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An Introductory Undergraduate Course on Fluid Power Systems*

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Fluid power systems play an essential role in modern industry, providing actuation means for a wide number of applications ranging from simple on–off movements, typically performed by pneumatic systems, up to complex servo hydraulic mechanisms used in industry. Despite this relevance, the studies of fluid power systems at an undergraduate level are often only focused on analytical analysis, creating a gap between the theory presented in the classroom and real world industrial problems. This paper presents an introductory graduate course on pneumatics and hydraulics where the more theoretical contents are complemented with unique educational laboratory experiments using 'off-the-shelf' industrial components and circuits. Sample lab assignments are described that emphasize the pedagogical value of this type of activities. The five different evaluation components used to assess students are presented and discussed. Finally, statistical results of the student's opinion and grades on the course over the last 5 years are presented and commented.

Keywords: education; laboratory; pneumatic systems; hydraulic systems; mechatronics

1. Introduction

Hydraulic and pneumatic systems can be found in a broad range of engineering applications whenever motion and force control are needed. Ranging from simple movements between two end positions, typically associated with pneumatics, to more evolved high force, high accuracy and high performance servo hydraulic systems, fluid power is extensively employed in a wide range of domains. Some of the more common application sectors include aerospace, construction, agriculture, forestry, leisure, manufacture, materials handling, marine among others [1].

The relevance of manufacturing related contents in a mechanical or industrial engineering degree has been discussed in detail in [2]. Typically, fluid power courses are included in a Mechanical, Industrial or Mechatronics Engineering degree but, despite the eminent technological nature of the subject, hydraulics and pneumatics are quite often only taught from a theoretical approach, by endorsing students with the abilities to analyse and synthesize pneumatic and hydraulic circuits [3]. This approach contrasts with the essential nature of engineering since, as emphasized in [4], engineering is a practising profession, so engineering education should prepare students to *practise* engineering. Instructional laboratories should therefore play major roles in engineering education in both undergraduate and graduate studies, so that conceptual understanding, social and professional skills of students are reinforced [4, 5]. Several benefits can be found in laboratory based teaching. It may promote social and team skills, potentially leading to a higher level of integration of students into the institution. This factor is known ultimately to contribute to students' decisions on whether or not to leave university [6, 7] and can therefore contribute to reducing attrition. In fact, research results suggest that there are several institutional variables that seem to encourage attrition, like large class sizes, inaccessible instructors, uninspiring teaching methods, insufficient student support networks and poorly integrated curricula [8–10]. Hands-on team work in a pneumatic and hydraulic laboratory may therefore contribute to increasing the students' interest in Engineering studies as a whole. In addition to the previously arguments, students of Mechanical Engineering at the University of Porto have long acknowledged the benefits of laboratory teaching [11].

The implementation of the Bologna process [12] at the Faculty of Engineering of the University of Porto (FEUP) in Portugal was performed in the academic year 2005/2006. The previous five-year Mechanical Engineering degree was replaced by a five-year integrated master degree composed of two parts: a three year bachelor followed by a two years master degree. In this way, the weight of industrial actuation systems was sharply reduced. This reduction forced the choice between a more theoretical approach, based on the synthesis and analysis of circuits, or a more hands-on, technological based approach. Several arguments sustained the option to favour the latter: first, pre Bologna students typically complained about the little or no time that they spent studying real pumps, motors and other pneumatic and hydraulic equipment. This is a common criticism of Mechanical Engineering students, not only at the University of Porto but also at

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other universities in Portugal [13]. This view is in fact in line with a study performed by Felder and Spurlin [14] where a student learning style model developed in [15] and [16] was applied to engineering students in different universities around the world. It was found that the majority of students prefer to perceive *sensory* information (physical sensations, sounds and sights) rather than *intuitive* information (memory, thoughts). Furthermore, students consider *visual* (diagrams, demonstrations) information to be more effective than *verbal* information (spoken and written explanations) and prefer to process information in an *active* way (participating in a physical activity or discussion) rather than in a reflective way (through introspection). The hands-on approach can therefore provide a natural way to achieve the aforementioned students' preferences. Second, in the years preceding the Bologna reformulation, a vast collection of new and used hydraulic components (typically donated by industry) was gathered and organized. Only in 2006 did this collection become coherent and sufficiently complete to enable a good set of work for students to perform.

It is possible to find several studies in literature concerning laboratory or hands-on activities in a wide range of engineering areas. For instance, in [17] Starrett and Morcos describe the developments performed at Kansas State University to deliver students with a more hands-on learning experience in the field of electrical power systems and machinery. In another study [18], Carryer provides heuristic guidelines that were used in the development of convenient mechatronic laboratory experiments in the Design Division of the Mechanical Engineering Department at Stanford University. Another interesting study can be found in [19], where a graduate course in Mechatronics and the laboratory experiences associated with it are described in detail. In [20], Arkin *et. al.* describe the strategies and procedures followed in forming an interdisciplinary mechatronic laboratory involving different institutions within Georgia Institute of Technology. This approach proved to be effective not only from a cost effectiveness perspective but also because it allowed students with different backgrounds to integrate their different learning experiences. Also in a recent study [21], Chen *et al.* describe a six year experience in a mechatronics course where emphasis is given to the linking between the theoretical and the practical contents of mechatronics control engineering. More specific studies can also be found like, for example, that developed by Petric and Situm in [22], where an undergraduate project within a mechatronic course is described. This project includes the modelling, control and actual implementation of the control law to a pneumatic driven inverted pendulum. Another example of specific mechatronics projects can be found in [23], where Stankovski *et al.* describe the use of a didactic manipulator by students enrolled in courses of Mechatronics and Industrial Engineering degrees. The hands-on approach is naturally not restricted to the mechatronics area. To state just a few examples, in [24] Shapira describes the development of a construction engineering laboratory at the Civil Engineering Department of the Technion–Israel Institute of Technology that tried to 'soften' the shock that recent graduates suffer when facing the real world of construction. In [25] a 'Mechanical Dissection' approach is followed, i.e., a mechanical system is studied by dismantling it to acknowledge how its specific function is realized. Another interesting study can be found in [26], where Todorovich *et al.* conclude that the development of a laboratory for programmable logic teaching ultimately paid back the effort made both financially and in human resources. Specific studies on hands-on activities regarding the teaching of pneumatic and hydraulic systems are harder to find, although an exception can be found in the study performed by Alleyne in [3], where the development of a fluid power lab at the Mechanical and Industrial Engineering Department of the University of Illinois is described. This laboratory is mainly focused on the control of fluid power systems and Alleyne emphasizes the pedagogical value of real world experiments regarding key aspects of Systems Dynamics and Control, namely unmodelled dynamics, modelling errors and nonlinear behaviour.

This paper presents the after Bologna course on Hydraulic and Pneumatic Systems at the Mechanical Engineering five-year integrated master degree at the University of Porto. The analysis is performed during the last five years, and does not include the transition year 2005/2006 as it represents a transient period involving the pre- and post- Bologna curriculum for which an analysis becomes difficult to perform. Emphasis is given to the laboratory experience as the authors are convinced they truly represent an added value to Mechanical Engineers graduating at the University of Porto and that this experience may benefit teachers in other universities. The positive and negative aspects of the approach that was followed are presented. This paper is organized as follows. In Section 2 a general description of the course is provided. Section 3 details several team work lab experiments performed by students. Section 4 presents the results that students obtained for the different components of the assessment procedures and Section 5 presents the students' perspective of the course. Finally, Section 6 presents the main conclusions and future directions to be followed.

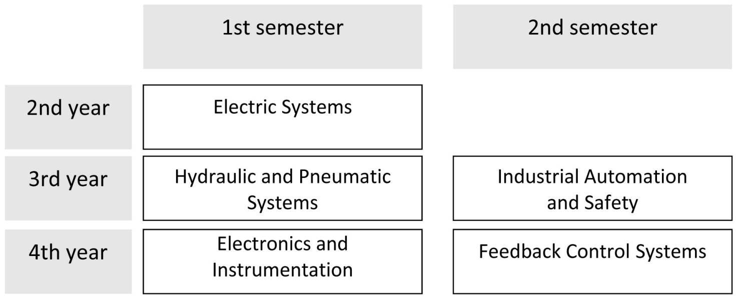

Fig. 1. Automation courses common to all students in the Mechanical Engineering master degree at FEUP.

Table 1. Average number of students in tutorial and laboratory classes

	Tutorial classes			Laboratory classes			
	Average number of students per class	Number of classes	Number of hours per week and class	Average number of students per class	Number of classes	Number of hours per week and class	Total number of matriculated students
2007/2008	105	2	3 × 1 h	19.1	11	1.5	210
2008/2009	78.5	2	3 × 1 h	13.1	12	1.5	157
2009/2010	91.5	2	3 × 1 h	16.6	11	1.5	183
2010/2011	97.5	2	3 × 1 h	17.7	11	1.5	195
2011/2012	99.5	2	3 × 1 h	17.1	12	1.5	199

2. Description of the course

The Mechanical Engineering master degree at the University of Porto is a five-year degree: the first four years are common to all students and in the last year the students have to choose one of the following five specialization areas: 1) fluid and energy systems, 2) materials and fabrication processes, 3) industrial management, 4) applied and structural mechanics or 5) automation. The Hydraulic and Pneumatic Systems (HPS) course is common to all students and appears in the third year as the second course of the automation area, after Electrical Systems, as shown schematically in Fig. 1.

2.1 Course organization and contents

The HPS course is based on tutorial and lab sessions. Students are divided into two classes for tutorial sessions and into an average of approximately twelve classes for laboratory sessions. This division leads to an average of approximately ninety-five students in each of the two tutorial classes and an average of approximately seventeen students in each laboratory class—see Table 1. It should be underlined that in the scholar year 2007/2008 a higher number of students and a lower number of classes led to an occasionally high number of students per class.

Tutorial sessions are devoted to present and discuss concepts, principles and technical issues of both pneumatic and hydraulic systems. Strong emphasis is given on the use of video clips, simulations and animations in order to make technological issues more perceptive. Table 2 lists the main topics covered in the tutorial sessions, giving as an example the contents of scholar year 2010/2011. Besides recommended books, students have online access to other types of support material: the lecture notes, the slides and videos shown in tutorial lectures.

In the lab sessions students are organized in groups of three or four elements that remain constant as a group during the course. In each session students have a script that guides their work towards the implementation of a particular circuit or towards a thorough study of working principles (or technological details) of pneumatic or hydraulic components; see Table 3. In component studying sessions, students are faced with a set of components and a script with questions that intend to induce the manipulation of the component under study so that its working principle or technological particularity

Table 2. Course tutorial contents in year 2010/2011

Subject	Hours
Basic concepts of pneumatic energy and systems	3
Pneumatic actuators and motors	4
Pneumatic valves	2
Synthesis and analysis of pneumatic circuits	4
Introduction to hydraulic systems	1
Hydraulic actuators	1
Hydraulic pumps and motors	6
Hydraulic valves	5
Synthesis and analysis of hydraulic circuits	8

Table 3. Course laboratory contents in year 2010/2011

Subject	Hours
Pneumatic	
P1—Introduction to laboratory sessions: generic view of pneumatic and hydraulic circuits and their applications.	1.5
P2—Elementary command of a pneumatic actuator: pneumatic and electropneumatic circuits. Symbolic drawing and simulation.	1.5
P3—Study and implementation of two pneumatic circuits: i) opening and closing a pneumatic actuated door and ii) unstacking a pile of components.	1.5
P4—Study and implementation of previous sessions circuits using an electropneumatic solution.	1.5
P5—Study and implementation of two circuits: i) a pneumatic circuit to automatically engrave a sheet metal band, ii) an electropneumatic circuit to perform automatic dosing.	1.5
Hydraulic	
H1—Study of hydraulic actuators: parts, construction solutions and sealing elements. Analysis of different hydraulic equipment	1.5
H2—Study and analysis of gear and vane type machines and power packs. Experimental determination of the flow rate of a gear pump.	1.5
H3—Study and analysis of piston machines and torque motors. Experimental evaluation of the volumetric efficiency of a gear pump.	1.5
H4—Study and analysis of directional and pressure valves. Experimental determination of a relief valve characteristic.	1.5
H5—Study and analysis of fluxometric and check valves. Experimental determination of two flow control valves characteristics, with and without pressure compensation.	1.5
H6—Analysis and implementation of several circuits: i) control of actuator with and without regeneration; ii) control of hydraulic actuator under gravitic load; iii) control of hydraulic motor; iv) manometric sequential movement of two actuators.	1.5

becomes clear. In circuit studying sessions, students are faced with a (didactic) industrial problem and experimental set-ups and they must design and build a circuit to solve them. Although these scripts typically present a possible (incomplete) solution to the problem under study, alternative solutions are encouraged and valued. Section 3 presents in detail two examples of such scripts. It should also be emphasized that an hour and a half is short for students to fully complete some of the tasks described in Table 3, as for instance in session H6. In these cases, the different subtasks are divided amongst groups at the beginning of the session. In the last twenty minutes of class time each group makes a presentation of the work developed to the other students, sharing both acquired knowledge and doubts with their colleagues.

2.2 Assessment methods

Evaluation is performed using five components that assess the different competences that students should develop, see Table 4.

These components correspond to discrete (part A) and distributed or continuous (part B) evaluation types and includes both individual (A, B1, B2, B3) and group based (B4) evaluation. The final grade is calculated as the weighted sum of all components and a minimum grade of 8.5 (over 20) in each part is mandatory for approval. The choice of a mixed distributed, continuous and discrete type of evaluation, albeit sharply increasing the work load on the teachers involved, was determined by the influence that the assessment method has on the students' attitudes towards their studies and on the way they work [27]. In fact, it was thought that a mixed method could potentially not only maintain students' interest all through the semester up until the final exam but also allow the stimulation of their communication and creativity skills, namely through the personal contact subjacent to item B4. Table 5 presents a typical time distribution of the several evaluation components along the semester.

On the final written exam (part A) all subjects taught during the semester are evaluated through classical methods that include the description/drawing of technological components, numerical exercises and circuit analysis and synthesis. A typical exam includes eight or nine question groups: two on (electro)pneumatic systems (regarding the analysis of components and the synthesis of circuits), two directly related to laboratory studied contents and the remainder on hydraulic systems (technological based questions regarding a particular component, a circuit analysis question requiring a numerical calculation and a synthesis question). As an example, Fig. 2 presents two representative questions of the circuit analysis and synthesis of the part A tests.

Table 4. Assessment components

	Final written exam	Tutorial sessions written short tests	Lab test on pneumatics	Lab test on hydraulics	Classes lab performance
	A	B1	B2	B3	B4
Weight	0.45	0.1	0.15	0.2	0.1

Table 5. Evaluation components distribution along a semester of 14 weeks (with corresponding weight)

Week	A	B1	B2	B3	B4
1					0.1/12
2					0.1/12
3					0.1/12
4		0.1/5			0.1/12
5					0.1/12
6					0.1/12
7		0.1/5			0.1/12
8			0.15		
9					0.1/12
10		0.1/5			0.1/12
11					0.1/12
12		0.1/5			0.1/12
13					0.1/12
14		0.1/5		0.2	
Exam period	0.45				

Analysis question

The upward and downward movement of a floodgate included in a mini hydraulic energy generation system must be driven. The floodgate can be stopped at any position. The downwards movement is 'fast' and gravity driven, except for the last part, where movement should be 'slow' and hydraulically driven. A tentative solution is partially presented in Fig. 2 (a). Please answer the following questions:

(a) Complete the circuit of Fig. 2(a) with a possible solution for electrovalves $\mathbf{V_4}$, $\mathbf{V_5}$ and $\mathbf{V_6}$.

(b) Complete the circuit of Fig. 2(a) with a possible solution for the piloting (X) of valve $\mathbf{V_8}$.

(c) Which are the valves used during the gravity driven downwards movement? Explain their function in a detailed but concise way.

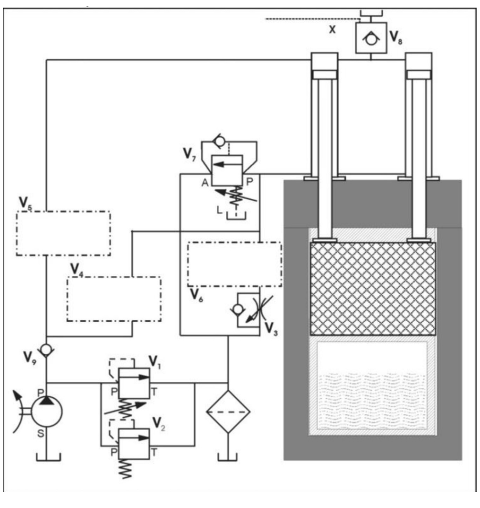

Fig. 2(a). Tentative solution for the driving of a floodgate.

Synthesis question

In order to drive a large dimension door gate, see Fig. 2(b), a hydraulic system comprising two long stroke hydraulic actuators to move the gates and two short stroke actuators to lock the door has to be devised. Please sketch a tentative hydraulic circuit ensuring the following requirements:

(i) during the closing movement, the large stroke actuators must be simultaneously moved (although their motions do not need to be properly synchronized);

(ii) when the closing movement ends, the short stroke cylinders should close without the need of an additional command.

(iii) during the opening movement, the sequence of movements should be opposite to that described above.

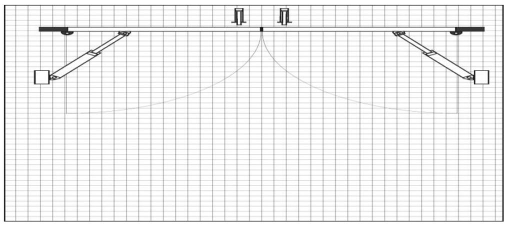

Fig. 2(b). Hydraulically actuated door gate.

Fig. 2. Representative questions of type A tests.

Part B1, is composed of five short questionnaires (with ten questions each) as part of some tutorial sessions. Students know a priori the total number of short tests but do not know the exact dates on which they occur. At the end of the semester the worst grade obtained in these tests is discarded. In the assessment of pneumatic contents, each question is presented in a slide during 30 seconds, the time students have to give a true/false answer. The hydraulic contents are assessed in a similar way except that the answers are provided either in written text (up to three word length answers) or numerical calculations. Two representative questions performed in B1 tests are presented in Fig. 3. It should be emphasized that these types of tests have an immediate benefit regarding the attendance of students to tutorial sessions: a medium attendance of approximately 75% of all enrolled students was achieved during the period under analysis.

Pneumatic

Consider the symbol in Fig. 3(a). Are the following propositions true (T) or false (F)?

- the symbol represents a 2/2 directional valve;
- the symbol represents an electric piloted valve;
- the symbol represents a soft starter valve.

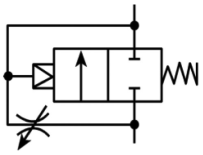

Fig. 3(a). Pneumatic valve symbol.

Hydraulic

Why aren't hydraulic actuators characterized by their 'nominal power'?

Write the mathematical power generated by a hydraulic pump.

Fig. 3. Representative questions of B1 tests.

Parts B2 and B3 occur each during a lab class at the middle and at the end of the semester, respectively. The pneumatic laboratory test has a length of twenty minutes and is focused on components and circuit analysis. Regarding the first item, typically the student is faced with a set of components (see Fig. 4) that must be identified and whose main features must be described textually. Regarding the second item, the student is typically faced with an already implemented circuit in one of the six pneumatic test-beds existing at the pneumatics laboratory. In order to answer the questions of the lab test, the student has to interact with the circuit and may possibly have to draw a diagram using normalized symbols, according to ISO 1219 standard [28, 29].

Two representative questions performed at B2 tests are presented in Fig. 5.

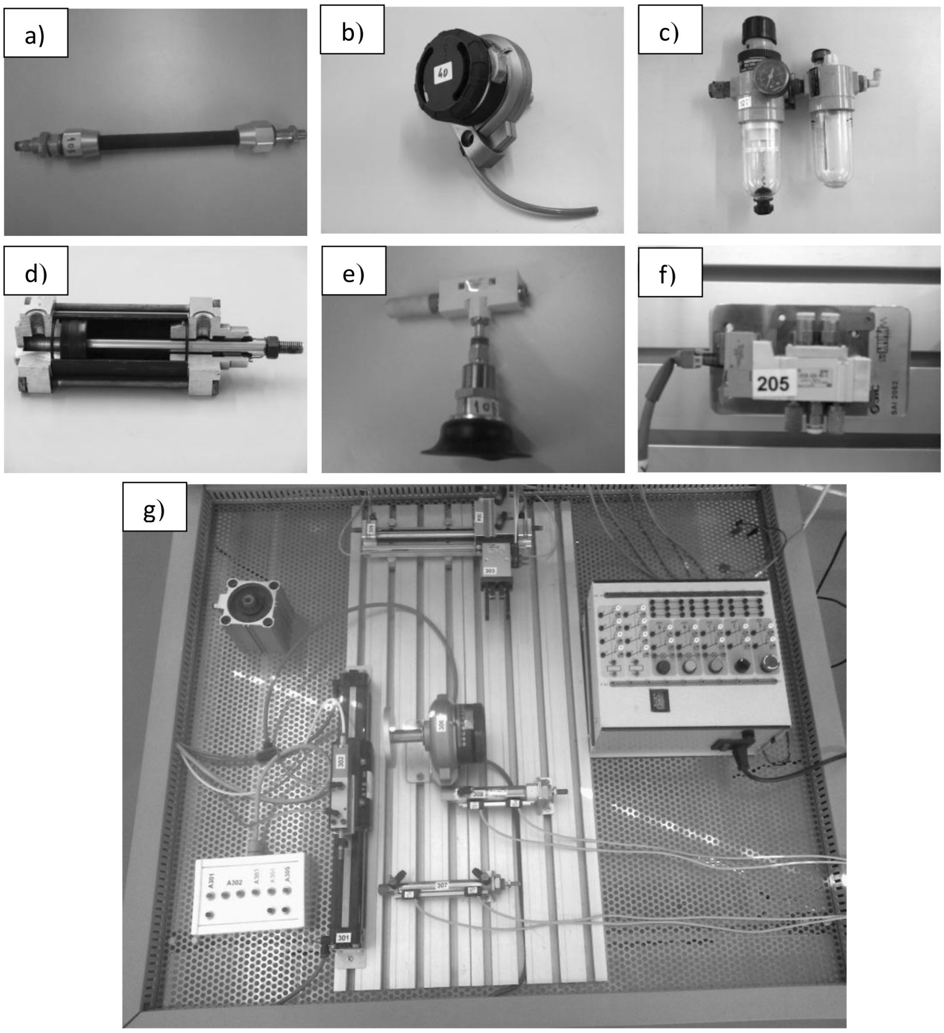

Fig. 4. Some pneumatic components and experimental test-bed existing at the pneumatics laboratory: (a) a pneumatic muscle, (b) an angular pneumatic actuator, (c) an air treatment unit, (d) a linear pneumatic actuator, (e) a vacuum generator + sucking cup, (f) electropneumatic valve, (g) experimental test-bed.

Component analysis
'Consider the pneumatic circuit in the experimental set-up next to you. Which is the reference tag and the designation of the valve responsible for the actuator motion? Draw the standard symbol of this valve according to ISO 1219 standard.'

Circuit analysis
'Consider the pneumatic circuit in the experimental set-up next to you. When the command valve is permanently pressed, the circuit presents a particular behaviour. Describe and justify that particular behaviour.'

Fig. 5. Representative questions of B2 tests.

The second laboratory exam (B3) is similar to B2 but is focused on hydraulic components and circuits (see Fig. 6) and lasts thirty minutes. The hydraulic circuits are implemented on four experimental test rigs existing at the hydraulics laboratory (see bottom picture of Fig. 6).

Two representative questions performed at B3 tests are presented in Fig. 7:

Component analysis
The component number 'xx' is part of a hydraulic actuator.

(i) How is it designated?
(ii) Which types of non-metallic elements are typically associated with this component? Justify your answer.

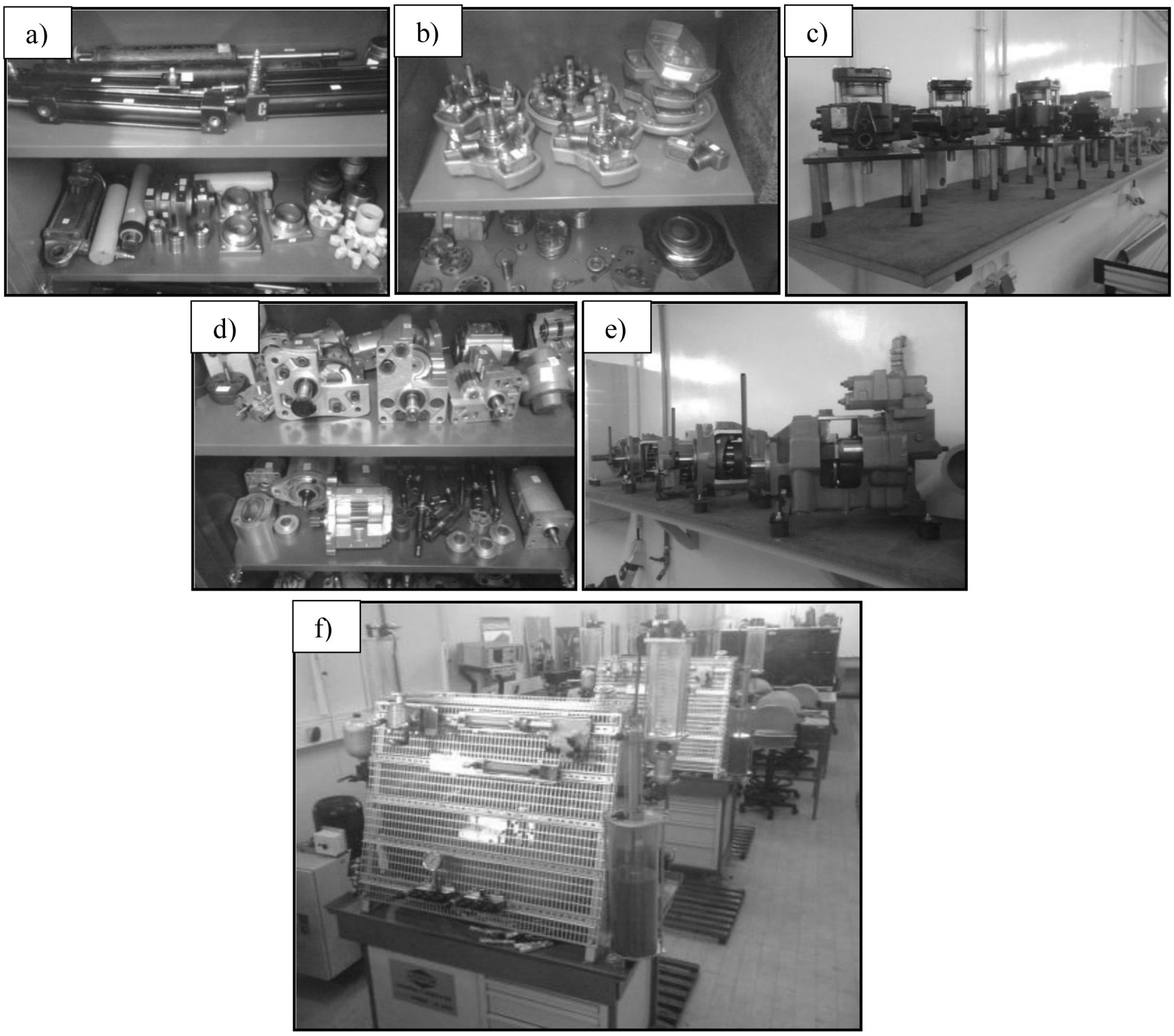

Fig. 6. Some examples of hydraulic components and experimental rigs at the hydraulics: (a) linear actuators and disperse components, (b) radial piston pumps, (c) vane pumps, (d) gear pumps, (e) axial piston pumps (f) experimental test-beds.

(iii) Draw a sketch of this component with the non-metallic elements inserted.

Circuit analysis
'Consider the circuit in the experimental set-up already built on the test bench next to you. Draw the circuit using standard symbols and make a short description of its working principle.'

Fig. 7. Representative questions of B3 tests.

3. Lab assignments/experiments: two examples

In this section two examples of lab assignments, one on pneumatic systems and one on hydraulic systems, are presented and discussed. The first example is a lab assignment performed at the second pneumatic lab session. The student has an experimental set-up at their disposal (see Fig. 8) and is faced with a short description of a problem as presented in Fig. 9. It should be underlined that the exercise in Fig. 9 is performed on second occasion that the students come into contact with the pneumatic systems lab. Consequently, the above example is quite simple, although covering the main topics of educational objectives as proposed in the revised Bloom's taxonomy [30]. Regarding the knowledge dimension, it covers the factual and conceptual knowledge as it requires the terminology and specific details on pneumatic components previously presented at the tutorial sessions. In the process of implementing the pneumatic circuit, students acquire the procedural knowledge associated with mounting pneumatic circuits. Finally, during the entire process, students are faced with their limitations and difficulties and consequently become more aware as to where their knowledge stands. In order to allow this self-awareness process to occur, the authors of this study leave, as much as possible, students on their own during the first part of the session. Regarding the cognitive process dimension, all topics are covered with the exception of the last one, relating to the process of 'Putting elements together to form a novel, coherent whole or make an original product' [30]. This is justified by the previously mentioned fact that this

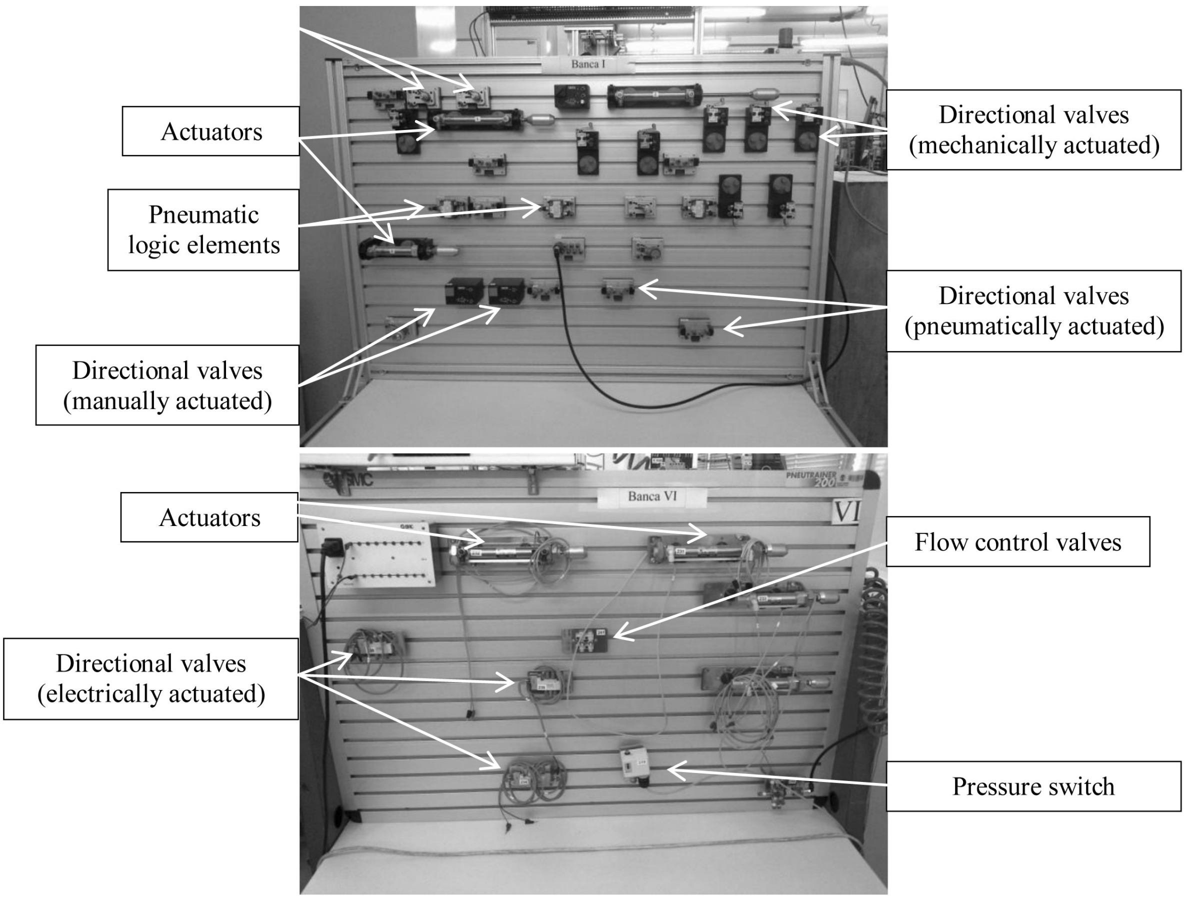

Fig. 8. Two experimental set-ups for pneumatic and electropneumatic systems training.

assignment is performed the second time that the students contact the pneumatic systems in the lab. More 'creative' assignments, where students have to (partially) design a circuit, are conveyed later on the course.

The experience of the authors shows that a very common difficulty among students is to make the correspondence between the circuit diagram and the actual physical components and connections between them. This is one of the reasons why students have two circuits from which to choose, as there are only components to implement one of them. Students are required to search the components of their experimental set-up that match one of the circuits and have to complete the components' name on the diagram. This activity of linking each symbol to its corresponding real component reinforces the knowledge associated with this 'translation' process. Finally, questions like the last one in Fig. 9 are typically quite appreciated by students, since they involve the adjustment of a very perceptive physical variable (velocity) in a circuit they have mounted (mostly) on their own. This question is usually used to assess the correctness of the circuit and also to explain and alert students to some of the limitations of pneumatic systems, namely, the several disadvantages that friction forces cause.

Doors and windows actuated by pneumatic actuators are quite common in industrial machines. The opening and closing of these devices must be performed at moderate speeds to avoid sudden movement. Figure 9(a) shows one such device schematically.

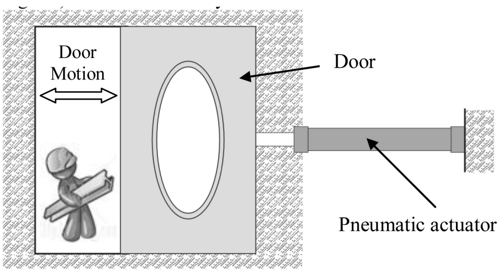

Fig. 9(a). A pneumatically activated device.

The pneumatic circuits (i) and (ii) shown in Fig. 9(b) are possible solutions to implement these types of devices with manual commands.

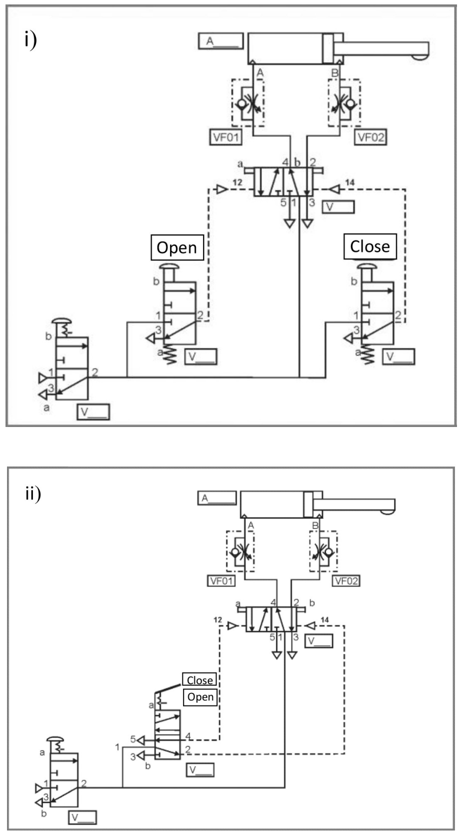

Fig. 9(b). Two possible solutions for the system in Fig. 9(a).

1. Carefully analyse both circuits in order to understand their behaviour. Describe the role of valves VF01 and VF02 in both circuits.
2. Check the pneumatic components available at your experimental set-up and compare them with the ones on Figs 9(a) and (b). Complete the components' names on the circuit using the material available at your experimental set-up and implement one of the circuits accordingly.
3. Make the necessary adjustments on the circuit so that the cylinder movement in each direction lasts approximately 4 s. Have you faced any difficulty in performing these adjustments?

Fig. 9. Representative lab assignment for pneumatic systems study.

The second example is the hydraulic lab assignment where torque motors and piston machines are studied, and where the volumetric efficiency of a gear pump is experimentally evaluated. With regard to the study of pumps and motors, students are faced with several questions as illustrated in the two cases below:

On your working table you will find a set of hydraulic piston machines and torque motors. Answer the following questions about these components.

Consider unit number 96 (see Fig. 10(a)).

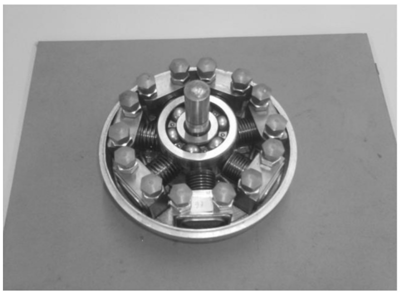

Fig. 10(a). Unit 96.

1. Which type of 'piston type' unit is it? How many pistons does it have?
2. Which is the unit volumetric displacement? Is it fixed? What is this unit's maximum continuous working pressure (read on the pump label)?
3. What is the nominal power of the electric motor required to drive this unit at 70% of its maximum working pressure?
4. Make a rough estimate of the unit volumetric displacement by measuring each piston stroke and area. Compare the value determined with the one obtained in item 2.

Consider unit number 163 (see Fig. 10(b)).

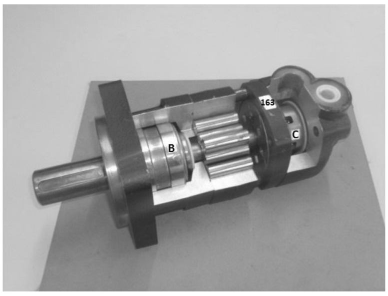

Fig. 10(b). Unit 163.

5. What is the designation of this unit?
6. What is the designation of elements 'A', 'B' and 'C'?
7. How many motoring cycles are performed during each shaft output rotation?

Fig. 10. Representative lab assignment for hydraulic components study.

As illustrated in these two examples, the approach followed is based on the presentation of industrial dismounted components/units and the asking of simple questions about their features and behaviour. It has been, in the authors' opinion, a successful strategy as students actually have the chance to see and feel how components work and to gain an intuitive perception of certain features. For instance, after seeing the inside of piston type and vane type pumps and motors, it becomes clearer to students that, in general, vane type pumps produce a less pulsed flow than piston type ones. Another interesting point on this approach is that some basic concepts (like the volumetric displacement of a pump) become clear and perhaps more easily memorized when the student, along with the working group, performs an approximate calculation by direct measuring. This can be justified by the previously mentioned study performed by Felder and Spurlin [14] where it was found that most students prefer information to be presented through physical sensations and sights and to process information by participating in a physical activity or discussion. With regard to hydraulic circuits, in the example provided in Fig. 11 students have to experimentally analyse, synthesize and implement a simple hydraulic circuit. This example is one of the five circuits that students study in the last hydraulic lab session. Since each session lasts 90 minutes, an option was made to assign only one circuit to each group. This option provides enough time for students to think critically about the problem at hand and for the tutor to highlight the existing options, thus enriching the knowledge outcome of the session. In order for all groups to have contact with the circuits that they haven't implemented, each group must present their work to all the other groups at the end of the session. This practice has been shown to be quite interesting and useful for several reasons. First, it allows the group that makes the presentation to set down the main ideas and outcomes of their work. Second, it allows the teacher to better understand the difficulties encountered and also any misunderstanding that might have arisen during the session. Third, students feel less uncomfortable questioning their colleagues than their teachers, so increasing the effectiveness of the laboratory session.

The goal of this assignment is to control of the hydraulic motor in one direction only. The speed of rotation should be adjustable in 'meter-out'. A pressure reducing valve is used to limit the motor maximum torque. A 2/2 directional valve is used to disconnect the motor from the energy source.

Consider the circuit partially represented in Fig. 11(a). Having in mind the hydraulic components available, complete the circuit drawing to achieve the behaviour described above. After completing the drawing, implement the circuit in the test bench next to you and adjust the maximum pressure to 50 bar.

1. Adjust the maximum torque of the motor to 50% of the maximum value allowed in this experimental set-up. Describe the steps you followed for this task.
2. Using the flow control valve, change the speed of rotation. Report any peculiar behaviour namely around zero speed adjustment.
3. Assuming the motor has a volumetric displacement of 6.5 cm^3, determine the maximum rotation speed it can achieve in this experimental set-up.

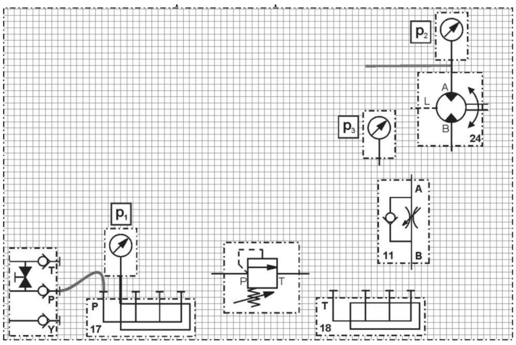

Fig. 11(a). Circuit for the control of a hydraulic motor.

Fig. 11. Illustrative lab assignment for hydraulic circuits study.

4. Students results

The overall results statistics from 2007/2008 to 2011/2012 are presented in Fig. 12. After an initial transition period from pre- to post- Bologna implementation, the number of approvals stabilizes around 50%, the number of failures around 30% and the number of students that give up around 20%. Notice that the 'Not evaluated' statistics include two types of students: those who effectively start the course and abandon it and those who although enrolled in the course didn't even start to attend classes. This last situation represents a large number of students and is a problem already identified in previous studies [31] focused at the University of Porto. Regarding the grades obtained by students that were approved, Fig. 13 presents the results of the last five years in a scale ranging from zero to twenty (a minimum of ten is required to be approved). The coloured rectangle represents the average value μ and the vertical dark line is drawn between $\mu - 2\sigma$ and $\mu + 2\sigma$, where σ represents the standard deviation. It can be seen that after the post Bologna transient period (approximately 2 years) the average value has been steadily increasing. Another interesting fact is that the top grades that students achieve have increased by an average value of 0.8/20 per year in the last three years. This may be explained by several factors. First, with the exception of the years 2005/2006 to 2006/2007, the admission grades have been increasing from 2005/2006 to 2009/2010 (see Fig. 14) so it doesn't come as a surprise that better students achieve better grades. For instance, the best student in 2005/2006 (the first one to be admitted) had an average grade of 18.45 while the best one admitted in 2011/2012 had an average grade of 19.8. The difference is even more pronounced when the worst students (last ones to be

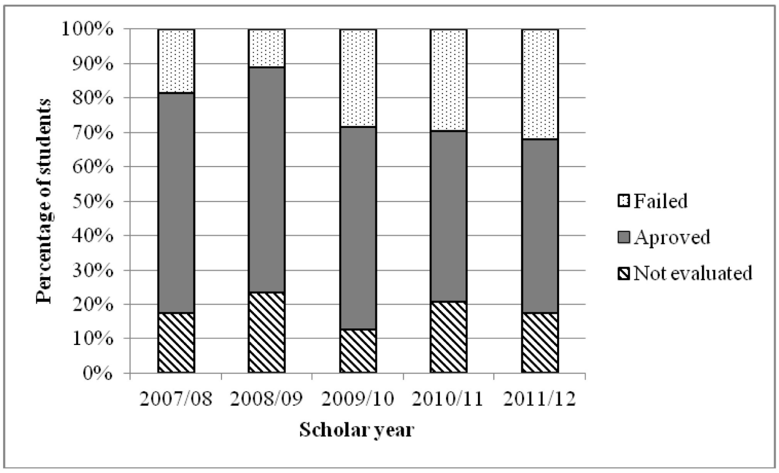

Fig. 12. Overall results from 2007/2008 to 2011/2012.

admitted) are compared: the last student admitted in 2005/2006 had an average grade of 13.08 while the last one admitted in 2011/2012 had an average grade of 16.43. Secondly, the assignments suffer incremental improvements every year to enhance their pedagogical value. Third, since 2007/2008, the course support material has been made available online with annual updates and improvements, including not only the slides shown in the classroom but also the answers to exams of previous years.

Another interesting tendency may be observed when comparing the average grade of approved students at HPS with the same average in all third year courses, as presented in Fig. 15. The average HPS grades are clearly lower than those obtained in all the 3rd year courses, but there seems to be an approximation between these two curves reflecting the fact that the average grades obtained at HPS are rising at a higher rate than those obtained on all 3rd year courses.

The decomposition of the results obtained in the five assessment topics, still considering approved students, is represented in Fig. 16. An overall tendency of increase in exam grade (component A) can be observed, as well as an overall increase in the group lab assessment grade (component B4). There also seems to be a slight tendency for a decrease in the hydraulic lab exam (B3) grades and there doesn't seem to be any defined evolution tendency regarding the pneumatic lab exam (B2) grades. Another relevant fact is the difference between the grades obtained at lab sessions (B4) and the other assessment components. This might be justified by the high level of interaction between tutor and students and by the fact that the B4 component naturally evaluates items like knowledge acquisition interest, group work, dynamic attitude and behaviour, etc., which are typically items that are prone to better grades since students have been typically quite interested, dynamic and well behaved. Another

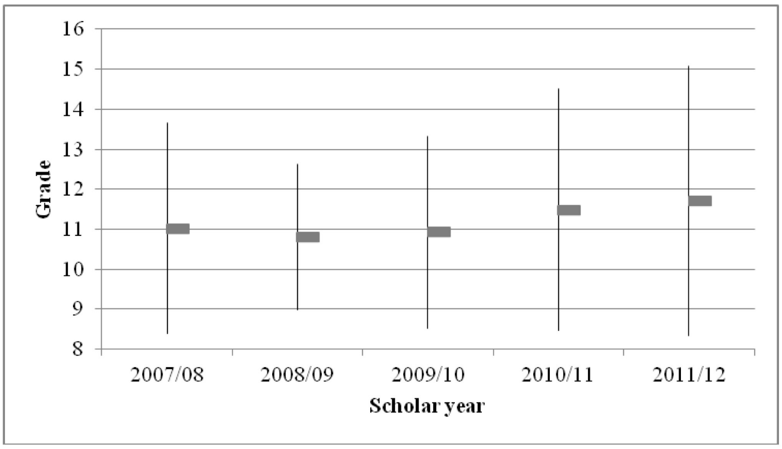

Fig. 13. Grade results of approved students from 2007/2008 to 2011/2012.

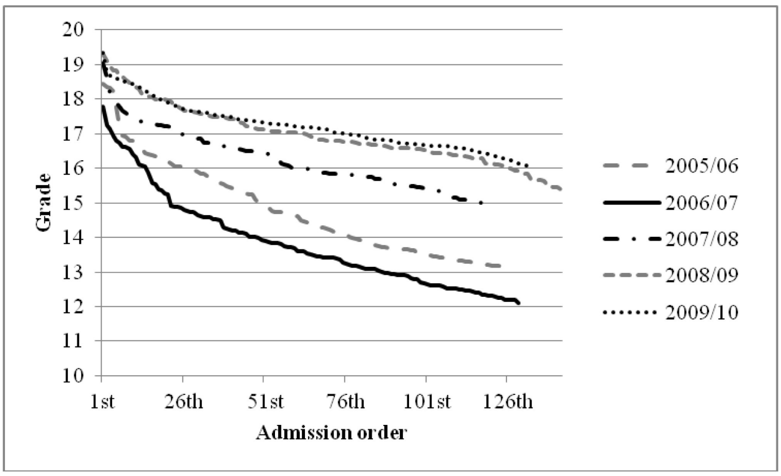

Fig. 14. Evolution of the admission grades in the Mechanical Engineering master degree: grade versus admission order.

relevant fact relates to the lower grades obtained on the final exam when compared with the other classification items (see Table 6). Two factors seem to concur towards this evidence. First, it appears that since students have invested in the distributed part of the evaluation during the semester, they shift their study concerns towards the courses that require only a final exam. This might mean that the mixed nature of the assessment method is not efficient in holding the attention of students up until the final exam(s). Secondly, given the big emphasis on technological issues given in the lab sessions, perhaps students become less prepared to deal with the more analytical questions of the final exam. This comes therefore as a natural consequence of the choice made when the course was initially developed (see Section 1) and is an issue that deservs attention from all the teachers involved. In the future it is intended to use an e-learning platform like Moodle to develop home assignments more devoted to the analysis and synthesis of circuits. It is expected that students take advantage of this facility out of the class time to enhance their skills.

5. Students opinion on the course

At the University of Porto students are asked, on a voluntary basis, to answer questionnaires at the end of each semester about the courses on which they enrol via an online tool. This procedure has been

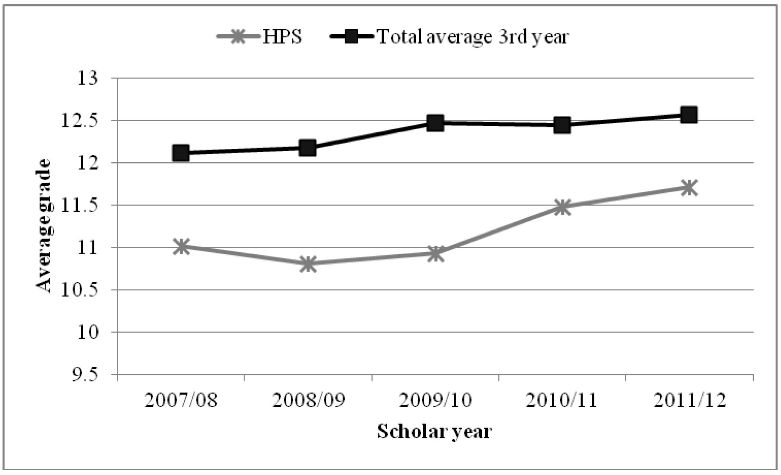

Fig. 15. Evolution of HPS and total average 3rd grades.

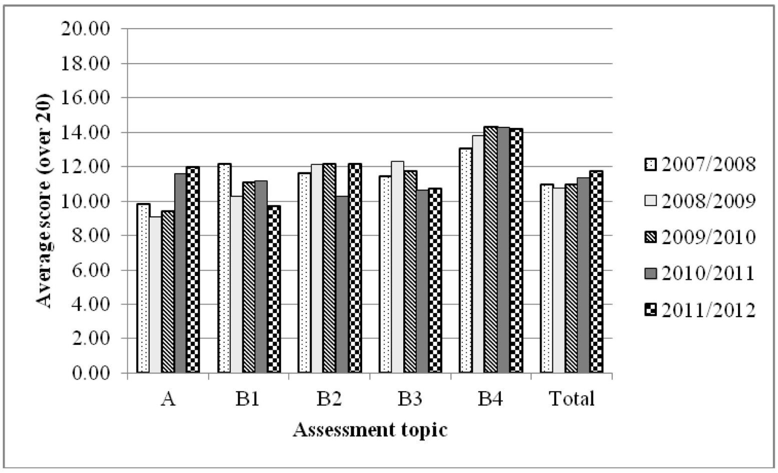

Fig. 16. Evolution of average results for the five assessment topics.

Table 6. Average five-year grade obtained in each evaluation component.

Component	A	B1	B2	B3	B4
Average five-year grade	10.39	10.90	11.67	11.39	13.95

Table 7. Students' opinion of the HPS course.

Group	Topic	Questions
C1	Span of contents	Different perspectives on the subject were given? Course contents were adequately contextualized in the mechanical engineering syllabus? The topicality of contents was discussed in lectures?
C2	Methods of assessment	My learning goals were helped by the different types of assessment performed? Assessment was adequate to attain the course objectives?
C3	Support material	The support material and support activities contributed to my learning goals? The recommended bibliography was useful?
C4	E-learning use	In this course the support material has electronic means that helps learning through knowledge sharing? The interactive contents of this course are helpful with self-evaluation?
C5	Global opinion	Global opinion on the course

implemented since scholar year 2007/2008 and the questions, presented on the right-hand of Table 7, are grouped in five classes: span of contents (C1), methods of assessment (C2), support material (C3), e-learning use (C4) and global opinion (C5). The answers range from 1 (strongly disagree) to 5 (strongly agree). Results obtained in HPS are presented in Fig. 17. The total number of students who answered this questionnaire (NSAQ) from 2007/2008 to 2011/2012 is presented in Table 8, which also includes the ratio between NSAQ and the number of evaluated students during this period (NES).

A first comment on the data in Fig. 17 relates to a general increase in all topics throughout the years. This is particularly clear in questions relating the span of contents of the course, the topic where best grades are obtained, about 3.8 in average. The assessment methods are evaluated with only 3.2 in 5. This is a matter that has been long discussed by the authors of this study. A possible interpretation of this low mark resides in the fact that students tend to prefer a course with either a continuous or a discrete type of evaluation. The mixed nature of the evaluation in HPS tends to increase the perception of the negative sides of each type of evaluation: on the one hand, students have to be in constant focus during the course to keep on track with the several assessment topics; on the other hand, during the exam period, students still have to keep up, since the final exam weighs considerably (45%) in the final classification. This has been transmitted through several conversations and comments by students throughout the years and might be affecting the overall opinion students have on the course, an average of three in five.

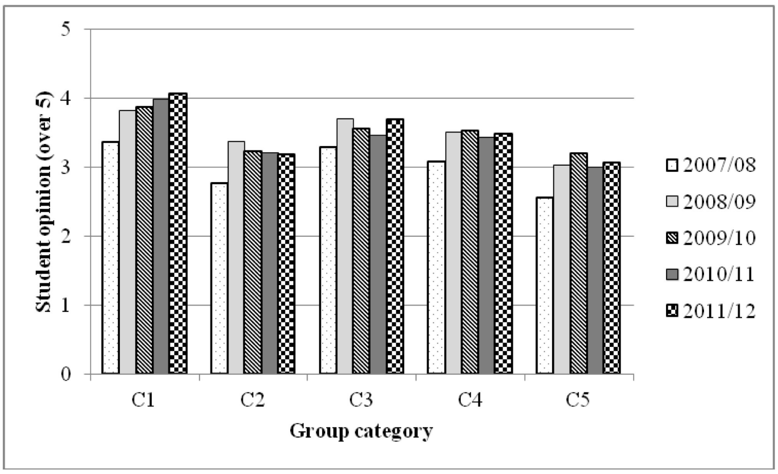

Fig. 17. Students' perceptions of the HPS course.

Table 8. NSAQ and ratio between NSAQ and NES.

Scholar year	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012
NSAQ	23	27	34	68	42
NSAQ/NES [%]	12.2	18.8	20.4	42.2	23.9

6. Conclusions

Fluid power systems play a key role in the contemporary world, covering a large set of application areas as far apart as flight simulators and agriculture machines. The eminent technological nature of these systems, along with the preference that engineering students show towards sensory information presentation and active information processing, makes a hands-on approach potentially increase knowledge retained by Mechanical or Mechatronics Engineer candidates. This paper has presented the five-year's experience of a fluid power course where hands-on activities are emphasized and where students are assessed through a mixture of five different components. The experience revealed very good results with regard to students' participation and enthusiasm in the course sessions, not only in lab activities but also in the tutorial sessions. In fact, although the existence of assessments in both lab and tutorial sessions naturally leads to an increase in the students' attendance at classes, a genuine interest in the subjects taught appeared to increase, indicated for example by the systematic raising of questions after class time. It should be also underlined that this type of course organization proved to be very time consuming for the teachers involved as it requires a weekly change in laboratory set-up and the evaluation of students on several occasions during the semester. Consequently, its implementation can only be successfully achieved if the time available from the lecturers is not a critical factor. Furthermore, it has been found that the model followed in this work is limited to graduate courses where a minimum time of 90 minutes can be dedicated to lab sessions. In fact, the authors consider that the sessions would be richer if their time was extended to 120 minutes, as this would allow more time for students to reflect on the subjects taught. Finally, the model presented in this work is limited to labs where a large collection of real (or didactic) pneumatic and hydraulic components is available. This collection can be obtained either by acquiring the components or by contacting local companies that usually are willing to donate used (or even new) components for educational purposes.

References

1. K. Edge, The control of fluid power systems-responding to the challenges, *Proc Instn Mech Engrs, Part I, Journal of Systems and Control Engineering*, **211**(2), 1996, pp. 91–110.
2. R. Todd, W. Red, S. Magleby and S. Coe, Manufacturing: A Strategic Opportunity for Engineering Education. *Journal of Engineering Education*, **90** (3), 2001, pp. 397–405.
3. A. Alleyne, A fluid power lab for undergraduate education, *American Control Conference*, Chicago, Illinois, USA, 28–30 June 2000, pp. 4398–4402.
4. L. Feisel and A. Rosa, The role of the laboratory in undergraduate engineering education, *Journal of Engineering Education*, **94** (1), 2005, pp. 121–130.
5. A. Hofstein and V. Lunetta, The laboratory in science education: Foundations for the twenty-first century, *Science Education*, **88** (1), 2003, pp. 28–54.
6. D. Knight, L. Carlson and J. Sullivan, Improving engineering student retention through hands-on, team based, first-year design projects, *31st International Conference on Research in Engineering Education*, Honolulu, Hawai, June 22—24, 2007.
7. V. Tinto, Leaving college: rethinking the causes and cures of student attrition, The University of Chicago Press, Chicago, USA, 1987.
8. E. Seymour and N. Hewitt, *Talking About Leaving: Why Undergraduates Leave the Sciences*, Westview Press, Boulder, CO, 1997, session 3553.
9. M. R. Anderson-Rowland, Understanding freshman engineering student retention through a survey, *American Society for Engineering Education Annual Conference*, Milwaukee, USA, 1997.
10. I. St. Omer, J. Hood and F. Swimmer, Student retention dialogue: focus group outcomes, *American Society for Engineering Education Annual Conference*, Nashville, USA, 2003, session 1430.
11. M. Restivo, F. Gomes Almeida, M. Chouzal, J. Mendes, A. M. Lopes, J. F. Carneiro and H. Lopes, In the way of a better methodology in teaching/learning instrumentation for measurements at mechanical engineering compulsory syllabus, *World Congress on Engineering and Technology Education*, March 2004, pp. 92–94.
12. The Bologna Declaration, Joint Declaration of the European Ministers of Education, The European Higher Education Area, Bologna 1999.
13. P. Flores, How do mechanical engineering students see their training and learning at university? Findings from a case study, *Global Journal of Engineering Education*, **14**(2), 2012, pp. 189–195.
14. R. M. Felder and J. Spurlin, Applications, reliability, and validity of the index of learning styles, *International Journal of Engineering Education*, **21**(1), 2005 pp. 103–112.
15. R. M. Felder and L.K. Silverman, Learning and teaching styles in engineering education, Engineering Education 1988, **78**(7), pp. 674–681.
16. R. M. Felder, Reaching the second tier: learning and teaching styles in college science education, *Journal of College Science Teaching*, **23**(5), 1993, pp. 286–290.
17. S. Starrett and M. Morcos, Hands-on, minds-on electric power education. *Journal of Engineering Education*, **90**(1), 2001, pp. 93–99.
18. J. Carryer, The design of laboratory experiments and projects for mechatronics courses, *Mechatronics*, **5**(7), 1995, pp. 787–797.
19. C. Ume, A. Kita, S. Liu and S. Skinner, Graduate mechatronics course in the school of mechanical engineering at Georgia Tech, *Mechatronics*, **12**(2), 2002, pp. 323–335.
20. R. Arkin, K. Lee, L. Mcginnis and C. Zhou, The development of a shared interdisciplinary intelligent mechatronics laboratory, *Journal of Engineering Education*, **86**(2), 1997, pp. 113–118.
21. D. Chen, X. Li, Z. Li and T. Wang, A mechatronics control engineering class at Beihang University, China: Practicing and exploring, *Mechatronics*, **22**(6), 2012, pp. 881–889.
22. J. Petric and Z. Situm, Inverted pendulum driven by pneumatics, *International Journal of Engineering Education*, **19**(6), 2003, pp. 597–602.
23. S. Stankovski, L. Tarjan, D. Skrinjar, G. Ostojic and I. Senk, Using a didactic manipulator in mechatronics and industrial engineering courses, *IEEE Transactions on Education*, **53**(4), 2010, pp. 572–579.
24. A. Shapira, Bringing the site into the classroom: a construction engineering laboratory, *Journal of Engineering Education*, **84**(1), 1995, pp. 1–5.
25. H. Aglan and S. Ali, Hands-on experiences: an integral part of engineering curriculum reform, *Journal of Engineering Education*, **85**(4), 1996, pp. 327–330.

26. E. Todorovich, J. Marone and M. Vázquez, Introducing programmable logic to undergraduate engineering students in a digital electronics course, *IEEE Transactions on Education*, **55**(2), 2012, pp. 255–262.
27. A. Berglund, M. Daniels, M. Hedenborg and A. Tengstrand, Assessment to increase students' creativity: Two case studies. *European Journal of Engineering Education*, **23**(1), 1998, pp. 45–54.
28. International Organization for Standardization, ISO 1219-2: Fluid power systems and components—Graphical symbols and circuit diagrams—Part 2: Circuit diagrams, *ISO standards,* Geneva, Switzerland, 2012.
29. International Organization for Standardization, ISO 1219-1: Fluid power systems and components—Graphical symbols and circuit diagrams—Part 1: Graphical symbols for conventional use and data-processing applications, *ISO standards,* Geneva, Switzerland, 2012.
30. D. Krathwohl, A revision of Bloom's taxonomy: an overview, *Theory into Practice*, **41**(4), 2002, pp. 212–218.
31. A. Soeiro and J. Cabral, Engineering students' assessment at University of Porto, *European Journal of Engineering Education*, **29**(2), 2004, pp. 283–290.

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