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Gamification for Teaching Integrated Circuit Processing in an Introductory VLSI Design Course

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Abstract: Gamification is being incorporated into university classrooms due to its educational benefits for students learning, including encouraging student behavior and engagement, and consequently improving learning outcomes. Despite gamification being increasingly used in education, little has been developed related to Very-Large-Scale Integration (VLSI). In this article, we describe two different gamification experiences applied to integrated circuit processing and design in an introductory VLSI design course for Electronic Engineers. While gamification in universities is still not very mature and our experience spans only two academic years, we observed that, with the practice of gamifying part of our course, the topics treated in games were profoundly learned and the experience was very positive in every aspect of the teaching–learning process.

Keywords: gamification; teaching/learning strategies; VLSI design; integrated circuit; semiconductor manufacturing; CMOS; design rules

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1. Introduction

Teaching usually involves several instructional actions and supporting materials. It can include lectures, homework, tutorials, projects, laboratories, class discussions, and collaborative work. In the last few years, other nontraditional methods such as flipped classroom, project-based learning, microlearning, case study self-learning, or gamification were introduced [1]. Gamification is understood as the application of typical elements of game playing to other areas of activity, such as education. For instance, in engineering it can be used for problem-solving skills enhancement [2,3]. Despite other methodologies having their strengths, gamification stands out for its ability to deeply engage and motivate students, offer immediate feedback, and support the development of both cognitive and social skills. During the game, the player receives immediate feedback after each action, facilitating learning through trial and error. Usually, students are concentrated in class only a few minutes [4], while they can play games for several hours a day [5]. Hence, integrating gamification into education promotes motivation, engagement, behavioral shifts, friendly competition, and collaboration among students. This fun, collaborative, and competitive environment is precisely what can engage the student in the process of learning.

Most studies on gamification use one or several online platforms such as Kahoot, Edpuzzle, Socrative, Mentimeter, Quizalize, and many others that provide excellent options for educators [6]. They can help to stop the class and shift the student attention to a fun activity, then captivate the student during the whole class [7]. These platforms can be used at regular intervals to break the monotony and keep the students on their toes. However, gamification in education has detractors too. If the class becomes a game, aspects such as distractions from the topic or unnecessary stress because of the competition can appear, that can have the opposite effect on students than expected [8]. It has been also reported that if the dynamics of the games are always the same, gamification is also detrimental because of the lack of novelty [7,9]. In the case of the simple online games commented before, it is also difficult to plan a constructivist learning process based on them.

Gamification is being applied at every educational level, including at university, where the majority of gamification studies focus on Computer Science (CS) and Information Technology (IT) [10]. Most times, gamification is applied to online courses [7,11,12], which usually require stronger motivation than in-person ones. Gamification is beneficial especially to Generation Y and Z, who can expect some type of interaction between learning and playing [13].

In Electronic Engineering (EE) and similar degrees, there is a growing demand for qualified experts addressing the technological challenges of the future. EE covers several topics, including semiconductor processing technologies, analog and digital electronics, embedded systems, signal processing, communication systems, and more. Nevertheless, the application of gamification to the teaching of EE is still quite scarce. It has been implemented in some related EE sub-areas at different education levels. At secondary schools, Mena [14] used a mobile phone app to teach electric circuits and Díez [15] experimented with gamification to introduce digital systems. In EE university degrees, some subjects have been introduced with gamification. Marasco [16,17] discussed Electronic Design Automation (EDA) for floorplanning, placement, and routing. Richardson [18] designed a game to learn about RF path loss and antenna design in a junior-level electrical engineering course. Martin [19] proposed a full set of gamification strategies for their signal processing classes. Balaji [20] used a more classical approach for gamifying a Very-Large-Scale Integration (VLSI) design course based on quizzes by using an online platform. However, to our knowledge, few games have been developed to date to help assessment as well as learning at an adequate university EE level.

In this research, we focus on the application of gamification to the microelectronics processing topic, in the frame of a VLSI design course from an EE degree. Microchip fabrication and VLSI design are fundamental pillars today and essential for an Electronic Engineer, as these topics are pivotal to communication, computing, medicine, and various other facets of today's society. Significant growth in this sector is anticipated in the coming years as the need for semiconductor chips increases continuously because of 5G, the Internet of Things, artificial intelligence, and other beyond-traditional sectors such as quantum computing. It will be accompanied with substantial employment opportunities for qualified engineers on chip design. It is estimated that by 2026, the semiconductor industry will create 70,000 new direct jobs in the USA, according to the Semiconductor Industry Association [21]. In Europe, the approval of the European Chips Act by the European Parliament in 2022 underscores the importance of investing in talent training and skills development in the semiconductor field [22].

The process of creating an Integrated Circuit (IC) is named VLSI design, and consists of integrating thousands, millions, or billions of transistors and other components on a single chip. The process consists of several stages requiring completion by design specialists. Very schematically, the VLSI design process involves the following:

- Definition of the requirement;
- Design capture by means of schematic edition or description in hardware description languages (HDL) and logic synthesis;
- Functional verification;
- Layout editing for analog parts of the design and place-and-route for the digital parts;
- Final verification steps, including, for example, Design Rule Checks (DRC) and Layout vs. Schematic (LVS).

Then, the chips are manufactured using specialized manufacturing processes and packaged. Chip fabrication is mostly performed in a CMOS process, where CMOS stands for Complementary Metal–Oxide–Semiconductor. This process uses complementary and symmetrical pairs of p-type and n-type MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) for logic functions. Manufacturing a chip is like constructing a building. Different processing steps are typically performed on a silicon wafer, with layers of conducting or insulating materials deposited on it. The elements of the chip are sandwiches of these materials with micro or nanometric dimensions. To achieve these patterns, materials are protected from chemical or physical attacks through photolithography. All these processes must be carried out in clean environments, free of airborne particles and with specialized equipment.

The VLSI subject is usually part of the curriculum of an Electronic, Electrical, or Computer Science Engineer. To follow a VLSI design course, this subject requires some previous content. Typically, it is given after some courses on digital basic design, electronic circuit analysis, computer architecture, and physics of electronic devices. So, the student should have a good knowledge of basic circuit analysis, electronic devices such as the MOSFET, and digital design. Moreover, the student usually will follow additional subjects related to VLSI design, on analog integrated circuits, digital synthesis, or specific integrated circuits for radiofrequency. So, the introductory course on VLSI is usually the starting point for VLSI design, where the student learns about microelectronic technologies, MOS transistors, their use to build simple gates, their parasitic components, calculate delays in gates, build more complex gates such as flip-flops, and study how delays affect the distribution of signals in the chip.

2. Materials and Methods

There are two key areas that deserve special attention due to their significance for the student and the gaps that have been identified. The first one is the essential link between the manufacturing and the design processes (layout). The second one is the need to enhance understanding of the microelectronic processes and materials involved in chip implementation. Over the years, it was observed that a large number of students confuse the order of layers in the microelectronic processing of an integrated circuit (Figure 1), the steps necessary for chip manufacturing, or the layers necessary to produce a transistor. Although microelectronic processing is a content given in the 2–3 initial hours of the course, the student needs to use such information over the whole course, especially in the laboratory. Because of the importance of these concepts, we opted to design two games that strengthen comprehension of CMOS processing and design rules, a construction game to improve the connection between processing and design, and a card game used to increase comprehension of the elements in chip manufacturing.

The assessment of the gamification activities was conducted for students and teachers. For students, a satisfaction survey was pursued, consisting of 8 questions and related to the two games designed. The results are given in the percentage of students who rated each item from 0 to 4. The total number of students was 65 in two academic years (29 and 36 in 2022 and 2023, respectively). Teacher assessment consisted of a theoretical and a practical evaluation. Results are compared with the ones obtained from previous years when gamification was not included in the activities of the course (from 2017 to 2021, with 26, 31, 33, 27, and 39 students, respectively). The statistics for the theory are based on a question related to layout, microelectronics processing, and design rules in the final exam. In the two years with gamification, a similar question was introduced in both the midterm and the final exams, and both are considered here. The statistics consist of the percentage of students that answered correctly these questions. Laboratory was valued with a single question to 10 students randomly selected across the class. Again, the statistics are based on the percentage of students answering correctly the question.

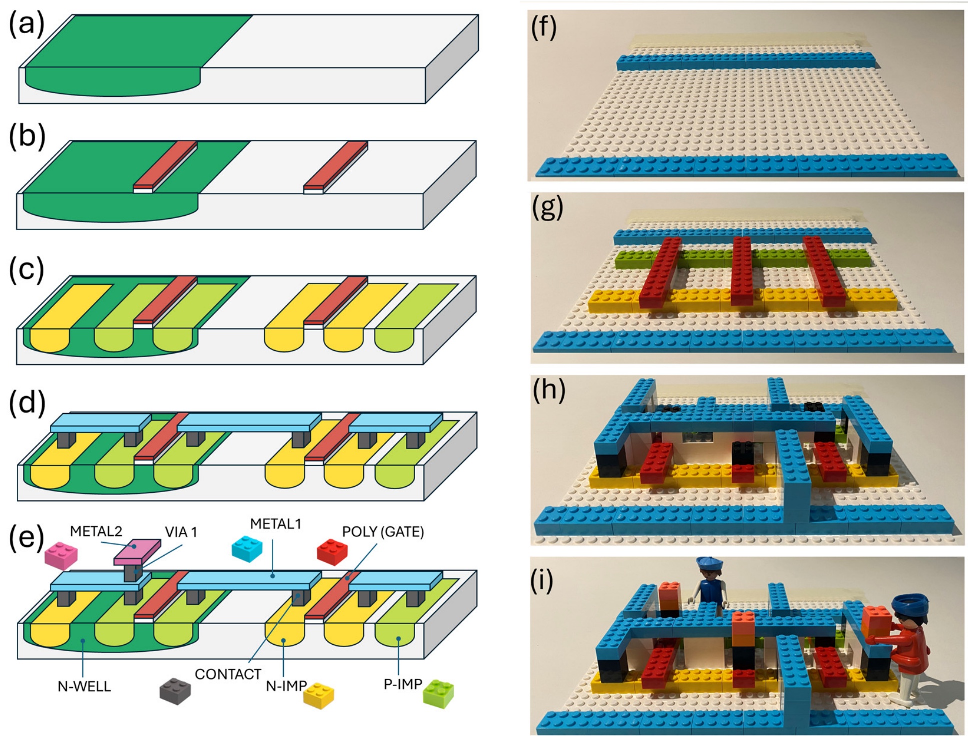

Figure 1. (**a**–**e**) Layout of the masks used to manufacture a CMOS inverter. (**f**–**i**) Corresponding simplified processing steps (from top to bottom) to build an AND2 gate made with LEGO pieces.

2.1. A Simple Construction Game

Mostly all of us have played with LEGO or similar games to build constructions. We proposed to use LEGO in class to show how different gates are built (Figure 1), showing the different layers (or processes) used. Colored bricks are associated with one layer in the process. Figure 1 from (a) to (e) shows a simplified process of building a CMOS inverter. A typical CMOS process starts by the N-WELL implantation on a type P wafer, then the gate oxide is grown, the polysilicon is deposited, the implantation of N and P regions is carried out, and finally the backend part of the process is performed, with the contact deposition, the first level of metallization, the via for the second metallization level, and so on. Figure 1e shows the equivalence that can be found within LEGO bricks of the different layers. Figure 1f–i shows a simplified process of building a layout of an AND gate with LEGO. As can be observed, the procedure is very similar.

Different games can be realized in class with the pieces. Students can simply play in a group to be the first ones in identifying the gate implemented by the teacher, or they can play to be the first ones in building a gate, etc. Important aspects of this constructive game are that students must discuss and agree about aspects as the order of the different layers, or the morphology used to build the gate. At the same time, they can compete and enjoy. This game, when made in collaboration, deploys the different personalities of gamers [23], i.e., killers, achievers, socializers, or explorers.

2.2. A Card Game to Learn Chip Processing

When applying gamification to teaching, more sophisticated games can be imitated. Storytelling has been reported to be very engaging for the learners [24] if it includes three elements, i.e., the character(s), a conflict, and a final objective. The game proposed here is called 'Conway' in honor of an engineer woman that revolutionized the semiconductor industry with a new methodology well at the beginning of microelectronics [25]. The narrative used in our game was as follows:

> 'Foundries around the world see global chip manufacturing in jeopardy. The world will be left without PCs, without mobile phones, without AI, because a

spiteful company (CONWAY) wants to apply incorrect design rules to prevent them from being manufactured. Your goal will be to work in groups of 4–5 and avoid it at all costs by fighting with (combining) the layers of the process or technological processes'.

Groups play in turns with 7 cards each. Cards are presented in Figure 2. There are cards for 'Items' (Figure 2b), 'Layers' that must be combined to achieve an 'Item' (Figure 2c), 'Processes' that combined are used to obtain an 'Item' (Figure 2d), and 'Rules' that the designer must follow to manufacture the 'Item' (Figure 2e). The active group takes one card from the deck, while they drop another one. With its hand of cards, the group has to achieve one of the 'Items' by combining the required 'Layers' (Figure 2g) or 'Processes' (Figure 2h). Thus, they discard the set of cards in order to get the corresponding points. At the same time, an attacking group can assault the group that is discarding cards with the set of associated 'Rules' cards (Figure 2i). An amount of 2–4 points are achieved each time a full 'Item' is achieved, depending on the complexity of the 'Item'. Also, points are drawn from an assaulted group to an attacking team if they are attacked with the complete set of 'Rules'. The number of points corresponding to each 'Item' is visible on the 'Item' card. The game finishes when one group achieves 10 points or more.

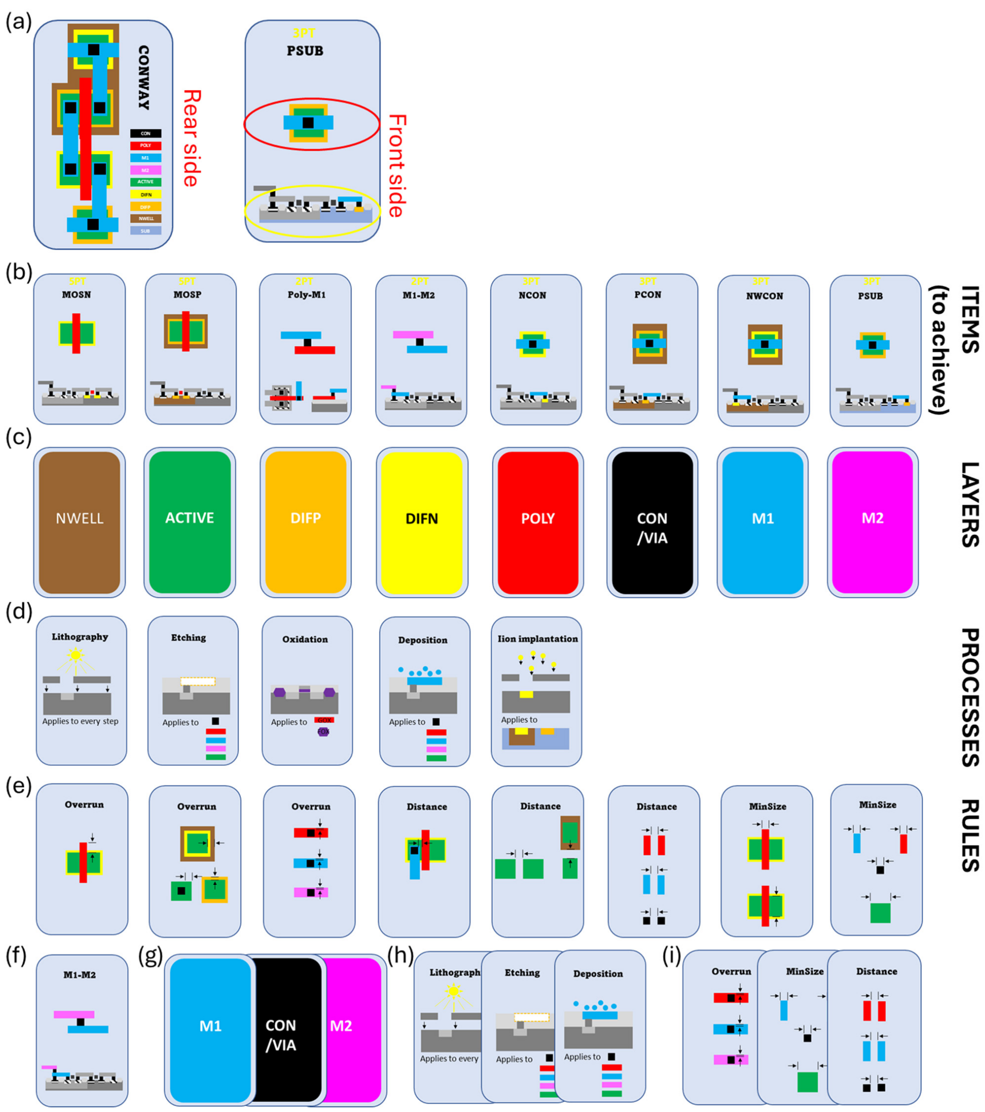

Figure 2. Card game to teach VLSI processes to Electronic Engineers. (**a**) Rear and front view of one 'Items' card. The red circle marks the top view of the item achieved. The yellow circle indicates the

cross-section of the gate with the achieved items marked in color. (**b**) 'Items' set of cards. (**c**) 'Layers' set of cards. (**d**) 'Processes' set of cards. (**e**) 'Rules' set of cards. (**f**) An example of item (Metal 1 to Metal 2 connection through a via) and sets of (**g**) 'Layers' and (**h**) 'Processes' needed to obtain the item, with (**i**) 'Rules' to obey. In that case, the groups would be playing for 2 points.

In this game, the group must decide which strategy it wants to follow, i.e., attack or build. In every situation, students must know or discuss what processes shape the manufacturing, what layers need to be considered in the layout, and what are the rules governing those layers. As in the previous case, this game also considers every gamer personality. However, it is much more complex than the previously presented construction game.

3. Results

In this section, a general description of the VLSI design course at the University of Barcelona is summarized, as well as the learning methodology used. Then, the results of the gamification experiences are presented. The analysis includes the opinion of the students and the impact on the learning process assessed by the teachers.

3.1. Framework

The gamification experiences were applied to an introductory course about VLSI at the University of Barcelona, as part of the Electronic and Telecommunication degree. In general, the course consists of—simplified—the following topics:

- Integrated circuit manufacturing and design rules;
- MOSFET, operation, model, and parasitic components;
- CMOS inverter: static and dynamic characteristics;
- CMOS combinational logic;
- Pass and pass-gate transistor logic;
- Dynamic logic;
- CMOS sequential logic: latches and flip-flops;
- Synchronization strategies: clock skew, clock distribution networks;
- Structured design: memories and datapaths.

These topics are usually accompanied by laboratory sessions, where the student uses a professional environment to put in practice the given theory. These sessions are conducted in a well-equipped room with Linux on computers and the Electronic Design Automation (EDA) tools and design kit. At the end, the students are able to design a complex Boolean gate following the typical design flow consisting of schematic edition, simulation, layout edition, Design Rule Checking (DRC), Layout vs. Schematic (LVS), Extraction (ERC), and post-layout simulation.

Because of the descriptive and graphic content of the subject, lectures are given by using electronic slides, which are delivered to students in advance. They are accompanied by a set of solved problems. In general, for most of the students, the laboratory is quite funny and motivating. The class is very participative thanks to the methodology used. The theoretical content has been reduced to the minimum, dedicating only 1 of 3 available hours per week to Theory and the other 2 h to Collaborative Problem Solving (CPS). In CPS sessions, the teacher presents a problem of increasing difficulty according to the course progress. Students are grouped in groups of three to five people and discuss the raised problem in the classroom. The teacher steps in, if the groups are stuck at some point. Problems are selected to animate discussions in the group.

At the University of Barcelona, the whole set of lectures correspond to 6 ECTS (European Credit Transfer System) and are distributed and evaluated as 60% theory and 40% laboratories, in 3 h for theoretical explanations and 2 consecutive hours for laboratory works per week. The average number of students enrolled in class is 25–40 per year. The introductory VLSI subject is very similar to other similar courses around the world. However, the CPS helps to introduce special activities like gamification.

3.2. Student Assessment

Gamification was introduced in the last two courses (2022 and 2023, with 29 and 36 students). Most of them were 21 years old, but all were young students under 24. Regarding gender distribution, the classes had a very high percentage of males (85% and 90%, respectively). All students had previous knowledge about basic digital design but were new to microelectronics or VLSI design.

To assess the subjective feelings and perceptions of the students, they answered an anonymous questionnaire after finishing each game, concerning usability, knowledge acquisition, and user experience. The questionnaire is presented in Table 1 and the results are summarized in Figure 3. Answers were expressed with marks from 0 to 4, where 0 is considered very disappointing and 4 a very satisfactory answer.

Table 1. Questionnaire for students about the games.

Usability
Q1. Was the game properly designed?
Q2. Was the game appropriate for your previous level?
Q3. Was the game easy to understand?
Knowledge Acquisition
Q4. Did the game cover knowledge gaps?
Q5. Did the game help you to understand VLSI concepts?
Q6. Did you require additional explanations to play?
User Experience
Q7. Did you enjoy playing the game?
Q8. Was the time to play available enough?

Figure 3. Student questionnaire results in terms of percentage of the total number of responses evaluated from 0 (very unsatisfied) to 4 (very satisfied) for the questions in Table 1.

Overall, as can be observed from all the figures, the results of both games are very positive. For clarity, questions with marks above 2 are shown with solid color in Figure 3 and those evaluated more negatively with dashed lines. The answers about the construction game were very satisfactory for every item. It could be expected because of the simplicity of the game. The answers to the card game were also positive but the results are more disperse. We attribute this to the higher complexity of the game, as can be deduced from Question 8 (Was the time to play available enough?) where only 17% of the students found the time available to play well enough and Question 3 (Was the game easy to understand?), because only 57% found the game easy to understand. But 67% of the student opinion was that the game helped them to learn (Question 4, Did the game cover knowledge gaps?) and 80% (Question 7, Did you enjoy playing the game?) thought that the game was funny. In both cases, the games seem designed adequately and were appropriate for the level of studies.

3.3. Teacher Assessment

Unfortunately, the number of students in the Electronic and Telecommunication engineering degree at our university was too small to have a control group. So, student performance and behavior were compared with previous years, when games were not used in the classroom. The results in terms of student engagement are spectacular. The class was very participative and had fun in the process. In spite of the considerable time required to play a game at class compared with the traditional master class, the benefit along the whole semester was observed to be really good because students remembered better the treated topics.

The assessment was conducted first comparing the questions about layout, design rules, and processing asked in years from 2017 to 2021, with a similar question in the midterms and final exams of 2022 and 2023. This part of the subject was answered correctly by 39% of the students in 2017, 46% in 2018, 35% in 2019, 29% in 2020, and 44% in 2021. The percentage of correct answers increased substantially in the second period analyzed, with 90% in the midterm of 2022, 86% in the final exam of 2022, 94% in the midterm of 2023, and 88% in the final exam of 2024. These results are plotted in Figure 4 together with horizontal markers at the averages of 49% and 89% corresponding to the two periods investigated.

A second test was performed in the laboratories, where students work on their own projects while teachers are accessible to solve issues. During the layout sessions, students were asked how they could identify a MOSFET and where it was located. Teachers tried to maintain the students' focus on their own work. For this reason, they only disturbed 10 students selected, taking advantage of an interruption caused by their questions. Even though they had placed the MOSFETs themselves, many times they were unaware that where the polysilicon crosses the implantation, there was a MOSFET. Figure 4 shows the percentage of correct answers from the 10 students to this question from 2017 to 2023 at different times over the course. Some improvement was observed from 2017 to 2021 from week 4 to week 8. However, for the gamified courses, 100% of the students answered it correctly even in week 4 of the course. It is clear that with this gamification approach, students in the laboratories never forgot the order of the layers and perfectly identified the layers composing transistors, contacts, etc.

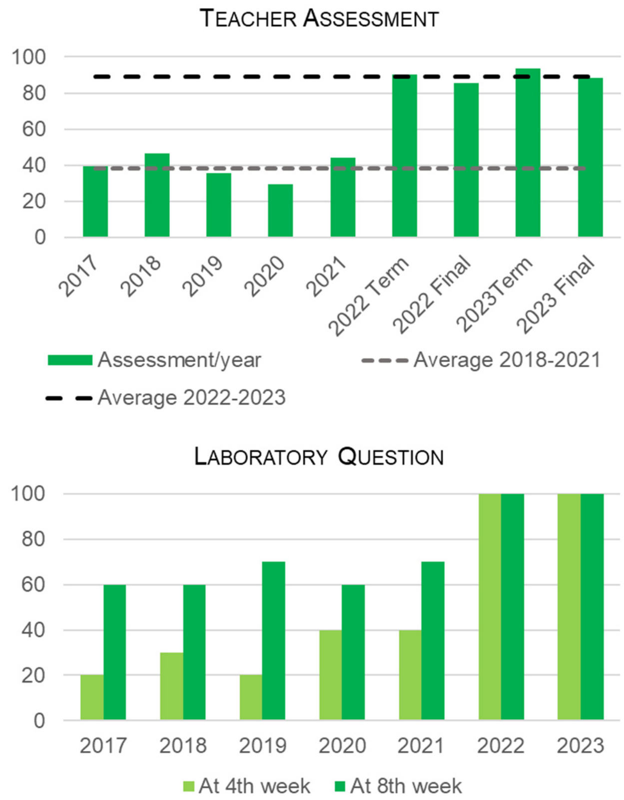

Figure 4. Teacher assessment in percentage via comparison with previous years, in exams and laboratories.

4. Discussion

Gamification was introduced as an additional activity of a subject already based on CPS. With CPS, the student must acquire the knowledge needed to solve problems in the theoretical classes. During the CPS session, the members of the group converse, interpret, ask themselves, debate, negotiate, and reach a consensus on every aspect regarding the problem. In general, working in collaboration allows the students to improve the interpretation of the initial information; they are able to find new information uncovered in class, understand better the problem, plan a solution, and identify a possible answer in most of the cases. Because the level of the students is diverse, those advanced reinforce their own learning by helping those with deficits to understand the exercises and to achieve enough confidence to attain the course goals. So, the differences between students in a group are minimized. The games designed here pursue the concept of learning by doing. None of the games was a revision tool. So, the games follow the same CPS spirit. The construction game is very easy to play and allows students to see in a simplified fashion how integrated circuits are made. The card game is more demanding to implement in the classroom. There, the cards' design has drawings that indicate the related 'Processes', 'Layers', and 'Rules' (Figure 2a), which helps the student to understand and memorize the processes and materials involved in the production of a device.

It is beneficial for students when the game is appropriately aligned with their academic level, i.e., primary, secondary, or higher education. In the construction game, the student can see how the layers are stacked in a VLSI process, following simplified design rules. Even though the game achieves the fundamental goals, it may seem simple for a higher education student, but it is so cost-effective that it deserves some time to be explained and played to promote motivation in students. On the other hand, with university degrees and secondary schools, the student is used to playing card games. The card game developed here has all the necessary elements involved in manufacturing chips, but it is still quite complex to put into practice in the classroom. With the habitual tight schedule over a course, finding time to dedicate one or two classes to play for the student to learn a unique concept can be a difficult task.

As a final remark, the shortage of chip designers in some countries is leading to considerations of introducing certain technological content for VLSI design learning in secondary education. The aim is to introduce the subject to students before they have to choose a university career. At this stage, games like those presented in this article would also be very attractive. Although the process of integrating games for teaching VLSI appears challenging, as there are presently no clear, practical guidelines on how to accomplish this in a cohesive and efficient manner, every single VLSI topic can be treated that way to make these studies more enjoyable and engaging, particularly at secondary schools.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All data are available as requested.

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