International Journal of Engineering Education Vol. 35, No. 3, pp. 938–946, 2019
Printed in Great Britain
0949-149X/91 $3.00+0.00

Application of a Flipped Classroom for Model-Based Learning in Electronics*

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This paper investigates the effectiveness of the flipped classroom methodology to build conceptual knowledge mental models. In particular, it examines the learning process and outcomes of 40 students of a course on Physical Electronics in the last year of a bachelor's degree program in Physics, for which specific educational resources have been developed to implement the flipped classroom. Among them, non-interactive resources are better to present topics and ideas, whereas interactive resources are more useful to establish links between them to build and check the models. The examined data entail grades, laboratory reports and rubrics, outcomes of learning activities, and direct observation, showing that the flipped classroom improves the construction of mental models, providing teaching resources where the topics and main ideas are presented, developed and exercised, and allowing students to establish links to build and check the models. Furthermore, this strategy increases the personal commitment of the students, fostering autonomy and cooperation with peers, all of which makes it an effective pedagogical tool to build knowledge mental models.

Keywords: flipped classroom; model construction; active learning; collaborative work; e-learning

1. Introduction and review

Gobert and Buckley defined model-based learning as the construction of mental models of phenomena [1], which is achieved by integrating information about their structure, function and causal mechanism, and mapping it into analogous systems. In the classical approach of Gilbert, models are built through induction based on simplified representations of systems [2]. Nowadays, model-based learning is an essential part in the evolution of scientific knowledge and, thus, it constitutes an important part of the strategies put in place in the teaching of science and engineering.

Despite the fact that it is not possible to know the nature and content of the mental models of the students, the instructors can address and evaluate them. In this respect, the flipped classroom is an effective instructional strategy because it addresses teaching by transferring the work to carry out certain learning processes to outside the classroom, allowing the use of class time for activities that facilitate and enhance other learning processes that focus on practising instead of just listening [3–5]. This combination of direct instruction and constructionism is of great help to direct the acquisition of the model.

1.1 The flipped classroom in higher education

Flipped classroom methodologies are attracting increasing interest in higher education [6–11]. Teachers design activities to work outside the classroom so that class time is discharged and can be used to encourage active participation through activities that promote the implementation and application of ideas [12–14].

Although there are many procedures to develop flipped classroom activities [15], the most common ones are those where students watch pre-posted lectures or read papers and solve exercises before class, freeing classroom time for active learning [16, 17]. This has important intrinsic benefits while at the same time it allows a closer monitoring of the learning process of the students.

2. Expectations of the current study

The classical implementation of model-based learning is carried out by engaging the students in an iterative process oriented to build successive approximations of a mental model of a given phenomenon. This can be accomplished by comparisons, inductive processes, simplifications, the integration of information, etc.

Despite model-based learning needs to be carried out by the students, the instructors can adopt strategies intended to facilitate the acquisition of those models, and to assess that they have been built correctly.

It is in this scenario where the flipped classroom

* Accepted 22 February 2019.

methodology stands out. Flipped classrooms are based on providing the students with activities to carry out outside the classroom, so that lectures can be devoted to implementing active learning activities aimed at reinforcing what students have learned outside the classroom.

In this way, by the application of a methodology based on the flipped classroom, the authors expect to contribute to a correct development of knowledge mental models. The activities are based on the use of a wide range of learning supporting materials, each of which plays a role in the intended outcome, which is facilitating the construction of mental models by the students. The implementation of the flipped classroom has increased student implication and satisfaction, which relates to a better performance and deeper learning [13, 14, 18].

3. Research method

This paper presents a methodology that combines the flipped classroom with other active methodologies and traditional lessons to improve the teaching/learning process of Electronics in bachelor's degree and master studies in Physics. It allows more classroom time for active learning so that the teacher can follow the student learning process and evaluate model construction.

The flipped classroom, thus, serves as a pedagogical strategy to help students to build their knowledge mental models, and also to assess their construction. Class time is used to improve, put into context and check the models, so the role of the instructor changes from a 'sage on the stage' to a 'guide on the side' who interacts with students and encourages them [19]. Classroom activities are given an innovative approach to promote other skills such as autonomy or multi-directional learning [20].

This work combines two lines of action: (i) before-class and face to face (F2F) activities based on information and communication technologies (ICTs), some with enhanced content; and (ii) F2F activities that use active learning strategies to apply the knowledge acquired [21, 22].

3.1 Participants and scope

Participants are the 40 students of the course Physical Electronics, taught in the last year of the degree in Physics. Students have long and successfully learned various areas of Physics, and they have a strong background in mathematical methods and relevant laboratory experience; thus, they are autonomous and can be faced with activities involving less guidance, leaving more space for active learning.

The course Physical Electronics introduces the basic properties and physical phenomena of electron transport in semiconductors, and uses these concepts to characterize semiconductor devices, build behavioural models and compare them to their real operation, and analyse their main applications.

It is expected that the proposed learning strategy will contribute to improve the construction of mental knowledge models by the students, which will result in an improvement in the achievement of the learning outcomes.

3.2 Research instruments

A set of specific teaching resources has been created and it has been allocated in the virtual learning environment of the authors' institution, making it possible to use them before and during class time. They provide an innovative approach to the discussion of models, facilitating the understanding of physical phenomena through a visual description that complements their conventional analytical treatment.

The resources are divided into learning supporting materials, and learning and model construction assessment materials, all of which support the teaching/learning process and its evaluation in the flipped classroom.

3.2.1 Learning supporting materials

- Webinars: Two modules are scheduled: a synchronous, specialized one of two hour-long sessions covering the design and fabrication of microelectronic circuits, and an asynchronous one that gives a realistic view of the industrial processes involved in the fabrication of integrated circuits (ICs).
- Applets: A library of Matlab interactive applications is presented [23] that covers: (i) the fabrication of ICs, (ii) semiconductor physics, and (iii) semiconductor devices [24]. Students can change the parameters that govern the phenomena, improving the understanding of the topics.
- Tutorials and lectures: Tutorials lead students into the most relevant aspects of the tools they use, providing them with working examples. The lectures are designed as standard explanatory sessions where the theoretical foundations of the topics studied in the course are given.
- Simulation tools: Students have access to academic licenses of the Cadence design environment [25]. Also, they are asked to find and use resources available in the Internet and compare them with the professional tools.
- Virtual laboratory: A set of virtual laboratory sessions on the design and characterization of electronic systems is scheduled.
- Problem-based learning (PBL) sessions: They are designed as a learning activity where students

must cooperate with their peers, in groups, with the assistance of the instructors. The problems require not only analyses or derivations, but also higher-order tasks such as designing structures to meet some requirements.

3.2.2 Learning and model construction assessment materials

- Quizzes: A set of quizzes is integrated to provide students with feedback about their learning process, fostering their metacognitive skills [26]. Also, the quizzes can be tailored to focus on key aspects in terms of the model construction.
- Problems: They consist of classical academic exercises and problems that students solve on their own, providing valuable training before PBL sessions. The problems exercise the basic theoretical concepts in different scenarios, which contributes to the construction of the mental models by comparing and integrating information.
- Reports: Their elaboration is relevant because students think about their findings within the theoretical framework. Also, they need to be written down in an ordered and clear way, contributing to a reflection on their mental models.
- Wikis: Students develop a wiki on physical devices, collecting and organizing information about their operating principles, electrical characteristics and other parameters of interest [27]. Wikis contribute to model construction because they are a product that results from cooperation and consensus between peers, which means that students need to check and confront their models.

4. Practical realization

4.1 Foundations of the topic of choice

The knowledge area is divided into three interdependent blocks: (i) 'specific tools and webinars', (ii) 'technologies and processes', and (iii) 'semiconductor devices'. All contain learning resources and activities for pre-class and classroom time.

In the following paragraphs, a deeper insight into the strategy is presented, analyzing how the resources operate, and in which way they contribute to building the knowledge mental models.

4.2 Example of the proposed strategy: Microelectronic circuits

The MOS transistor is by far the most used electronic device and the one that appears in the largest number of contexts. For this reason, it is used to illustrate how the learning resources, along with the flipped classroom, contribute to the construction of the mental models on how a real IC is built and how it operates.

The study of the MOS transistor, thus, uses resources from all three knowledge blocks, which are, respectively, devoted to 'specific tools and webinars', 'technologies and processes', and 'semiconductor devices'. Figure 1 shows how before-class and F2F activities are distributed, and which resource is used, respectively, to help students to incorporate the information to their own mental model of the transistor.

Figure 1 shows a key distinction between the resources designed for the activity. On the one hand there are resources aimed to guide the students through the different topics whereas, on the other hand, there are other resources that have been designed to assess the understanding of the topics, and in particular, the degree of construction of the mental models. Samples of these resources are shown in Figs. 2 and 3, corresponding to the description given in Fig. 1.

The following paragraphs analyse the resources in the context of the activity presented in this paper. Despite being concrete examples of the activities proposed to students, they serve to analyse the type of process and the outcome that is expected from the students, and how it can help in the construction of their mental models and its assessment.

- Quizzes (Fig. 2): They are related to the webinar and lecture sessions, the interactive applets, and the virtual laboratory. Depending on the type of supporting material to which they are related, the

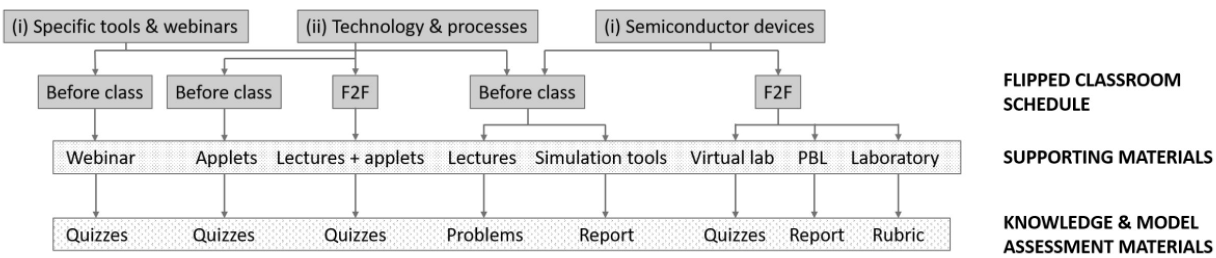
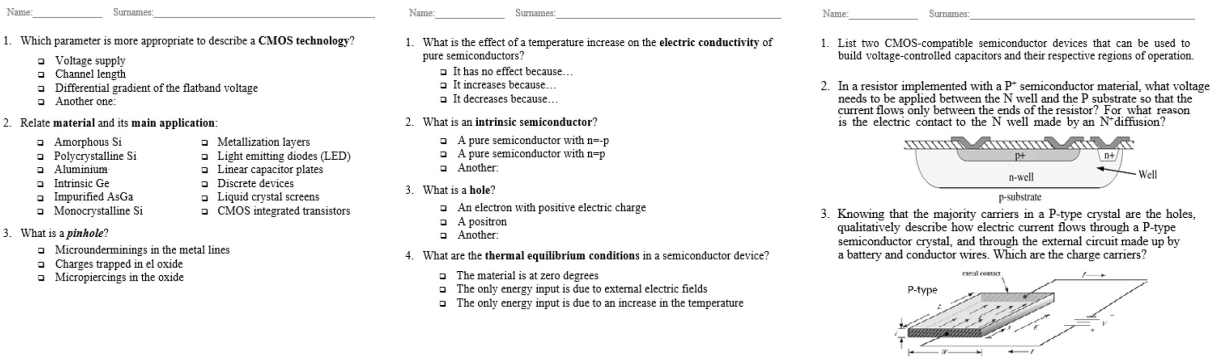


Fig. 1. Diagram showing how the activities to implement the flipped classroom methodology are distributed. The resources presented to students are grouped under 'supporting materials' whereas the resources designed to assess the understanding of the topics and the degree of construction of the models are grouped under 'knowledge & model assessment materials'.



Name:__________ Surnames:____________________

1. Which parameter is more appropriate to describe a **CMOS technology**?
   - ❑ Voltage supply
   - ❑ Channel length
   - ❑ Differential gradient of the flatband voltage
   - ❑ Another one:
2. Relate **material** and its **main application**:
   - ❑ Amorphous Si ❑ Metallization layers
   - ❑ Polycrystalline Si ❑ Light emitting diodes (LED)
   - ❑ Aluminium ❑ Linear capacitor plates
   - ❑ Intrinsic Ge ❑ Discrete devices
   - ❑ Impurified AsGa ❑ Liquid crystal screens
   - ❑ Monocrystalline Si ❑ CMOS integrated transistors
3. What is a ***pinhole***?
   - ❑ Microunderminings in the metal lines
   - ❑ Charges trapped in el oxide
   - ❑ Micropiercings in the oxide

(a)

Name:__________ Surnames:____________________

1. What is the effect of a temperature increase on the **electric conductivity** of pure semiconductors?
   - ❑ It has no effect because…
   - ❑ It increases because…
   - ❑ It decreases because…
2. What is an **intrinsic semiconductor**?
   - ❑ A pure semiconductor with n=-p
   - ❑ A pure semiconductor with n=p
   - ❑ Another:
3. What is a **hole**?
   - ❑ An electron with positive electric charge
   - ❑ A positron
   - ❑ Another:
4. What are the **thermal equilibrium conditions** in a semiconductor device?
   - ❑ The material is at zero degrees
   - ❑ The only energy input is due to external electric fields
   - ❑ The only energy input is due to an increase in the temperature

(b)

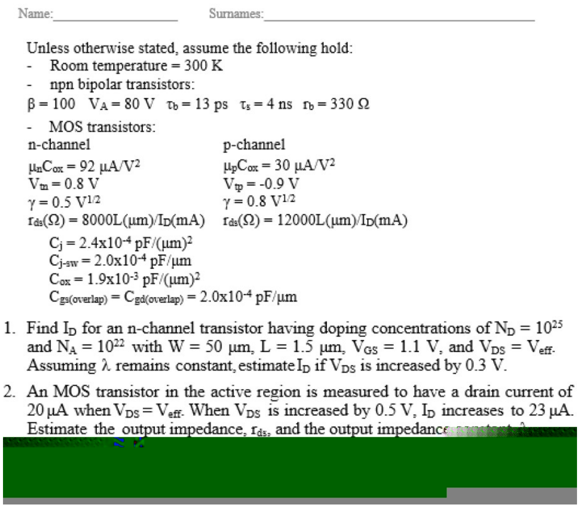
Name:__________ Surnames:____________________

1. List two CMOS-compatible semiconductor devices that can be used to build voltage-controlled capacitors and their respective regions of operation.
2. In a resistor implemented with a P^+ semiconductor material, what voltage needs to be applied between the N well and the P substrate so that the current flows only between the ends of the resistor? For what reason is the electric contact to the N well made by an N^+diffusion?

3. Knowing that the majority carriers in a P-type crystal are the holes, qualitatively describe how electric current flows through a P-type semiconductor crystal, and through the external circuit made up by a battery and conductor wires. Which are the charge carriers?

(c)

Fig. 2. Examples of the quiz-type activities proposed to students for the different learning activities planned throughout the course: (a) for the webinar sessions, (b) to work with the applets, and (c) to be used collectively in F2F theoretical sessions.



Name:__________ Surnames:____________________

Unless otherwise stated, assume the following hold:
- Room temperature = 300 K
- npn bipolar transistors:

$\beta = 100$ $V_A = 80$ V $\tau_b = 13$ ps $\tau_s = 4$ ns $r_b = 330\ \Omega$

- MOS transistors:

n-channel	p-channel
$\mu_n C_{ox} = 92\ \mu A/V^2$	$\mu_p C_{ox} = 30\ \mu A/V^2$
$V_{tn} = 0.8$ V	$V_{tp} = -0.9$ V
$\gamma = 0.5\ V^{1/2}$	$\gamma = 0.8\ V^{1/2}$
$r_{ds}(\Omega) = 8000L(\mu m)/I_D(mA)$	$r_{ds}(\Omega) = 12000L(\mu m)/I_D(mA)$

$C_j = 2.4\text{x}10^{-4}$ pF/(µm)^2
$C_{j\text{-}sw} = 2.0\text{x}10^{-4}$ pF/µm
$C_{ox} = 1.9\text{x}10^{-3}$ pF/(µm)^2
$C_{gs(overlap)} = C_{gd(overlap)} = 2.0\text{x}10^{-4}$ pF/µm

1. Find I_D for an n-channel transistor having doping concentrations of $N_D = 10^{25}$ and $N_A = 10^{22}$ with W = 50 µm, L = 1.5 µm, $V_{GS} = 1.1$ V, and $V_{DS} = V_{eff}$. Assuming λ remains constant, estimate I_D if V_{DS} is increased by 0.3 V.
2. An MOS transistor in the active region is measured to have a drain current of 20 µA when $V_{DS} = V_{eff}$. When V_{DS} is increased by 0.5 V, I_D increases to 23 µA. Estimate the output impedance, r_{ds}, and the output impedanc

Fig. 3. Example of a problem activity designed as academic exercises to apply theoretical knowledge to different cases.

quizzes might have a more open or closed structure, which provides useful and diverse information about the foundations upon which the models are constructed.

In particular, quizzes with a closed structure assess how students have incorporated the general concepts, whereas quizzes based on sets of open questions, aimed at F2F activities where general concepts and basic ideas are set out to be discussed, allow students to reflect on their knowledge and thus modify or adapt it as inferred from that of their peers.

- Problems (Fig. 3): Associated to before-class lectures, problems are designed as academic exercises where students are asked to apply their theoretical knowledge to different cases. Problems, owing to their ideal nature, allow to focus on specific relevant aspects while neglecting others, so that particular theoretical aspects can be exercised, contributing to strengthen them in the construction of the mental models.
- Reports: The realization of reports is common practice in any scientific or technological field. A report contains not only a description of the work that has been done and the results obtained, but also a general description of the state-of-the-art, a motivation, and a discussion of the results, all of which are valuable for the construction of the mental models.

Finally, the experience entails the realization of laboratory sessions, where students carry out experimental activities in the laboratory, using the appropriate techniques and instruments, and in a limited amount of time. The correct realization of a laboratory session, thus, depends to a great extent on the skills acquired throughout the course, and therefore it is expected that the proposed methodology can result in an overall improvement of the laboratory performance.

Students form groups of two to three people, which fosters the exchange of ideas and contributes to the construction of their mental models by contrasting and comparing them to those of their peers.

5. Results

The evaluation actions use the resources created for the activity, including specific quizzes, problems, laboratory reports, and a wiki page with information on the devices, their operating principle, fabrication process and other relevant aspects. All this is intended to produce learning outcomes associated with the contents of the course Physical Electronics. In particular, it is sought that students be able to:

- Describe the manufacturing process of electronic devices.
- Model electronic devices using approximations.
- Describe electronic devices analytically using the model.
- Use circuit elements to model the static behaviour

of semiconductor devices in different regions of operation.

- Design a bias network for a basic amplifier based on a single transistor and analyse its small-signal operation.

The products created by the students using every resource that is set for assessment are used to obtain their grades in the course. Every activity, as detailed in the previous section, is designed to evaluate specific competencies and processes, which in turn translates into complementary relevant information to assess the construction of the mental models. It has to be noted, though, that our framework is limited for some evaluation strategies due to the reduced number of participants (40), which makes it difficult, for instance, to perform a statistical analysis. Also, it is not feasible to carry out a parallel study between a group working in a conventional class and another one working in a flipped classroom.

The assessment of the topic 'MOS transistor' is done using the different knowledge and model assessment materials shown in Fig. 1. In particular, Table 1 shows a detailed listing of the concrete activities used to assess each knowledge block ('specific tools and webinars', 'technologies and processes', and 'semiconductor devices'), when they are scheduled in the development of the course, and the weigh that the grades are given. The activities are graded using a scale from 0 to 10 (being 10 the maximum grade), which can be afterwards linked to a scale from D (insufficient) to A (excellent).

Table 1. Computation of grades for the MOS block

Resource	Activities	Schedule	Weight %
(i) Specific tools & webinars			20
Webinar-quizzes	$WQ_{1\text{-}4}$	BC	5
Lectures-problems	$LP_{1\text{-}2}$	BC	10
Simulation tools-report	STR_1	BC	5
(ii) Technology & processes			20
Applets-quizzes	$AQ_{1\text{-}2}$	BC	10
Lectures/applets-quizzes	$LAQ_{1\text{-}2}$	F2F	10
(iii) Semiconductor devices			60
Lectures-problems	$LP_{3\text{-}4}$	BC	10
Simulation tools-report	STR_2	BC	10
Virtual lab-quizzes	$VQ_{1\text{-}2}$	F2F	20
PBL-report	PBLR	F2F	20

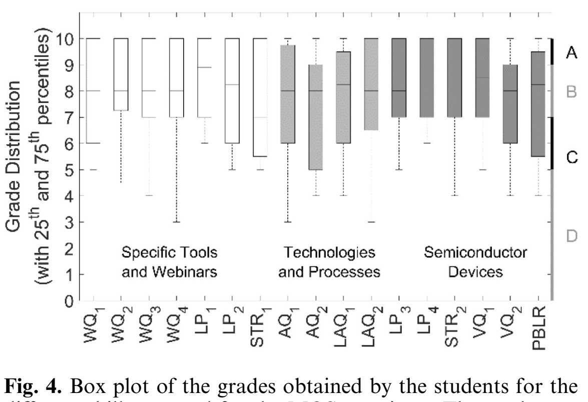


Fig. 4. Box plot of the grades obtained by the students for the different skills assessed for the MOS transistor. The grades are shown broken up into the different assessment actions and sorted out into the three knowledge blocks.

A box plot of the results obtained by the students, broken up into the different assessment actions listed in Table 1 and sorted out into the three knowledge blocks, is presented in Fig. 4.

The evaluation of the laboratory sessions is done attending to seven skills that students are expected to develop along the course. The skills encompass technical aspects such as the implementation of the experimental set-up, the operation of the instrumentation or the measurement process; and also behavioural aspects such as student autonomy and attitude, time spent, or the elaboration of the final report.

The assessment of the skills related to the assembly of the experimental set-up and operation of the instrumentation is carried out by a questionnaire previous to the laboratory session; the skills related to the measurement process, autonomy, time and attitude by direct observation in the lab; and the assessment of the skill related to the communication of the results, by a report that students have to hand out within the following seven days after the realization of the lab session.

The assessment is carried out using the rubric displayed in Table 2, using a scale from 0 to 10, where the correspondence with a scale from D (insufficient) to A (excellent) is given by 0 to 4.9: D, 5 to 6.9: C, 7 to 8.9: B, and 9 to 10: A.

The results obtained by the students for each skill assessed in the laboratory sessions are presented as a box plot in Fig. 5. It can be seen that the majority of the grades, in all skills assessed, belong to grades ranging from high-C to A, although there are some students who have failed. The maximum spread of the grades obtained are for the skills related to the measuring process and the communication of results. Finally, in all cases, students having obtained the maximum grade can be found.

To have an overall view of the performance of the students in the course, as well as a comparison with the results obtained for the same topics during the previous academic year when the strategy proposed in this work was not put into practice, the grades obtained for the two activities have been combined to give a total grading. In the case of the MOS transistor, the weight in the overall grade of the separate assessment activities is given in Table 1, whereas for the laboratory sessions, it is given in Table 2. The results are given in Fig. 6.

Table 2. Rubric designed for the assessment of the laboratory sessions

Weight %	Skills	Insufficient (D)	Sufficient (C)	Good (B)	Excellent (A)
40	Experimental set-up	Contains numerous errors	Contains errors occasionally.	Correct.	Correct and optimized.
	Instrumentation operation	Inappropriate use of equipment. No previous review of manuals.	Appropriate use of equipment. Errors in operation. No previous review of manuals.	Appropriate use of equipment. Minimum errors in operation. Previous review of manuals.	Appropriate use of equipment. No errors in operation. Previous review of manuals.
	Measurement process	No register of experimental conditions. Not all needed instrumentation used. No interpretation of results.	Little register and documentation of results and experimental conditions. All needed instrumentation used.	Register and documentation of results and experimental conditions. All needed instrumentation used. Correct treatment and interpretation of experimental data.	Register and documentation of results and experimental conditions. All needed instrumentation used in a precise way. Hypotheses are checked. Correct treatment and interpretation of experimental data.
40	Autonomous work	Needs frequent help for the assembly of the set-up and the registration of data.	Needs occasional help for the assembly of the set-up and the registration of data.	Capable of assembling the set-up and only requiring occasional help for the registration of data.	Carries out the assembly of the set-up and the registration of data autonomously.
	Realization time	Greater than expected and the average.	Greater than expected but within the average.	In the expected time and below the average.	Below expected and the average.
	Attitude in the laboratory	Passive and hardly cooperative.	Participative and cooperative.	Participative, cooperative and showing some leadership.	Leads the teamwork. Initiative.
30	Communication of results	Results are incomplete, disorganized, and difficult to follow. Not presenting conclusions.	Communicates some important results. Not well organized but sufficiently to back some conclusions.	Communicates the most important results. Creates plots. Argues the results and draws conclusions.	Full communication of results. Expresses data and results. Creates plots and interprets them. Argues the results and draws conclusions.

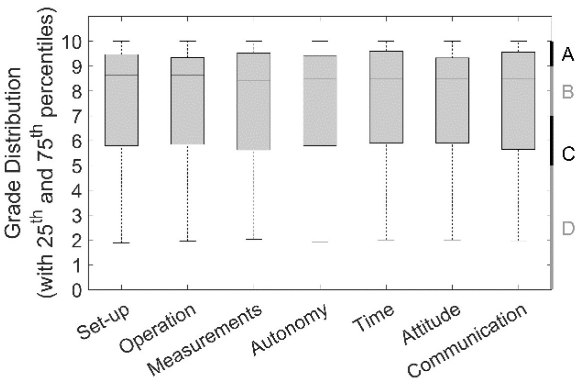


Fig. 5. Box plot of the grades obtained by the students for the different skills assessed for the laboratory sessions.

Although there is no increase in the number of students who pass, in both cases grades are shifted upwards, which seems to indicate that the flipped classroom produces a more significant learning than conventional teaching. Because the evaluation actions assess different aspects of the learning process, their combination gives a general idea of the achievement in the construction of the mental models, which results in a deeper understanding of the theoretical concepts, and in a better performance in different learning scenarios.

A survey has been carried out at the end of the course to gather student feedback on the activity. Students are satisfied about the teaching resources designed, both in terms of their own work and their autonomous learning. In terms of the concrete benefits that the flipped classroom strategy has on the understanding of the topics, there seems to be a difference between descriptive topics such as the fabrication of an IC and analytic/mathematical topics such as the operation of devices. Finally, students assess very positively the flipped classroom approach, indicating that they find the level of the activities fair but at the same time effective to achieve deep learning.

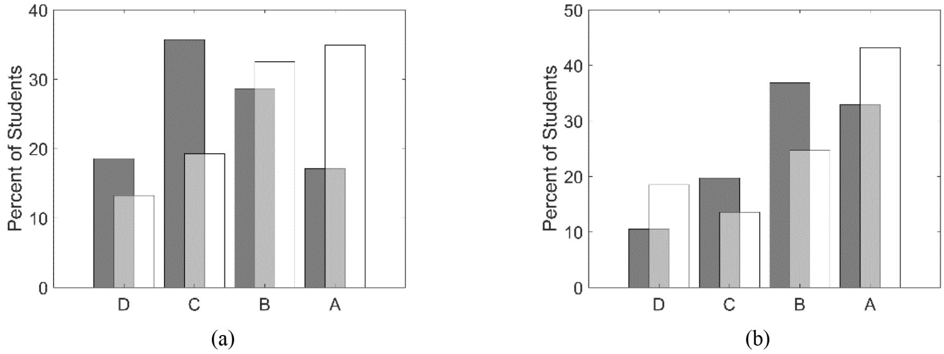


Fig. 6. Grades obtained before (gray) and after (white) putting in place the flipped classroom methodology, corresponding to (a) the MOS transistor, and (b) laboratory session on a basic amplifier stage. (D = insufficient; C = sufficient; B = good; A = excellent).

6. Discussion

This work presents the use of flipped classrooms in combination with other active methodologies and traditional lessons, as a pedagogical tool to implement model-based learning in higher education.

The most relevant and adequate methodology can be chosen at each time, which has shown advantages over the traditional approach such as increased student motivation and autonomy, or a deeper understanding of difficult concepts.

The methodology proposed in this work allows students to map the different pieces of information into a general system to develop their own mental model. In this respect, it can be considered that non-interactive resources are better suited to present the topics and main ideas, while interactive resources are useful to establish links between them to build the models, and to check whether the conclusions drawn from the models are true.

Students engage in a process where they develop mental models of the topics covered in class with tools that facilitate their construction and also assess their correctness. This process requires the personal commitment of every student and therefore fosters their learning autonomy, but also the exchange and social cooperation with their peers to analyse their own knowledge models, which entails sharing hypotheses, amending their thoughts and working with their cognitive disagreements. In this respect, it is important to promote this exchange of information, for example reviewing the meetings that the students have, to prevent them from cooperating to carry out only 'their' part of the work and not know anything about what the others have done.

Finally, the flipped classroom allows more time for active learning to happen in the classroom, and the teacher can follow the learning process more effectively.

7. Conclusions

This work presents the use of flipped classrooms as a pedagogical tool to implement model-based learning in higher education. A set of specific teaching resources, following a flipped classroom strategy, has been designed to enhance the construction of mental models by students of Electronics. The resources also serve to evaluate the models and to assess the effectiveness of the model-based learning approach.

The methodology described in this work, which combines flipped classrooms with other methodologies, has shown advantages over a traditional approach such as increased student motivation and autonomy, or a deeper understanding of difficult concepts. Also, the flipped classroom allows more time for active learning to happen in the classroom, and the teacher can follow the learning process more effectively.

To the authors' knowledge, the flipped classroom has not been reported as a pedagogical strategy to help students in higher education with the construction of their knowledge models.

Acknowledgements—This work has been partially supported by the Universidad de Zaragoza under grants PIIDUZ 17 065, PIIDUZ 15 001, and PIIDUZ 14 021; and by the Spanish Ministry of Economy and Enterprise (MINECO) under grant EDU2016-76743-P. The authors would like to thank the BEAGLE research group and the Institute of Research into Environmental Sciences - IUCA (Universidad de Zaragoza) for their assistance in this work.

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