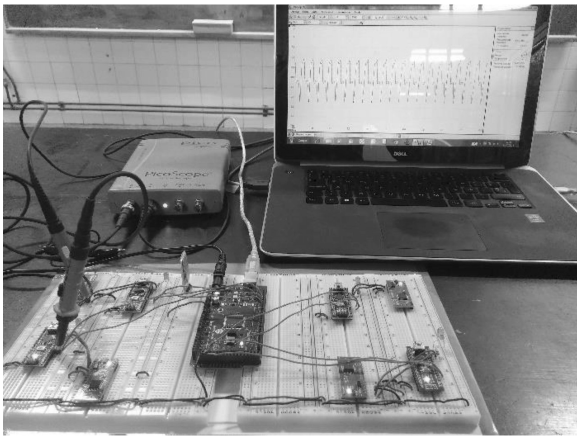


Fig. 8. Hardware platform supporting the VLE.

remote infrastructure is similar to a real microcontroller programming laboratory.

4. Experimental results

The proposed tools have been implemented and integrated into two different subjects focused on microcontroller programming in two different degree programs: Telecommunication Engineering and Bioengineering. In this section we are describing the context of this experience, and presenting the results obtained for the last three years.

4.1 Context

The proposed experiment has been developed in two microcontroller programming courses belonging to Telecommunication Engineering and Bioengineering degree programs. Considered subjects are mandatory in the degree programs under study. The experience was running for three years, from 2015 to 2017. Selected subjects in the considered degree programs are organized as theoretical sessions, based on professors' notes, and experimental sessions where problems are discussed, worked and programmed to be executed by real devices. Four hours per week are dedicated to these subjects. Only nine experimental sessions are considered along each course; the other sessions are theoretical.

Table 1 and Table 2 describes the subjects' organization, including the number of students each year, the units considered in each subject, and the usual schedule. The total number of pro-

Table 1. Context description for Subject A. Number of students and subject structure

Year	Total number of students	Contents. Number of problems					
		Hardware	Instructions	Architecture	Interruptions	I/O	Timing
2015	338	8	10	8	7	8	10
2016	311	8	8	8	10	10	10
2017	306	8	8	8	10	10	10
Weeks		1	3	1	2	3	4

Table 2. Context description for Subject B. Number of students and subject structure

Year	Total number of students	Contents. Number of problems					
		Basic information	Assembler	Configuration	Programing	I/O	FPGA and DSP
2015	115	9	9	6	12	9	3
2016	99	9	9	6	12	9	3
2017	117	9	9	6	12	9	3
Weeks		1	4	2	3	3	1

blems included in the proposed Industry 4.0 tools for each subject and unit is also described. To anonymize results and not contaminate the experience with pre-existing ideas, we label subject in Telecommunication Engineering as "Subject A" and subject in Bioengineering as "Subject B".

The final objective of this experiment is to answer some questions regarding the effectiveness of the proposed Industry 4.0 tools, in terms of students' motivation, learning level and Industry 4.0 competencies. Three research questions were formulated:

- Q1: Do the proposed Industry 4.0 tools enable students to improve their academic results?
- Q2: Does the use of the proposed educational tools enhance the students' motivation?
- Q3: Does the use of the proposed Industry 4.0 tools enable students to acquire Industry 4.0 competencies?

4.2 Method and participants

The validation described in this paper was planned, guided, monitored and evaluated by its authors (hereafter *experts*), who have more than five years of experience in knowledge management, Internet of Things and data analysis.

The experts chose, from general groups, a specific pilot group of students each year to validate the proposed tools. The other students were employed as control group. The pilot group was selected and configured to guarantee its homogeneity and statistical relevance. The selection process performed by experts took into account different profiles, with various technical skills and experience levels. Groups were configured considering the principles of gender equality. It was guaranteed that all groups were composed of comparable populations. Table 3 shows the characteristics of pilot groups for each year.

All the participants were treated anonymously by experts. No personal data related to the students' identification were stored or diffused outside the official platforms. All the experiments were performed under the conditions of respect for individual rights and ethical principles that govern research involving humans.

Participants in the pilot groups were always evaluated following the general criteria. Practical exercises have a weight of 50% in the final mark (either they are resolved using traditional methodologies or the proposed Industry 4.0 tools); but students must pass the final theoretical exams to take into account the results in the practical exercises. Official solutions to be evaluated manually by professors must be submitted to the official e-learning platform before the due date. All due dates are fixed after completing all theoretical sessions about each unit.

Table 3. Pilot groups configuration: statistical data

Year	Total number of students		Mean age		Standard deviation in age		Women percentage		Percentage of second enrollments	
	A	B	A	B	A	B	A	B	A	B
2015	26	18	18.7	18	0.23	0.18	39	70	8	2
2016	25	15	18.3	18	0.27	0.13	42	72	7	2
2017	25	17	18.5	17.5	0.31	0.12	40	73	7	1

4.3 Results: academic results

In order to evaluate the impact of the proposed tools in the students' academic results, we have divided the entire pilot group in different sub-groups: GQ4 includes students that solved less than 25% of proposed problems; GQ3 refers students that addressed between 25% and 50% problems available in the Industry 4.0 tools; GQ2 includes all students that solved more than 50% but less than 75% of problems; and finally GQ1 refers students that solved more than 75% of problems. Table 4 shows the evolution of these sub-groups in terms of number of students along the years.

As can be seen, students in Subject B tend to address a higher number of problems than students in Subject A. However, in both groups, most students address at least 50% of available problems. Considering these groups, the academic results are evaluated. Fig. 9 and Fig. 10 shows the results in boxplots for both subjects. Results are normalized to range between zero and the unit. The control group (made of non-participant students in the experience) is also represented. Most important statistical parameters about these results are also showed in Table 5, Table 6 and Table 7.

As can be seen, in general, students in Subject B are obtaining better academic results than students in Subject A. On the one hand, academic results show the mean mark is always above 0.5 in Subject A, except in the group GQ4 during 2017 and 2015. Besides, in the subgroup GQ1 mean marks are always above 0.75 in Subject A. On the other hand, in Subject B, mean marks are in general slightly higher (6%, approximately). Besides, all students in GQ1 obtained marks above 0.825, and all students got marks above 0.5 except during 2017 in the group GQ4. Dispersion in marks is also slightly lower in Subject B, showing that students evolve in a more homogeneous manner. Note that, in Subject B, moreover, results are more stable in time, especially in the first two quartiles (GQ1 and GQ2).

If now we analyze academic results in the control group, we note that marks have increased with time, especially in Subject B. In a general overview, global mean marks tend to be higher in the experimental groups than in groups with a traditional methodology (control group). This is a first evidence to ensure an affirmative response to the first research question (Q1: Do the proposed Industry 4.0 tools enable students to improve their academic results?).

However, as boxplot present overlapped areas, it is not possible to scientifically determine if there is a global and relevant improvement in the academic results by using the proposed Industry 4.0 tools. Therefore, we are employing a Mann-Whitney U test to evaluate this improvement. The Mann-Whitney U test is a nonparametric test of the null hypothesis that two samples come from the same population against an alternative hypothesis, comparing the mean values of the two samples. It is used to evaluate if two different data populations are similar or different (higher or lower). The p-value indicates the significance level of Mann-Whitney U

Table 4. Distribution of students into the different sub-groups defined in the pilot group

ADVANCED CORRECTION AND VALIDATION SYSTEM WITH REAL-TIME FEEDBACK

	GQ1		GQ2		GQ3		GQ4		Total	
Year	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
2015	8	5	12	6	4	5	2	2	26	18
2016	6	6	13	5	4	3	2	1	25	15
2017	8	5	10	5	5	5	2	2	25	17

INDUSTRY 4.0 VIRTUAL LEARNING ENVIRONMENT

	GQ1		GQ2		GQ3		GQ4		Total	
Year	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
2015	10	5	10	6	4	5	2	2	26	18
2016	9	6	10	5	4	3	2	1	25	15
2017	11	5	8	5	5	5	1	2	25	17

TOTAL (BOTH TOOLS)

	GQ1		GQ2		GQ3		GQ4		Total	
Year	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
2015	9	5	11	6	4	5	2	2	26	18
2016	9	6	10	5	4	3	2	1	25	15
2017	11	5	8	5	5	5	1	2	25	17

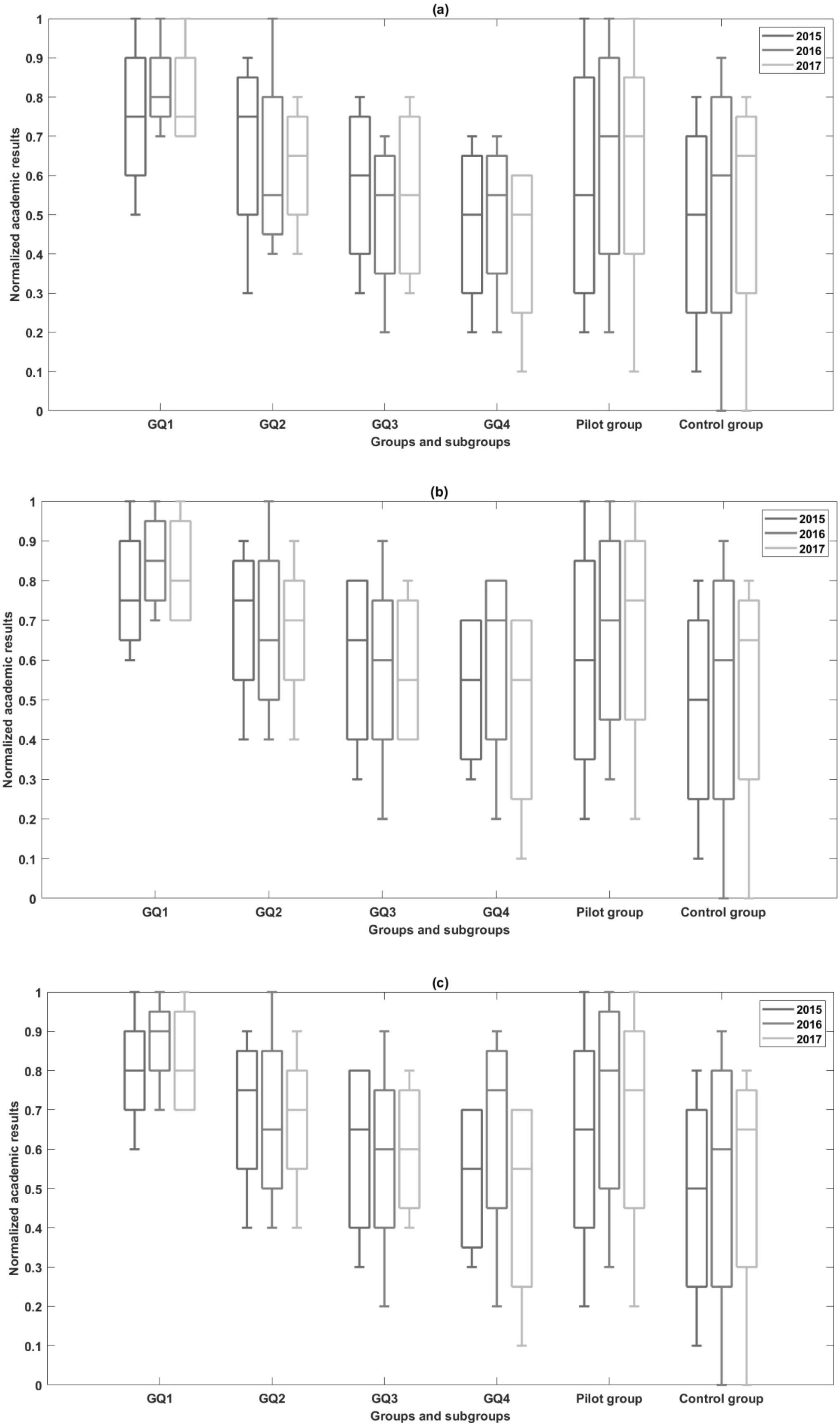


Fig. 9. Distribution of academic results of students in the pilot group (Subject A). (a) Students using the advanced correction and validation system with real-time feedback. (b) Students using the Industry 4.0 Virtual Learning Environment. (c) Global results.

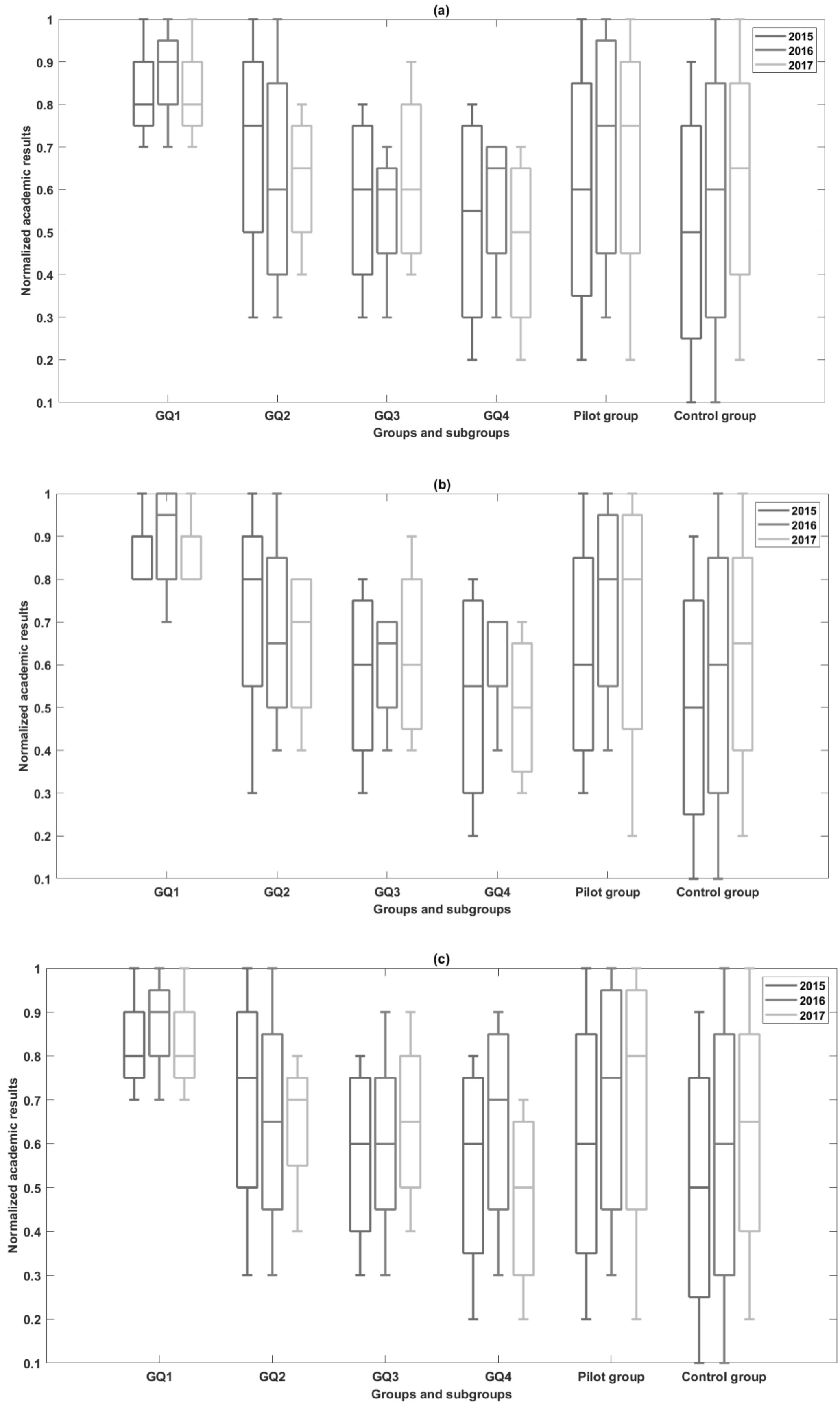


Fig. 10. Distribution of academic results of students in the pilot group (Subject B). (a) Students using the advanced correction and validation system with real-time feedback. (b) Students using the Industry 4.0 Virtual Learning Environment. (c) Global results.

Table 5. Normalized academic results of students in the pilot group. Statistical parameters. Subject A

ADVANCED CORRECTION AND VALIDATION SYSTEM WITH REAL-TIME FEEDBACK										
	GQ1		GQ2		GQ3		GQ4		Total	
Year	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std
2015	0.75	0.2082	0.675	0.263	0.575	0.2217	0.475	0.2217	0.575	0.35
2016	0.825	0.1258	0.625	0.263	0.500	0.2160	0.500	0.216	0.650	0.342
2017	0.8	0.1414	0.625	0.1708	0.550	0.238	0.425	0.2363	0.625	0.378
INDUSTRY 4.0 VIRTUAL LEARNING ENVIRONMENT										
	GQ1		GQ2		GQ3		GQ4		Total	
Year	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std
2015	0.775	0.1708	0.70	0.216	0.60	0.245	0.525	0.206	0.60	0.337
2016	0.85	0.1291	0.625	0.25	0.575	0.287	0.60	0.283	0.675	0.269
2017	0.825	0.15	0.625	0.206	0.575	0.206	0.475	0.2872	0.675	0.34
TOTAL (BOTH TOOLS)										
	GQ1		GQ2		GQ3		GQ4		Total	
Year	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std
2015	0.80	0.1633	0.70	0.216	0.60	0.245	0.525	0.206	0.625	0.33
2016	0.875	0.1258	0.675	0.250	0.575	0.287	0.65	0.311	0.725	0.31
2017	0.825	0.15	0.675	0.2062	0.60	0.183	0.475	0.287	0.675	0.34

Table 6. Academic results of students in the pilot group. Statistical parameters. Subject B

ADVANCED CORRECTION AND VALIDATION SYSTEM WITH REAL-TIME FEEDBACK										
	GQ1		GQ2		GQ3		GQ4		Total	
Year	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std
2015	0.8250	0.126	0.700	0.294	0.575	0.222	0.525	0.275	0.600	0.337
2016	0.8750	0.126	0.625	0.299	0.550	0.173	0.575	0.189	0.700	0.316
2017	0.8250	0.126	0.625	0.171	0.625	0.222	0.475	0.222	0.675	0.304
INDUSTRY 4.0 VIRTUAL LEARNING ENVIRONMENT										
	GQ1		GQ2		GQ3		GQ4		Total	
Year	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std
2015	0.850	0.100	0.725	0.299	0.575	0.222	0.525	0.275	0.625	0.299
2016	0.900	0.141	0.675	0.250	0.600	0.141	0.625	0.150	0.750	0.265
2017	0.850	0.100	0.650	0.195	0.625	0.222	0.500	0.181	0.700	0.356
TOTAL (BOTH TOOLS)										
	GQ1		GQ2		GQ3		GQ4		Total	
Year	Mean	std	Mean	std	Mean	std	Mean	std	Mean	std
2015	0.825	0.294	0.700	0.294	0.575	0.222	0.550	0.267	0.600	0.337
2016	0.875	0.129	0.650	0.289	0.600	0.245	0.650	0.265	0.700	0.316
2017	0.825	0.129	0.650	0.173	0.650	0.208	0.475	0.222	0.700	0.356

Table 7. Academic results of students in the control group. Statistical parameters

	Subject A		Subject B	
Year	Mean	std	Mean	std
2015	0.475	0.299	0.500	0.337
2016	0.525	0.386	0.575	0.378
2017	0.525	0.359	0.625	0.330

test. Table 8 shows the obtained results from the selected statistical test for Subject A, and Table 9 shows the equivalent results for subject B.

As can be seen, in Subject A, a relevant improvement in the academic results is reported in groups employing proposed Industry 4.0 tools and methodology. In general, besides, marks tend to be better as students address a higher number of problems.

Table 8. Evaluation of impact of proposed Industry 4.0 tools in the academic results. Results obtained from Mann-Whitney U statistical test. Subject A

ADVANCED CORRECTION AND VALIDATION SYSTEM WITH REAL-TIME FEEDBACK

	2015		**2016**		**2017**	
Test	***p*-value**	**Significance**	***p*-value**	**Significance**	***p*-value**	**Significance**
GQ1 – GQ2	2.64E-03	**	1.65E-03	**	1.66E-03	**
GQ2 – GQ3	1.24E-02	*	0.2851	NS	0.19003	NS
GQ3 – GQ4	3.147E-03	**	3.88E-03	**	0.00140	**
GQ1 – CONTROL	9.058E-10	***	4.134E-03	**	6.324E-04	***
PILOT – CONTROL	1.27E-03	**	2.22E-02	*	0.0403	*

INDUSTRY 4.0 VIRTUAL LEARNING ENVIRONMENT

	2015		**2016**		**2017**	
Test	***p*-value**	**Significance**	***p*-value**	**Significance**	***p*-value**	**Significance**
GQ1 – GQ2	2.785E-03	**	1.706E-03	**	1.419E-03	**
GQ2 – GQ3	3.469E-03	**	0.01022	*	0.05854	NS
GQ3 – GQ4	2.575E-03	**	3.572E-03	**	1.003E-03	**
GQ1 – CONTROL	9.649E-13	***	4.854E-05	***	1.419E-05	***
PILOT – CONTROL	1.576E-04	***	2.003E-03	**	4.128E-03	**

TOTAL (BOTH TOOLS)

	2015		**2016**		**2017**	
Test	***p*-value**	**Significance**	***p*-value**	**Significance**	***p*-value**	**Significance**
GQ1 – GQ2	1.922E-03	**	2.432E-03	**	3.922E-03	**
GQ2 – GQ3	9.595E-03	*	0.17125	NS	0.0605	NS
GQ3 – GQ4	3.557E-03	**	2.878E-03	**	1.155E-03	**
GQ1 – CONTROL	3.57E-12	***	7.577E-04	***	1.712E-05	***
PILOT – CONTROL	1.491E-03	**	2.431E-03	**	5.000E-03	**

NS not significant; * significant at $p < 0.05$; ** significant at $p < 0.005$; *** significant at $p < 0.001$.

Thus, even in this context, the students' effort is the most important parameter affecting the final academic results in higher education. It must be noted that results between students belonging to GQ2 and GQ3 sometimes do not show a statistically significant difference, while results from students in GQ1 are always much better than results in the control group.

Although, globally, the proposed Industry 4.0 tools have a relevant impact (with a medium statistical significance), some differences can be noted. On the one hand the impact of the Industry 4.0 VLE is higher than the impact of the automatic correction system. This situation is constant in time for all years under study. On the other hand, in 2015 results were slightly better than during the next years. A phenomenon we can explain by the initial interest caused by the new tools, a common situation in educational experiments [30].

Comparing these results with students' marks in Subject B (see Table 9) we noted the impact of Industry 4.0 is higher in this second case. First, academic results in the experimental groups showed a statistically relevant improvement for all tools, subgroups and years. Later, it can be seen the relevance of the generated impact is higher in Subject B than in Subject A. However, some patterns are seen in both subjects. Industry 4.0 VLE has a greater impact for both subjects, and the experience during the first course had much more significant impact due to the novelty of the proposal. Finally, as in Subject A, results show a significant improvement in the students' academic results when using the proposed tools.

Considering all these results and discussions we can conclude that the use of the proposed Industry 4.0 tools enables students to improve their academic results; answering the first research question.

4.4 Results: surveys

Previous analyses have answered Q1, about improvement in the academic results. However, two additional research questions must be also answered. In order to answer these last two questions a study based on surveys was carried out each year. Students and professors were asked every year to fulfill a questionnaire about the experience and their perception. In that way, two perspectives were considered: learning and teaching. Besides, professors offered their professional experience and contacts to enrich this study with the work market's perception.

Table 9. Evaluation of impact of proposed Industry 4.0 tools in the academic results. Results obtained from Mann-Whitney U statistical test. Subject B

ADVANCED CORRECTION AND VALIDATION SYSTEM WITH REAL-TIME FEEDBACK						
	2015		2016		2017	
Test	*p*-value	Significance	*p*-value	Significance	*p*-value	Significance
GQ1 – GQ2	4.898E-06	***	2.760E-03	**	9.597E-05	***
GQ2 – GQ3	4.456E-03	**	6.797E-03	*	3.404E-02	*
GQ3 – GQ4	3.463E-03	**	6.551E-03	*	2.853E-03	**
GQ1 – CONTROL	7.094E-29	***	1.626E-03	**	2.283E-17	***
PILOT – CONTROL	1.547E-03	**	1.190E-03	**	1.513E-03	**
INDUSTRY 4.0 VIRTUAL LEARNING ENVIRONMENT						
	2015		2016		2017	
Test	*p*-value	Significance	*p*-value	Significance	*p*-value	Significance
GQ1 – GQ2	5.472E-05	***	2.543E-05	***	2.160E-03	**
GQ2 – GQ3	1.386E-03	**	2.293E-03	**	4.733E-02	*
GQ3 – GQ4	1.493E-03	**	3.500E-03	**	3.157E-03	**
GQ1 – CONTROL	2.575E-17	***	1.966E-13	***	8.308E-39	***
PILOT – CONTROL	8.143E-07	***	2.511E-04	***	5.803E-07	***
TOTAL (BOTH TOOLS)						
	2015		2016		2017	
Test	*p*-value	Significance	*p*-value	Significance	*p*-value	Significance
GQ1 – GQ2	5.947E-06	***	1.693E-03	**	1.450E-03	**
GQ2 – GQ3	1.172E-03	**	5.499E-03	*	0.01209	*
GQ3 – GQ4	2.858E-03	**	3.340E-03	**	2.342E-03	**
GQ1 – CONTROL	5.752E-23	***	4.694E-04	***	4.607E-26	***
PILOT – CONTROL	5.676E-06	***	4.108E-04	***	1.200E-03	**

NS not significant; * significant at $p < 0.05$; ** significant at $p < 0.005$; *** significant at $p < 0.001$.

Fig. 11 shows the most relevant results from the students' survey, aggregating the responses from all years. Questions are related to two topics: their motivation and how they feel about their new competencies and qualification. Each question was graded following the Likert scale [31] where the unit represents "strongly disagree", and the maximum value (five) represents "strongly agree".

As can be seen, for all questions, the percentage of students answering "agree" or "strongly agree" is higher in the pilot group than in the control group. First two questions refer the students' motivation, and the two last questions refer the acquisition of Industry 4.0 competencies. In particular, in the pilot group, more than 80% of students consider the subject caught their interest, contrary to 65% in the control group. Besides, 70% of students think the competencies they work with Industry 4.0 are useful in companies, contrary to 40% (approximately) in the control group. This is a first evidence about the obtained improvement in the student motivation and the acquisition of Industry 4.0 competencies. As Fig. 11 shows the "learning" perspective (students), it is especially important the obtained results about the students' motivation.

In order to complement the previous results, Fig. 12 shows the most relevant professors' answers (teaching approach), aggregating the responses from all years. The proposed survey had the same structure as explained before, using the Likert scale as main instrument. Also, as before, first two questions refer the students' motivation and the two last questions refer the acquisition of Industry 4.0 competencies. The obtained results show clear and relevant differences between the pilot and the control group. While more than 80% professors noticed and reported students were motivated in the pilot group, only around 50% did the same in the control group. Especially relevant is the incredible difference in the percentage of professors thinking students have acquired Industry 4.0 competencies: only 35% in the control group, up to 65% in the pilot group.

The use of the Likert scale enables us to employ statistical techniques in order to provide scientific validity to answer the last two research questions. In particular, we are using the Mann-Whitney U test, using the same configuration as explained in the previous section. Table 10 shows the obtained results. As can be seen, a very statically relevant improvement is reported in both, the students' motivation and the acquisition of Industry 4.0.

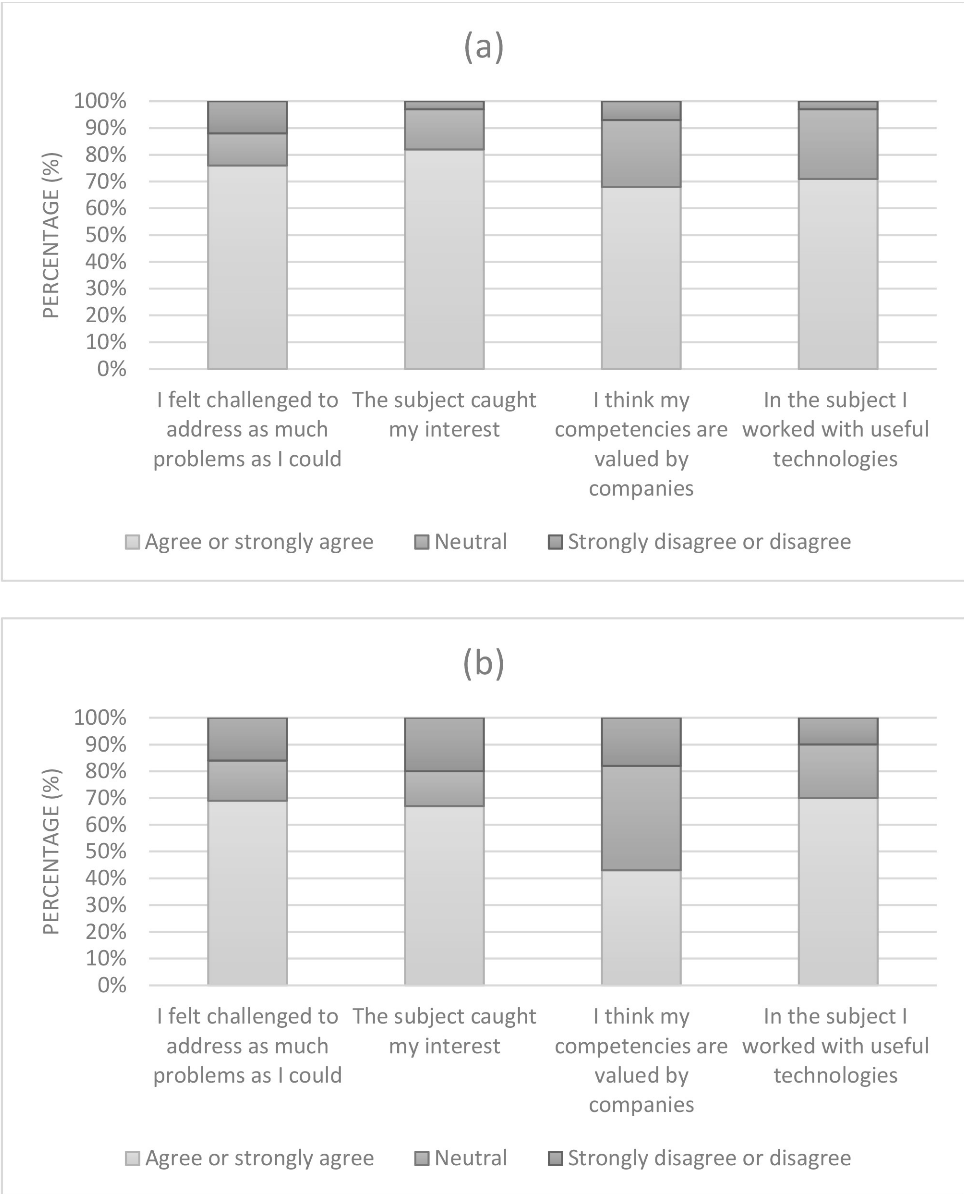


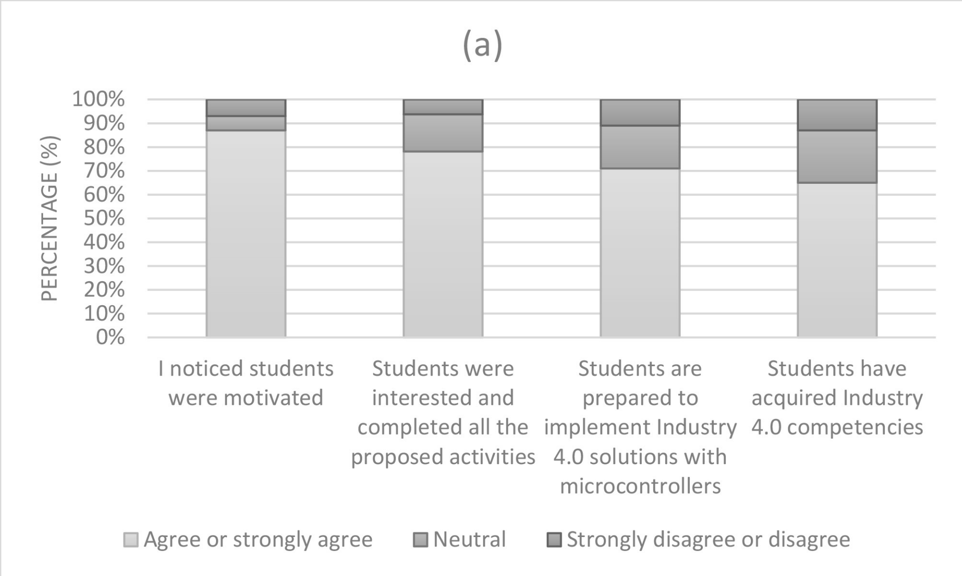
Fig. 11. Results from the students' survey. (a) Results for the pilot group. (b) Results for the control group.

This improvement is constant in time and especially important from the ''teaching'' view (professors). These results allow us to provide an affirmative answer to the two last research questions (Q2: Does the use of the proposed educational tools enhance the students' motivation?; Q3: Does the use of the proposed Industry 4.0 tools enable students to acquire Industry 4.0 competencies?).

5. Conclusions and future work

This paper evaluates the impact of the early adoption of Industry 4.0 tools and methods on engineering education. The proposed analysis considers two points of view: professors (teaching) and students (learning). In this context, two experiences were conducted with two tools: an advanced correction and validation system with real-time feedback and a virtual learning environment supported by a remote laboratory. In this paper we describe two different, but complementary, experiences focused on addressing these challenges in the IT area, specifically in microcontroller programming. During several consecutive courses, two new Industry 4.0 learning tools were employed (by an experimental group of students, different each year) in two subjects where surveys showed a very low motivation level among students, a great failure rate and a decreasing students' working time.

From the obtained results the following conclu-



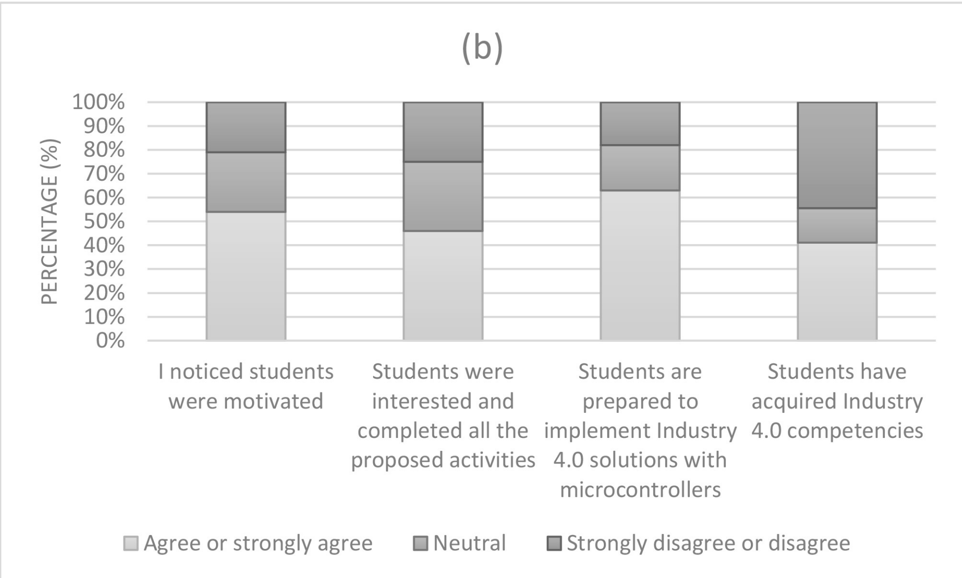


Fig. 12. Results from the professors' survey. (a) Results for the pilot group. (b) Results for the control group.

Table 10. Evaluation of impact of proposed Industry 4.0 tools in the students' motivation and Industry 4.0 competencies acquisition. Results obtained from personal surveys through the Mann-Whitney U statistical test

STUDENTS (LEARNING)				
Question	**2015**	**2016**	**2017**	**Total**
I felt challenged to address as much problems as I could	**	*	**	**
The subject caught my interest	**	**	*	*
I think my competencies are valued by companies	*	**	*	*
In the subject I worked with useful technologies	*	**	**	**
PROFESSORS (TEACHING)				
Question	**2015**	**2016**	**2017**	**Total**
I noticed students were motivated	***	***	***	***
Students were interested and completed all the proposed activities	***	**	**	**
Students are prepared to implement Industry 4.0 solutions with microcontrollers	**	**	**	**
Students have acquired Industry 4.0 competencies	***	***	***	***

NS not significant; * significant at $p < 0.05$; ** significant at $p < 0.005$; *** significant at $p < 0.001$.

sions may be extracted. Using Industry 4.0 tools in education, engineering students improve their academic results. Besides, Industry 4.0 educational tools enhance the students' motivation. Finally, the proposed Industry 4.0 tools enable students to acquire Industry 4.0 competencies, required in the future work market.

Future works will consider the complete implementation of this experience for all students in the subjects under study.

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