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A Game-Based Learning Approach in Digital Design Course to Enhance Students' Competency †

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Abstract: Digital Design is a laboratory course, and the educator must focus on the students' need to know why they study the theory and mainly on the transition from knowledge-based learning to competency-based learning. This study consists of five surveys that were conducted during 2017–2021. First, we evaluated students' learning outcomes in order to define possible learning problems. According to the literature, gamification can have a positive impact on students' motivation and learning outcomes. Therefore, we used ready-made digital games in order to evaluate students' satisfaction and willingness toward their integration in the educational process. This process was repeated in the next academic year. The feedback we received from the previous surveys has helped us to adapt to the new approaches of teaching due to the current pandemic caused by COVID-19. We proposed an online holistic environment based on Keller's (1987) ARCS model and Malone's (1981) motivational model, which was applied in distance learning. Each student participated in a student-centered learning experience. He took an active role and was self-manager of his learning process. He was given the opportunity to develop capabilities and strategies through practice and engagement in higher-order cognitive activities, acquire self-learning skills, learn how to solve problems, and participate in teamwork. This study's innovation is that students experienced a combination of learning approaches: (a) a virtual lab consisting of simulation-based activities, which allowed students to access new laboratory experiences, (b) a project-based digital game without a processor, which developed their motivation, creativity, and hands-on ability, as opposed to the other relevant studies that use ready-made games, and (c) asynchronous videos as feedback, which ensured the educator's emotional support and social presence. Finally, this study developed research to evaluate the effectiveness of this online holistic environment and used a questionnaire, which was created based on Keller's Instructional Materials Motivation Survey tool. The results showed that its integration in distance learning is probable to motivate students to learn and affect positively their attention, relevance, confidence, and satisfaction.

Keywords: distance education and online learning; games; simulations; media in education; post-secondary education

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1. Introduction

The concept of Information Technology (IT) refers to the combination of computer-based technologies for information management. These technologies are found in almost every aspect of daily life and in addition have almost inseparably intersected and involved their application branches, such as industry, commerce, administration, education, medicine, work, entertainment, and housework. Therefore, computers are changing the way people communicate, work, entertain, and educate themselves [1]. Computer science is one of the most in-demand professions, which implies the need for an effective higher education and mainly for educators who are willing to integrate new approaches and techniques in the educational process.

This study deals with the problems encountered in learning engineering in higher education. An important problem [2] is that the theory is not application-oriented. Due to a lack of hands-on experience, although students build some basic professional knowledge, most of them become used to thinking mathematically and end up losing their interest in courses related to hardware. The combination of textbooks and practical use of engineering leads to an effective teaching, piques up students' interest, and strengthens their hands-on ability. It should be stressed that although academics support practical activities in engineering to develop student's holistic skills, they do not acknowledge their value due to the education reform, reality constraints, and the traditional status of technical knowledge [3].

The current pandemic caused by COVID-19 has affected the educational process in which new tools and teaching methods have been integrated in higher education. The use of digital supporting technologies in distance teaching can increase students' academic performance in engineering [4]. Our strategic aim was to develop an online holistic environment in order to help students to enhance their motivation to learn and improve their well-being. Miller's (2007) principles of holistic education are balance, inclusion, and connection. The balance can help students to develop their analytical skills through individual and group work. The inclusion can transmit the knowledge, transact the understanding, and transform the student's physical, mental, emotional, aesthetic, spiritual, and moral development. Finally, the connection can strengthen the communication between students, teachers, schools and communities [5]. The teaching and learning approaches that we combined were (a) virtual labs and simulations, (b) gamification and project-based approach, and (c) asynchronous videos.

1.1. Virtual Labs and Simulations

Distance learning is a concept widely used for learning and teaching. The advantages of virtual labs are: flexibility, multiple access, benefit of savings [6], reduced possibility of an injury or an accident, collaborative work by the academic community, and more realistic user experience [7]. The disadvantages, respectively, are that they do not really exist and therefore nothing negative can happen; students behave less seriously, responsibly, and carefully [6]; the ease of students being absent from the class, the lab maintenance and course management are time-demanding processes; the increased probability of bugs; the lack of friendliness to use some resources; and their high sensitivity to operating systems [7]. Researchers also suggested the combination of virtual and real labs in teaching and learning engineering [8]. The virtual reality and a holistic experiential learning process in higher education can be combined [9] and social virtual reality platforms have positive effects on users' well-being [10]. Integrating gamification features into a virtual context enhances students' motivation [11].

1.2. Gamification and Project-Based Approach

To increase students' interest and to improve the educational process, many universities have radically altered their approach by introducing the context of "gaming" into the curriculum [12]. According to Kapp, "Gamification is using game-based mechanics, aesthetics, and game thinking to engage people, motivate action, promote learning, and solve problems" [13] and also "Gamified learning is difficult, challenging and stressful, but if well designed games can help learners acquire skills and knowledge in a safe environment and abilities in concentrated periods of time with high retention rates and effective recall" [14]. Furthermore, the effectiveness of gamification in teaching "Computer Science" in higher education was studied and proved [15]. Additionally, researchers designed educational scenarios for teaching "Python programming language", incorporating game elements and a micro-controller, which strengthened the students' motivation [16]. An approach of gamifying in the course of "Microprocessors and Micro-controllers", has been reported [17], which significantly improved students performance. An interesting teaching approach incorporating a mobile educational game into the course "Computer Architecture", was presented [18], which allowed learners to learn in an interesting way. Finally, engineering students in the course of "Multimedia Content Production" compared the gamified educational material to other courses and stated that it seems to be more interesting, motivating, and easier to learn [19]. According to [20], there are 68 digital games and 40 non-digital games available for teaching computer science in higher education. The games such as "Digi Island" [21], "BINX" [22], "The Mystery of Traffic Lights" [23], "Digital Logic and Electronics Concepts" [24], and "Digital System Game" [25] are available for learning Digital Logic. The integration of mobile games into educational process can enhance students' level of knowledge in higher education [26].

Gamification can have a positive impact in health and well-being [27], and its use in health apps is very popular [28]. The gamification strategy through a mobile app was successful in improving users' mental health and well-being [29]. On the contrary, there are large discrepancies in the way that researchers have conceptualized the role of gamification in health behaviour change theories [30]. Elements of game design can develop both emotional and cognitive skills [31]. The intention to use gamification relates with the attitude, enjoyment, and usefulness [32]. An important factor, on which the success of Mass Open Online Courses is based, is a gamified learning environment [33].

The effective online project-based learning in engineering combines technical support with instant feedback and promotes social connections between students and academics [34]. Group work in project-based learning in engineering education enhances students' learning experience, building their self-confidence, developing their critical and creative thinking as well as their affective skills [35]. Combining a project with games improves student's involvement [36].

1.3. Asynchronous Videos

In the last decade, videos have become a kind of resource that is widely used in distance learning. Most academics offer the recording and distribution of lectures in order to facilitate the attendance of courses, and videos play an important role in Massive Open Online Courses. The use of videos are related with video streaming websites such as YouTube, as the process of recording, editing, and distributing a video document through the internet is very easy [37]. According to dual coding theory [38], concreteness, imagery and verbal associative processes play major roles in various educational domains: the representation and comprehension of knowledge, learning, and memory of school material, effective instruction, individual differences, achievement motivation and test anxiety, and the learning of motor skills. The use of instructional videos has a positive impact on the possibility of achieving higher academic outcomes [39]. Students have very positive attitudes toward video podcasts thanks to the usefulness, helpfulness, effectiveness, enjoyment, motivation, and stimulation that they provide [40]. Asynchronous videos and screencasts of digital projects are very useful, as they maintain connection and engagement during the pandemic and provide feedback to students [41]. Educators should ensure the emotional support, mental wellness, and social presence during the pandemic by implementing video for communication and feedback [42]. Asynchronous videos can improve online social presence and make educators seem more real, present, and familiar [43].

1.4. Related Work

Digital Design is an introductory course that is included in the curriculum of most departments of Informatics and Computer Engineering of Universities. Students of the respective departments can develop their skills in the classroom and in the lab. However, the lack of in-classroom activities causes a lack of students' willingness to engage with the cognitive object of this course. Several studies have integrated digital simulators and platforms into the teaching of a Digital Design course. We identify a few sample studies relevant to ours. The most recent research work [44] concluded that digital platforms and conventional laboratory activities can provide roughly similar experiences, while another approach [45] proposed that active learning in and out of the classroom can be fully supported by the learning technology. Digital simulators may be used as tools [46] for engaging the students to interactive design of digital circuits, and the students liked the majority of the newly designed labs. Furthermore, researchers suggested specifically the SDLDS simulator and showed its effectiveness by the increasing number of students electing to take the course, the rising percentage passing the exam, and the improving average grade [47]. Finally, the inclusion of games in capstone projects in a Digital Logic course has been studied and proved that effectively motivated students to get engaged more effectively in the learning process [48].

1.5. Competency-Based Learning

Recently, ACM and IEEE-CS released Computing Curricula 2020, Global Guidelines for Baccalaureate Degrees in Computing [49]. One of the main additions is the “transitioning from knowledge-based learning to competency-based learning”. Considering competency-based learning, the most recently proposed Computing Curricula [49] define it as the sum of knowledge, skills, and disposition of the student to enter the profession. Since the dispositions term refers to behavioral characteristics of the student, we excluded it and focused our interest on the other two terms. The knowledge term refers to the the understanding of core concepts of the course, and it is the most typical approach in learning in Higher Education, highlighting the “know-what” dimension. The enhancement of the motive to follow a course and succeed in it is the core concept of most of the works presented previously. Our study focuses on the skills term, which refers to the ability of the student to develop capabilities and strategies over time through practice and engagement in higher-order cognitive activities, highlighting thus the “know-how” dimension.

1.6. Study’s Innovation

The purpose of this study was the enhancement of the educational process through the integration of an online alternative and holistic environment related to students’ daily life into distance learning. This online environment could be integrated in the future into traditional teaching in the classroom. Our study differs from existing studies in several ways. One of the basic foundations of our teaching and learning approach is motivation theories. It was designed based on Keller’s (1987) ARCS model and Malone’s (1981) motivation model and included educational material that attracted students’ attention, aroused their curiosity, and developed their fantasy. Challenging activities related to their daily lives increased students’ levels of confidence and satisfaction.

1.6.1. The ARCS Model

The ARCS model is a method for improving the motivational appeal of instructional materials, which defines four major conditions that have to be met for people to become and remain motivated. The first condition, attention, is an element of motivation and learning. As an element of motivation, the concern is for getting and sustaining attention, and as an element of learning, the concern is for directing attention to the appropriate stimuli. Keller’s (1987) six strategies for attention include (a) incongruity/conflict, (b) concreteness, (c) variability, (d) humor, (e) inquiry, and (f) participation. Game-based learning environments [50] and video watching with or without feedback [51] can captivate learners’ attention. The second condition, relevance, can come from the way something is taught. It does not have to come from the content itself. To the extent that a course of instruction offers opportunities for an individual to satisfy these and other needs, the individual will have a feeling of perceived relevance. Keller’s (1987) six strategies for relevance include (a) experience, (b) present worth, (c) future usefulness, (d) needs matching, (e) modeling, and (f) choice. Students’ perceived relevance of educational games as a tool to develop their competencies influences their positive attitude. Therefore, teachers must be careful when choosing the features of the game so that these features meet students’ criteria for being perceived as relevant [52]. The third condition, confidence, is the expectancy for success.

Keller's (1987) five strategies for confidence include (a) learning requirements, (b) difficulty, (c) expectations, (d) attributions, and (e) self-confidence. Two of the most commonly used learning outcomes for the use of game-based learning are confidence and motivation [53]. Instructional video podcasts have the potential to have an impact on improving student confidence [54]. The fourth condition, satisfaction, incorporates research and practices that help make people feel good about their accomplishments [55]. Keller's (1987) six strategies for satisfaction include (a) natural consequences, (b) unexpected rewards, (c) positive outcomes, (d) negative influences, and (e) scheduling. Problem-based games [56] and the use of video-based instructional materials to learn practical skills at a distance [57] enhance students' learning satisfaction.

1.6.2. Malone's Motivational Model

Malone suggested that "if students are intrinsically motivated to learn something, they may spend more time and effort learning, feel better about what they learn and use it more in the future" [58]. Game elements can be integrated into activities enhancing someone's motivation. Computers can be used to create motivating environments, such as computer games. Malone's (1981) motivational model includes curiosity, challenge, and fantasy. Additionally, after a few years, Malone presented that sensory curiosity includes the value of observing the attention to variations and changes in the light or sound [59]. Cognitive curiosity is evoked by the expectation of modifying higher-level cognitive structures. When the uncertainty of the outcomes of an activity increases, so does the motivation. Computer games used in instructional environments can make outcomes uncertain for students by providing variable difficulty levels, multiple levels of goals, hidden information, and randomness. Fantasy evokes mental images of physical or social situations not actually present. Emotional aspects of fantasy are related with experiences of power, success, fame, and fortune that may not be available in real life. Cognitive aspects of fantasy, in the case of simulations and modeling systems, are related with the presentation with information and experience to students in an imaginary context that they will later be asked to apply to real-world simulations.

1.6.3. Educational Strategies

The holistic education Miller (2007) guided the design of the online environment. Three educational strategies were followed: (a) virtual-based approach and simulations, (b) game-based approach and project, and (c) asynchronous instructional videos, which allowed students to access new laboratory experiences, develop their motivation, creativity, and hands-on ability, and support self-learning. Games can be used as educational strategies in two ways. The first method is to give students ready-made games that they can play with, and the second method is to teach the object through game development. Few studies have been conducted based on the second method. The present study started with the first method from which there was a positive feedback and continued with the second method, where students were asked to develop a project-based digital game without the use of a processor as opposed to the other relevant studies.

1.6.4. Research Questions

Based on the literature review, a set of research questions was proposed:

RQ1. What are the students' learning outcomes in the course?

RQ2. How effective are ready-made digital games in motivating students to be more involved with the course?

RQ3. Is the integration of an online holistic environment in educational process probable to motivate students to learn the course?

RQ4. Is there a statistically significant effect on student's attention, relevance, confidence, and satisfaction through the integration of an online holistic environment in the educational process of the course?

RQ5. Are there relationships among the attention, relevance, confidence, and satisfaction (ARCS) elements used in the Instructional Materials Motivation Survey (IMMS)?

2. Method

2.1. Procedure

The research methodology consists of five stages, as shown in Figure 1: receiving feedback, learning goals, tools, lab experiences, and evaluating the lab experiences.

Figure 1. Stages of the methodology.

2.1.1. Receiving Feedback

First, a survey was performed in order to receive feedback by students about the educational process and define possible learning problems, which confirm the literature. One method, with which games can be used as educational strategy, is to give students ready-made games that they can play with. Although there are remarkable games for teaching computer science, there is a lack of integration into the learning context [20]. Afterward, the ready-made digital games, free android applications, that were integrated in educational process were: (a) Logic Gates–Electronic Simulator and learning (https://play.google.com/store/apps/details?id=pl.cyfrogen.gates.android&hl=en, accessed on 1 February 2022), which contains lots of levels, allows player to learn by playing, to create his own electronic circuits, and to test his skills, (b) Circuit Scramble (https://apkpure.com/circuit-scramble-computer-logic-puzzles/com.Suborbital.CircuitScramble, accessed on 15 December 2021), which consists of challenging puzzles based on real-world logic gates with custom-made levels and limitless supply of randomly generated levels, (c) Logic Gates: Simulator (https://www.apkmonk.com/app/com.pmx10.game.android/, accessed on 15 December 2021), which provides great hands-on experience of manipulating binary signals using logic gates and/or constant inputs, switches, and light bulbs, (d) Logic Gates apk (https://www.apkmonk.com/app/kobs, accessed on 15 December 2021), which helps the player to learn the integrated circuit of logic gates in a effective and interactive manner, (e) And Logics (https://apkpure.com/logics/com.hexastyle.andlogics, accessed on 15 December 2021), which is a logic circuit simulator with an integrated scheme editor and a waveform browser consisting of schematic components such as transistors, logic gates, flip flops, multiplexers, demultiplexers, indicators, displays, switches, and constants, and finally, (f) Logic Circuit Simulator (https://apkgk.com/com.lartox.logiccircuitsimulator, accessed on 15 December 2021), which contains multiple voltmeter helpful features such as logic gates resistor, buttons, lamps, displays, clocks, flip-flops, latches, and multiplexers. Finally, a survey was performed in order to assess the students' satisfaction and willingness toward the integration of ready-made digital games in educational process.

2.1.2. Learning Goals

The three major domains of Bloom's taxonomy of educational objectives are: the cognitive, the affective, and the psycho-motor. The cognitive domain is related to the goals of the retrieval or recognition of knowledge and the development of intellectual abilities and skills. The affective domain is related to goals that describe changes in interest, attitudes, and values, and the development of appreciations and adequate adjustment. The psycho-motor domain is the manipulative or motor-skill area [60]. Engineering courses are dominated by cognitive, affective, and psycho-motor aspects. Communication skills, creativity, and motivation are included to the affective domain. Skills that are related with design projects are included in the psycho-motor domain [61]. The learning goals of this research were focused on developing students cognitive skills in Combinational and Sequential Logic and their affective and psycho-motor skills using the educational strategies described above.

2.1.3. Tools

In our teaching and learning approach, free web-applications were used, which are described below. (a) Tinkercad, a free and user-friendly application for electronics, was used in order to give the students the opportunity to design and simulate electronic circuits. (b) Logisim, an educational tool for designing and simulating digital logic circuits, was used in order to design the logic diagrams. (c) Loom, a free screencasting software, was used to record screens with audio and produce the instructional videos. (d) Google Forms, a free online tool, was used to create the questionnaires of the surveys. (e) eClass platform, a complete course management system, was used to assign activities to students as quests.

2.1.4. Laboratory Experiences

We focused on providing the students with all the knowledge but at the same time to transmit it in an effective way that is attractive to them. The student participated in a student-centered learning experience. He took an active role and was self-manager of his learning process. He was given the motivation for being able to self-direct, self-assess, and self-monitor, acquiring self-learning skills, learning how to solve problems, and participating in teamwork. His goal was to be creative and responsible in the development of activities without the purpose of obtaining an external reward such as bonuses or benefits or an other extrinsic motivation. To achieve this, we designed a holistic online environment for self-learning, which consists of an educational material with simulation-based activities, a virtual lab, and instructional videos.The educational process was organized as follows:

- Educational material with simulation-based activities
  Students were given on a weekly basis during the semester (12 weeks) an appropriate educational material. It has been divided into six modules, and it was available on the e-class platform. The six modules were: Logic Gates, Arithmetic and Logic Circuits, Multiplexers and Decoders, Flip–Flops, Registers, and Electronic Tic-Tac-Toe. Each module consists of the objectives, which prepare the students for the subject they are called to learn; text, which describes the operation of each logic circuit; logic diagrams, which illustrate the implementation of each logic circuit using Logisim; truth tables, which indicate the output values of each logic circuit with all combinations of input values; learning activities, which must be implemented by students; photos, which illustrate the implementation of each logic circuit using Tinkercad; links to digital electronic circuits, which implement the logic circuits using Tinkercad; and links to short and fast talking instructional videos, which include an audiovisual explanation of each logic circuit.
  Students were asked to retrieve their theoretical knowledge and realize why they study the theory implementing 34 circuits, interacting with them, and verifying the corresponding truth tables. In addition, it was proposed to them to upload their work on the platform as well as see and comment on their classmate's work, transmitting their feelings. Social influence and positive recognition have a positive effect on people's willingness to exercise [62]. The module "Logic Gates" consists of 12 learning activities (Not Gate, And Gate, Or Gate, Xor Gate, Nand Gate, Nor Gate, Not Gate (using Nor Gate), And Gate (using Nor Gate), Or Gate (using Nor Gate), Not Gate (using Nand Gate), And Gate (using Nand Gate), and Or Gate (using Nand Gate)). The module "Arithmetic and Logic Circuits" consists of 10 learning activities (And Bitwise, And Masking, Or Masking, Xor Masking, Half Adder, Full Adder, Half Subtractor,

Full Subtractor, 4-Bit Adder/Subtractor, 4-Bit Adder). The module "Multiplexers and Decoders" consists of 2 learning activities (Multiplexer, Binary Decoder). The module "Flip–Flops" consists of 3 learning activities (JK Flip-flop, D Flip-flop, T Flip-flop). The module "Registers" consists of 2 learning activities (SIPO left shift register, SIPO right shift register). The module "Electronic Tic-Tac-Toe" consists of 5 learning activities (Block Circuit, Player Circuit, Winner Circuit, Draw/Win Circuit, Result Circuit).

- Virtual lab
  Clive Maxfield, a distinguished contributor to Multimedia Logic, and Brown remarked that one of the best ways to learn something and remember it afterward is by means of hands-on ("fumble and stumble") experience (1995). Combining a simulation system and a tutoring system can alleviate the disadvantages of having each system operating by itself [63]. Virtual Labs have been designed to facilitate the teaching–learning process for engineering courses at universities and bring the students closer to the real [8]. Using the simulation tools does benefit the students learning the Digital Design [64].
  Therefore, it was proposed to students to visit links to the Tinkercad platform to compare their work with the 34 circuits of the virtual lab and also buy the required tools in order to organize their personal lab. The provided circuits' designs have been developed by the author and are freely available for inclusion to other courses under the Creative Commons license. Until this day, the circuits have been shared and used hundreds of times by students and professors around the world. Thus, one of the contributions of this work is the provision of a freely available collection of circuits, fully simulated and tested, for educational purposes.
- Instructional videos
  Shoufan provided an ordered list of factors [65] that affect students' perception relatively to educational videos of the "Digital Design course" and "Embedded Systems course" which were collected from YouTube. At the top of this list is the quality of explanation followed by the technical presentation, the content, the efficiency, the speaker's voice and language, and finally, the interestingness of the video. According to [66], short videos during 0–3 min, videos produced with a more personal feel, and videos where instructors speak fairly fast and with high enthusiasm are much more engaging. To maximize student engagement, instructors must plan their lessons specifically for an online video format. Although presentation styles have worked well for centuries in traditional lectures, they are not always suitable for online instructional videos.
  Therefore, it was proposed to students to visit links to the Loom platform and receive feedback watching 34 corresponding instructional videos. The narrative that accompanies the video demonstration is spoken by a female voice, and the mouse pointer is used in order to highlight screen objects. The narration uses simple language, is detailed, without leaving gaps in explanation, without leaving questions unanswered, synchronizes the simulation process and explanation, and does not provide too much information. The average video length is 1.69 min, and the video length ranges from 0.42 to 3.22 min.
- Game as a capstone project
  One method with which games can be used as educational strategy is to teach the object through game development. The students participated collaboratively in the implementation of digital electronic circuits, which simulates Tic-Tac-Toe as a project. They could use simple digital design tools and integrated circuits but no processor. Projects can fulfill some educational objectives in contrast to lectures. A project can allow a student to explore in depth a topic, become very strongly motivated, and continue the project long after the class is over [67]. In order to complete the gamified project successfully, the students were asked to achieve the following:

  (A) Identify the rules of the game. We chose this game because it is already known and has simple rules. This game is played with two players and consists of

9 blocks arranged in 3 rows and 3 columns. Its difference from the classic version is that every time a player selects a block using a dip switch, his color (red or blue) lights up on an RGB LED. Therefore, a player wins the game when three LEDs are lit with the same color in horizontal, vertical, or diagonal order.

(B) Identify constraints of the game. (a) Each player selects one of the 9 blocks using a dip switch, and the confirmation of their selection is indicated by the color of an RGB LED of that block. The blue color corresponds to player_1 and the red one corresponds to player_2. The game starts with player_1. (b) Each block can be selected by only one player. (c) The player should be able to reset the game. (d) An LED must be lit when the game ends with either a draw or a win. (e) In case the game ends with a player's win, an RGB LED should lit with his corresponding color. (f) The result must be locked in case a player wins.

(C) Divide the game into individual steps.

(D) Identify the required tools, the inputs and the outputs of each step, implement each step of the game, verify its functionality.

(E) Think about the game as a whole through the combination of the individual steps.

(F) Visit links to Tinkercad platform and links to Loom platform.

- Implementation of the game.
The implementation of Tic-Tac-Toe (see Appendix A) was analyzed in 5 simpler digital electronic circuits, as shown in Figure 2. The tools that were used as well as the input and the output of each circuit are described below:

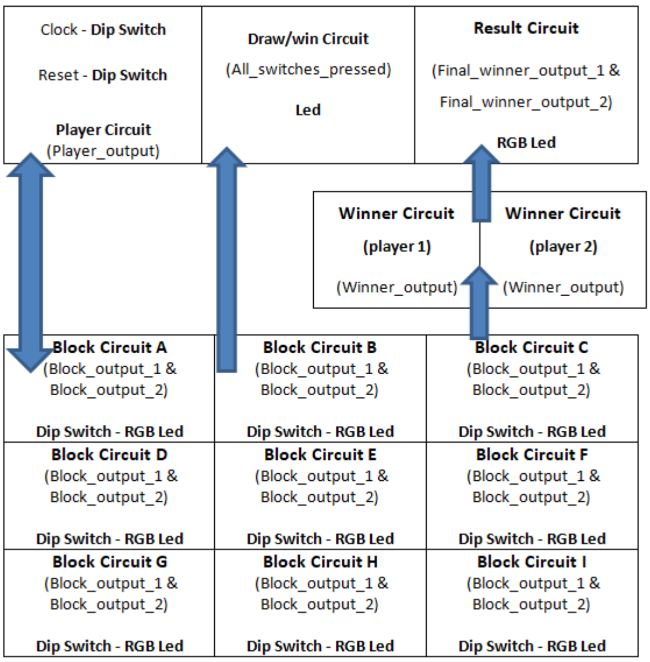

Figure 2. Functionality of game.

(A) The 1st step describes the Block circuit. As input, we used (a) a Dip switch (S1) that corresponds to the player's selection, and if a player switches it from 0 to 1, that indicates that the same player selects this block; otherwise, this block has not been selected by anyone, (b) a Dip switch (S2) that corresponds to the clock, (c) a Dip switch (S3) that corresponds to the player's turn, if a player switches the (S3) from 0 to 1, that indicates that the player_1 plays and from 1 to 0 indicates that player_2 plays, and (d) a Dip switch (S4) that resets the game if a player switches the (S4) from 0 to 1 where the LED goes out. As output, the block circuit produces block_output_2, which affects the red color of the RGB LEDand block_output_1, which affects the blue color of the RGB led. As shown in Figure 3, switch (S3) has the value 1, so it was the turn of player_1, and switch (S1) has the value 1, so the specific block has been selected by the player, switch (S4) has the value 0, so the game continues, and switch (S2) has changed from value 0 to value 1. Therefore, the blue color of the RGB LED was expected to light up.

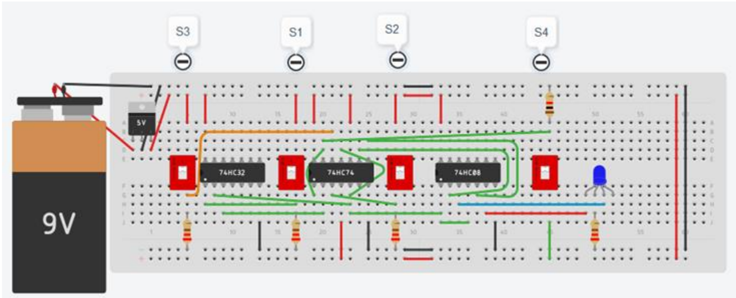

Figure 3. Block circuit (Tinkercad).

(B) The 2nd step describes the Player circuit. The rotation of players is done automatically. As input, we used 9 Dip switches (S5, S6, S7) that correspond to the value of the (S1) in each of the blocks A, B, C, etc. As output, the player circuit produces a sequence where player_output has the value 0 where the LED is off if it is player_1's turn and player_output has the value 1 where the LED is on if it is player_2's turn. As shown in Figure 4, two blocks have been selected, so the LED is off. This means that player_2 played last, and it is player_1's turn.

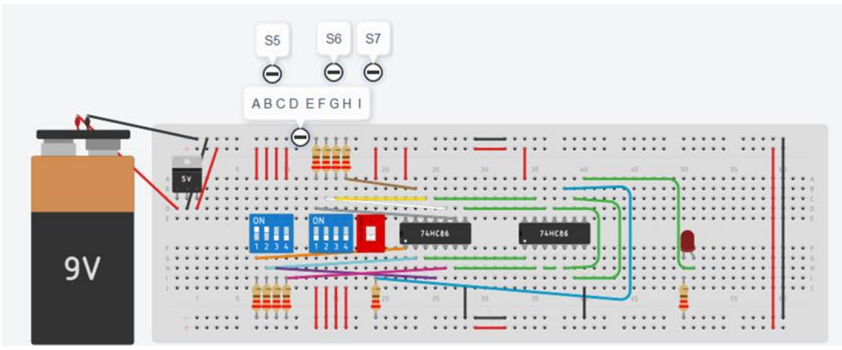

Figure 4. Player circuit (Tinkercad).

(C) The 3rd step describes the Winner circuit. It is possible to end the game with or without a winner. That is, a winner exists if the switches have the value 1 at three specific blocks, in one of the cases ABC, DEF, GHI, AEI, CEG, ADG, BEH, or CFI. The winner check is repeated twice: once to check if player_1 won and once to check if player_2 won. As input, we used 9 Dip switches (S8, S9, S10), which correspond to block_output_1 for player_1 and block_output_2 for player_2 at each of the blocks A, B, C, etc. As output, the winner circuit produces winner_output the value 1 in case all three specific switches have the value 1 where the LED is on; otherwise, it produces as winner_output the value 0 where the LED is off. As shown in Figure 5, blocks A, B, and C have been selected, so the LED is on, and the game ends with a winner.

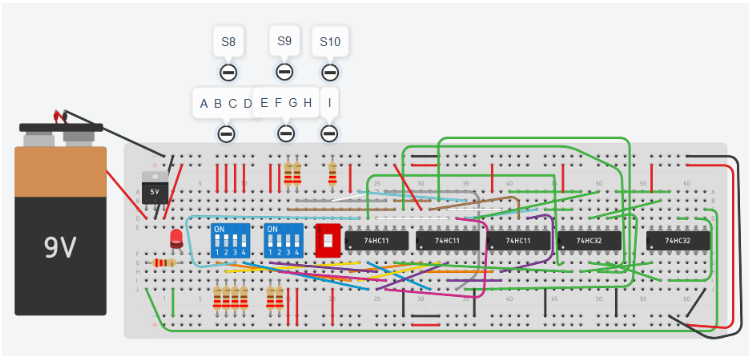

Figure 5. Winner circuit (Tinkercad).

(D) The 4th step describes the Draw/Win circuit. If all the switches have been selected and all RGB LEDs are on, respectively, it means that there is a draw or a winner. As input, we used 9 Dip switches (S11, S12, S13), which correspond to the value of (S1) in each of the blocks A, B, C, etc. As output, the Draw/Win circuit produces all_switches_pressed the value 1 in case all the switches have the value 1 where the LED is on and all_switches_pressed the value 0 in case not all switches have the value 1 where the LED is off. As shown in Figure 6, all blocks have been selected, so the LED is on. During the implementation of the game, the All_switches_pressed is connected to an LED, which lights up when the game is over.

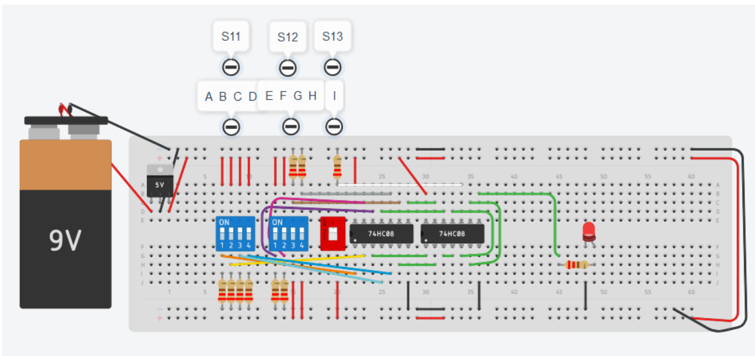

Figure 6. Draw circuit (Tinkercad).

(E) The 5th step describes the Result circuit. As input, we used Dip switch (S14), which corresponds to the winner_output of player_1 and Dip switch (S15), which corresponds to the winner_output of player_2. As output, the resulting circuit produces final_winner_output1 the value 1 in case player_2 has not won where player_1's LED is on and final_winner_output2 the value 1 in case player_1 has not won where player_2's LED is on. As shown in Figure 7, although initially switch (S14) changed to value 1 and then switch (S15) changed to value 1, only player_1's LED is on. During the implementation of the game, the final_winner_output1 is connected to the blue color of an RGB LED and the final_winner_output2 is connected to the red color. Therefore, the color of the RGB LED will also show the winner.

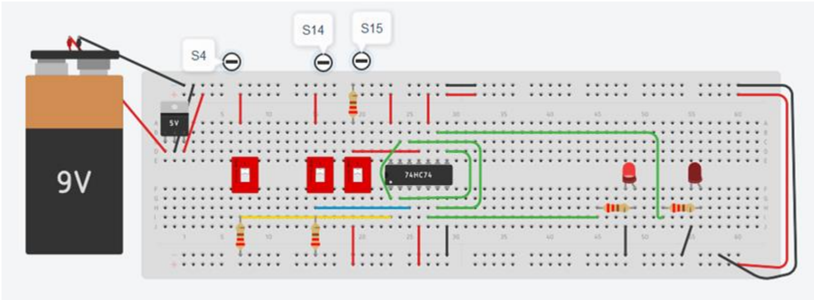

Figure 7. Result circuit (Tinkercad).

- The design features that confirm ARCS and Malone's motivation model are described below. The incompleteness of knowledge through the images illustrating the logic circuits, the speaker's voice of the instructional videos, and the use of RGB LEDs with color changes in their light can evoke students' sensory curiosity, and the continuous evolution of circuits' design can evoke their cognitive curiosity. Students simulate and implement the game imagining that they play the game in a real world with paper and pen. The implementation of the electronic Tic-Tac-Toe consists of five logic circuits, and the combination of the game is not divulged beforehand in order to challenge them to combine the circuits. Additionally, there are module objectives in order to attract students' attention. The electronic Tic-Tac-Toe offers the opportunity for the student to satisfy his need to implement a game and have a feeling of perceived relevance. Students' repetitive interaction with the circuits and the instant feedback can increase their self-esteem and build their confidence. Simulating the circuits, the students validate the output and feel satisfaction.

2.2. Participants

For all the surveys that were conducted during 2017–2021, undergraduate students of the authors' department participated voluntarily. Firstly, we aimed to receive feedback by students about the educational process and define possible learning problems. In this survey, 28 students participated during the second semester of the 2016–2017 academic year. Regarding demographics, 57.1% of the students were female and 42.9% were male. One-quarter (25%) of the students were interested in the field of bioinformatics, 57.1% were interested in medical technology, and 17.9% were interested in informatics. It was repeated in the second semester of 2017–2018 in which 19 students participated. Regarding demographics, 68.4% of the students were female and 31.6% were male. Nearly one-third (31.6%) of the students were interested in the field of bioinformatics, 47.4% were interested in medical technology, and 21.1% were interested in informatics. After receiving feedback by students, we performed a survey in order to to assess the students' satisfaction and willingness toward the integration of ready-made digital games in the educational process. In this survey, 14 students participated during the second semester of the 2016–2017 academic year. It was repeated in the second semester of 2017–2018 in which 6 students participated. Finally, after receiving feedback by students and aiming to strengthen their motivation and well-being during the pandemic, a survey was performed in order to assess the impact of a holistic online environment that we designed on student's motivation. In this survey, 15 students participated in the second semester of the 2020–2021 academic year. Regarding demographics, 66.7% of the students were female and 33.3% were male, and all the students were 18–19 years old. The small sample size may affect the results of the surveys, prevent generalizations, and make the conclusions simple estimates. The small sample size perhaps depends on external problems that can prevent students from being motivated in their studies [67]. Mental health problems such as anxiety, depression, and self-reported stress are common psychological reactions to the pandemic [68]. The discomfort caused by excessive anxiety can reduce motivation [67]. We observe that there were more female participants than male participants in all the surveys. In addition, the students' responses about the field in which they are most interested showed that the majority of students are interested in medical technology, a lower percentage is interested in bioinformatics, and finally, a lower percentage is interested in informatics. The above results can be considered as expected, since the Digital Design course is a hardware-based course.

2.3. Questionnaires

The first questionnaire consists of 25 questions (see Appendix B) and was analyzed on students' learning outcomes, and the cognitive skills evaluated are shown in Table 1. Students' responses were sought on the scale of three options (1: not at all comprehensible, 2: moderately comprehensible, and 3: very comprehensible). The Cronbach's alpha had a good value both years (0.837) in 2017 and (0.863) in 2018.

The second questionnaire consists of 5 questions (see Appendix C) and was analyzed on two parameters. (a) The first was students' satisfaction toward the integration of ready-made digital games in the educational process. Students' responses were sought on the scale of three options (Option 1: not at all interesting/helpful, Option 2: moderately interesting/helpful, Option 3: very interesting/helpful). (b) The second parameter was students' willingness toward the integration of ready-made digital games in the educational process. Students' responses were sought on the scale of two options (Option 1: Yes, Option 2: No).

The third questionnaire consists of 36 sentences (see Appendix D) and was divided into 4 sub-scales. The sub-scales were attention, relevance, confidence, and satisfaction according to the IMMS Keller's tool (1993). We calculated the average score of every sub-scale and the overall scale, and we measured students' motivation to learn using a holistic online environment. The answers were based on the psychometric 5-point Likert scale. For the sentences that were stated in a negative way (Questions Q3, Q7, Q12, Q15, Q19, Q22, Q26, Q29, Q31, and Q34), the scores of the respective answers were reversed before being added to the total. The Cronbach's alpha of motivation has an excellent value (0.918), attention has an acceptable value (0.788), relevance has a questionable value (0.613), confidence has an acceptable value (0.704), and satisfaction has a good value (0.801).

2.4. Data Analysis

The tools that were used through the data analysis process were (a) the Excel package to calculate the percentages of the responses and to create the corresponding charts, and (b) SPSS package to use statistical tests such as Cronbach's alpha (measurement of internal consistency), Shapiro–Wilk test (measurement of normality), One-Sample *t*-Test (comparison of the sample's mean to the value = 3), and Spearman's correlation coefficient (measurement of relationships between paired data).

3. Results

3.1. Research Question 1

The first above-mentioned study research question evaluated students' learning outcomes and their cognitive skills, as shown in Table 1. The charts, as shown in Figures 8 and 9, illustrate the responses of students in percentages.

Table 1. Cognitive skills.

Q1. Digital and analog system.	Q11. Equivalent logic gates.	Q21. Clock's frequency.
Q2. Transistors.	Q12. Circuit's truth table.	Q22. Memory circuits.
Q3. Boolean algebra.	Q13. Karnaugh map.	Q23. Flip-Flop.
Q4. Number systems.	Q14. Minterms and maxterms.	Q24. Finite-state machine.
Q5. Logic (objective or subjective).	Q15. Circuit's simplification.	Q25. Detection and self-correction in a finite-state machine.
Q6. Logic expressions.	Q16. Sequential circuits.	
Q7. Digital circuit's design.	Q17. Half-Adder/Full Adder.	
Q8. TTL logic family.	Q18. Decoder/Demultiplexer.	
Q9. Ways of circuit's design.	Q19. Synchronous circuit.	
Q10. Logic gates.	Q20. Circuit's clock.	

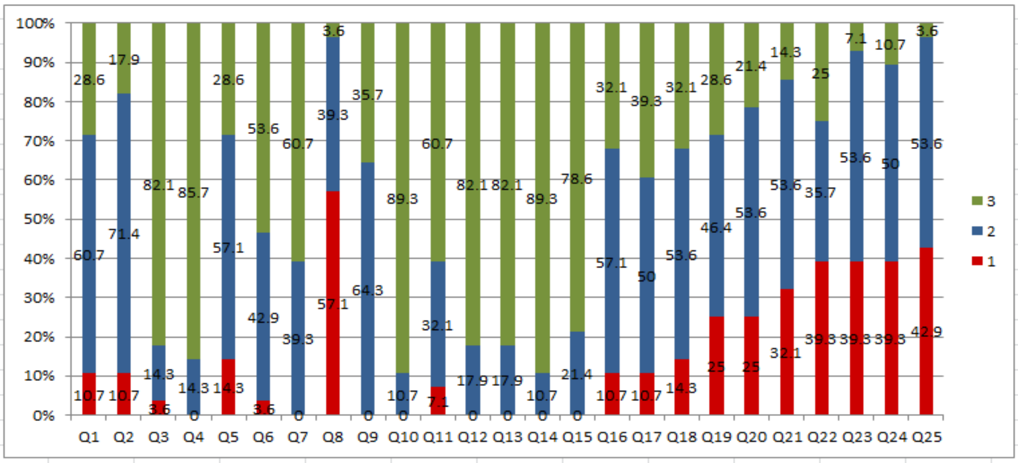

Figure 8. Evaluation of students' learning outcomes—2017.

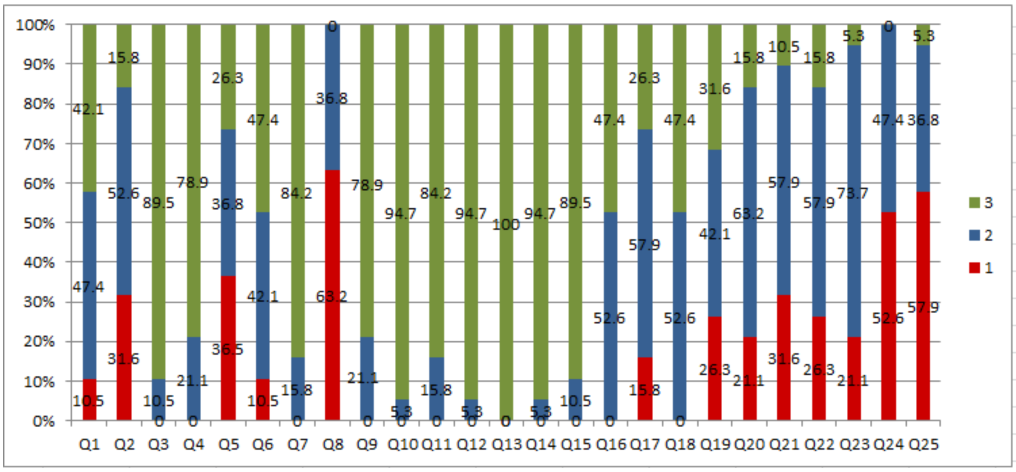

Figure 9. Evaluation of students' learning outcomes—2018.

Both years, in answers to questions 1, 2, 5, 8, and 16–25, the majority of students encounter difficulties in understanding the cognitive object. Most of these questions are relative to circuits such as Half-Adder, Full Adder, Decoder, Demultiplexer, Circuit's clock, Flip-Flops, etc., which require more competencies than knowledge from the student. On the contrary, in answers to questions that are relative to Boolean algebra, Number systems, Logic expressions, Karnaugh map, Minterms and maxterms, etc., the majority of students do not encounter difficulties. Over 70% of the students, as shown in Figure 10, in answers to questions 2, 5, 8, and 20–25, declared that they not at all or moderately comprehend the cognitive object and particularly clock, memory circuits, flip-flop, and finite-state machine. According to [67], students can have a variety of motivational problems. The students find engineering classes in general distasteful, too competitive, or feel they never get rewarded for their efforts or want only a grade or a degree and do not care about learning the material. Considering students' learning outcomes and their possible motivation problems, we integrated games in the educational process in order to motivate them.

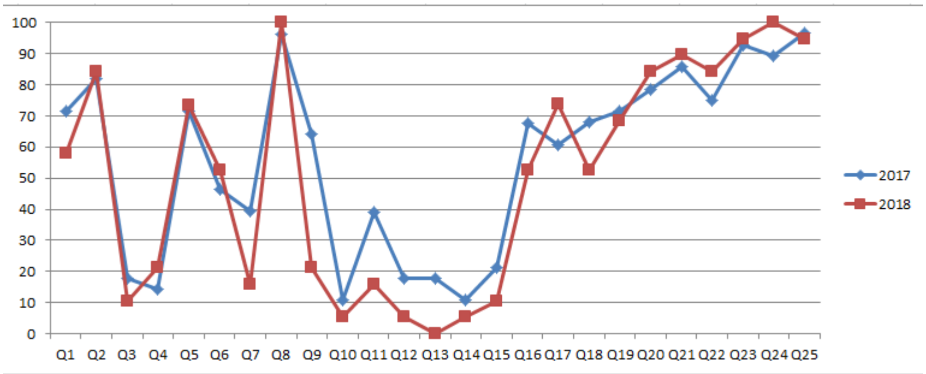

Figure 10. Sums of percentages of Option 1 and Option 2 in 2017 and 2018.

3.2. Research Question 2

The second above-mentioned study research question was tested evaluating students' satisfaction and willingness toward a gamified approach of the educational process, and the results are shown in Table 2.

Table 2. Evaluation of students' satisfaction and willingness.

	2017			2018		
	Option 1	**Option 2**	**Option 3**	**Option 1**	**Option 2**	**Option 3**
Students' Satisfaction						
Q1. Interest	0.0%	35.7%	64.3%	0.0%	66.7%	33.3%
Q2. Helpfulness	0.0%	64.3%	35.7%	0.0%	83.3%	16.7%
Q3. Motivation	78.6%	21.4%		66.7%	33.3%	
Students' Willingness						
Q4. Integration of a greater variety of games	92.9%	7.1%		83.3%	16.7%	
Q5. Integration of games in other courses	100.0%	0.0%		100.0%	0.0%	

In both years, in answers to questions 1 and 2, the majority of students have shown their satisfaction toward the gamified approach of the educational process. In both years, 0% of students considered this approach not at all interesting; in 2017, 35.7% and in 2018, 66.7% considered this approach moderately interesting; and in 2017, 64.3% and in 2018, 33.3% considered this approach very interesting. In both years, 0% of students considered it not at all helpful; in 2017, 64.3% and in 2018, 83.3% considered this approach moderately helpful; in 2017, 35.7% and in 2018, 16.7% considered this approach very helpful. In 2017, 78.6% and in 2018, 66.7% of students found it motivating.

In answers to questions number 3, 4, and 5, the majority of students are still looking for innovative pedagogical tools for effective learning, confirming the literature. In 2017, 92.9% and in 2018, 83.3% of students answered that they would prefer the integration of a greater variety of games into the educational process. In both years, 100% of students answered that they would prefer the integration of games in other courses.

3.3. Research Question 3

The third above-mentioned study research questions were tested through the following potential hypotheses, and the results are shown in Table 3.

Table 3. Evaluation of students' motivation, attention, relevance, confidence, and satisfaction.

	Shapiro–Wilk Normality Test	*t*-Test (One-Sample)	Mean
Motivation	0.635	0.000	3.7778
Attention	0.412	0.000	3.8611
Relevance	0.210	0.000	3.9037
Confidence	0.304	0.002	3.4741
Satisfaction	0.766	0.000	3.8778

- H0: It is probable to use the integration of an online holistic environment in the educational process to motivate students to learn the course.
- H1: It is not probable to use the integration of an online holistic environment in the educational process to motivate students to learn the course.

At the a = 0.05 level of significance, the data are normally distributed, as *p*-value (0.635) has a greater value than 0.05. At the a = 0.05 level of significance, null hypothesis is rejected, as the *p*-value of Motivation (0.000) has a value less than 0.05. Additionally, the mean score of motivation (3.7778) is considered satisfactory, and we conclude that it is probable to use the integration of an online holistic environment in the educational process to motivate students to learn the course.

3.4. Research Question 4

The fourth above-mentioned study research questions were tested through the following potential hypotheses, and the results are shown in Table 3.

- H0: There is not a statistically significant effect on students' attention, relevance, confidence, and satisfaction through the integration of an online holistic environment in the educational process of the course.
- H1: There is a statistically significant effect on students' attention, relevance, confidence, and satisfaction through the integration of an online holistic environment in the educational process of the course.

At the a = 0.05 level of significance, the data are normally distributed, as the *p*-values of attention (0.412), relevance (0.210), confidence (0.304), and satisfaction (0.766) have a greater value than 0.05. At the a = 0.05 level of significance, the null hypothesis is rejected, as the *p*-values of attention (0.000), relevance (0.002), confidence (0.000), and satisfaction (0.000) have a value less than 0.05. Additionally, the mean scores of attention (3.8611), relevance (3.9037), confidence (3.4741), and satisfaction (3.8778) have a greater value than 3 and are considered satisfactory. Therefore, we conclude that there is a statistically significant effect on students' attention, relevance, confidence, and satisfaction through the integration of an online holistic environment in the educational process of the course.

3.5. Research Question 5

Table 4 shows the positive correlation for all the components of the ARCS model, which means that the increase of the one component implies the increase of the other one. Spearman's correlation coefficient shows that there is a strong correlation (a) between attention and relevance (0.676), (b) between attention and confidence (0.799), (c) between relevance and satisfaction (0.725) at the a = 0.01 level of significance, and (d) between relevance and confidence (0.629) at the a = 0.05 level of significance. In addition, there is a very strong correlation (e) between attention and satisfaction (0.910) and (f) between confidence and satisfaction (0.854) at the a = 0.01 level of significance.

Table 4. Spearman's correlation coefficient.

	Relevance	Confidence	Satisfaction
Attention	0.676 **	0.799 **	0.910 **
Relevance		0.629 *	0.725 **
Confidence			0.854 **

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

4. Discussion

In the following paragraphs, we discuss the impact of incorporating a combination of educational strategies in the learning context on students' motivation. Our first research question was "What are the students' learning outcomes in the Digital Design course?". After evaluating the learning outcomes of a group of students, the results revealed that the majority of students encounter difficulties in activities that require more competencies than knowledge from the student. This learning problem is probably due to students' lack of hands-on experience, which is a conclusion in line with that of [2,63]. The second research question was, "How effective are ready-made digital games in motivating students to be more involved with the Digital Design course?". We integrated ready-made digital games into the educational process and measured both students' satisfaction and willingness relative to this approach. The majority of students showed their satisfaction and that they are still looking for effective learning. This result is in line with that of [26]. The third research question was, "Is the integration of an online holistic environment probable to motivate students to learn in the Digital Design course?". After receiving positive feedback relative to gamified learning, we proposed an online holistic teaching and learning environment based on Keller's (1987) ARCS model and Malone's (1981) motivational model, which was applied in distance learning. The aim of this online environment was to improve students' motivation and well-being during the pandemic. First, we organized a virtual lab with the use of the Tikercad platform where the students could upload or simulate their activities or leave their comments about the activities of other students in order to [62] develop their willingness to exercise through social influence and positive recognition. Many researchers [8–10] stated the positive effects of virtual labs on students. Gamification can have a positive impact in health, well-being [27], emotion, and cognition [31]. More specifically, game-based learning can be effective, which resembles the results of previous studies in teaching "Computer Science" in higher education [15–19]. Second, we assigned them a gamified-project without a processor in order to develop their motivation, creativity, and hands-on ability as opposed to the other relevant studies, which use ready-made games. Integrating a gamified learning environment into mass open online courses can be effective [33], since combining a project with games improves student's involvement [36], and incorporating gamification features within a virtual context enhances motivation [11]. The project-based learning [34] promotes social connections between students and academics. Ismail considered the affective domain to be critical [35] while Wankat and Oreovicz presented the most effective techniques for a student to become strongly motivated [67]. Third, we integrated asynchronous instructional videos with the usage of the Loom platform in educational process as feedback. Some researchers stated the positive attitudes toward video podcasts [40], asynchronous videos, and screencasts on digital projects as feedback [41] and instructional videos [39]. Educators ensure emotional support, mental wellness, and social presence during times of crisis by implementing videos for communication and feedback [42], and in this way, they are considered more real, present, and familiar [43]. The fourth research question was, "Is there a statistically significant effect on students' attention, relevance, confidence, and satisfaction through the integration of an online holistic environment in the educational process of the Digital Design course?". Educational games can positively affect student's attention [50], perceived relevance [52], confidence, motivation [53], and satisfaction [56]. The use of video-based instructional materials can captivate students' attention [51] and improve their confidence [54] and satisfaction [57]. Our results revealed that there is a statistically significant effect on students' attention, relevance, confidence, and satisfaction through its integration into the educational process, which resemble the results of previous studies. The fifth research question of our study was, "Are there relationships among the attention, relevance, confidence, and satisfaction (ARCS) elements used in the Instructional Materials Motivation Survey (IMMS)?" According to the results, there is a positive correlation for all the components of the ARCS model. This online holistic environment gave the students the opportunity to access new laboratory experiences.

5. Conclusions

The usage of virtual labs, simulations, game-based learning, projects, and asynchronous videos are seen as promising approaches to enhance students' motivation as well as improve their learning outcomes and well-being. Considering the literature and the results of our first research question about the difficulties that the students encounter in understanding the cognitive object of hardware-based courses, we focused on the development of students' hands-on experience and motivation, integrating ready-made digital games into the educational process. Answering our second research question, the majority of students found this approach interesting, helpful, and motivational, and they stated that they were willing to use a greater variety of games either in this course or in another. Modern engineering education must take into account a combination of teaching and learning approaches [69] and support the transition from knowledge-based learning to competency-based learning [49]. Our online holistic environment gave students the opportunity to (a) experience a combination of educational approaches integrating a virtual lab, a game-based project, and asynchronous instructional videos, (b) develop capabilities and strategies over time through practice and engagement in higher-order cognitive activities, and (c) acquire self-learning skills. The evaluation of this environment indicated that (a) it was effective in motivating students to learn, which is a result that is related to our third research question, (b) there is a statistically significant effect on students' attention, relevance, confidence, and satisfaction, which is a result that answers our fourth research question, and (c) there is a positive correlation for all the components of the ARCS model, which is a result that concerns our fifth research question. Some limitations should be taken into account when interpreting the results of the current study. Firstly, perhaps, the pandemic period caused the lack of students' motivation to participate voluntarily in this survey. Second, we did not evaluate students' prior gaming and instructional video experience, which could influence their perceptions. Third, we used a self-reported measure of the parameters that were evaluated, which may be limited by the students' ability to reflect and rate correctly. Future research could use a larger sample size in order to minimize the possibility of errors and should address whether this online holistic learning environment has a positive impact on both students' well-being and learning performance.

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Appendix A

A block circuit is shown in Figure A1. D flip flop (U1) stores the status of the switch (S1), whether it was pressed or not. More specifically, D flip flop (U1) receives as input the output of an OR gate (U5) (which receives as input the value of switch (S1) and the output of D flip flop (U1)) and produces as output value 1 either when switch (S1) has the value 1 for the first time or when a player has already selected this block. D flip flop (U2) stores information about the player’s turn. More specifically, it receives as input the value of the switch (S3), the value 1 indicates that player_1 played last and 0 for player_2 and is triggered by the output of the D flip flop (U1). If player_1 played last, (the output value of D flip flop (U2) is 1 and the inverse output value is 0), the AND gate (U3) receives as input the output of D flip flop (U1) and the inverse output of D flip flop (U2) and produces as output block_output_2 the value 0 where the red color of the RGB is off and the AND gate (U4) receives as input the output of D flip flop (U1) and the output of D flip flop (U2) and produces as output block_output_1 the value 1 where the blue color of the RGB LED is on. If player_2 played last (the output value of D flip flop (U2) is 0 and the inverse output value is 1), the AND gate (U3) receives as input the output of D flip flop (U1) and the inverse output of D flip flop (U2) and produces as output block_output_2 the value 1 where the red color of the RGB LED is on and the gate AND (U4) has as input the output of D flip flop (U1) and the output of D flip flop (U2) and produces as output block_output_1 the value 0 where the blue color of the RGB LED is off.

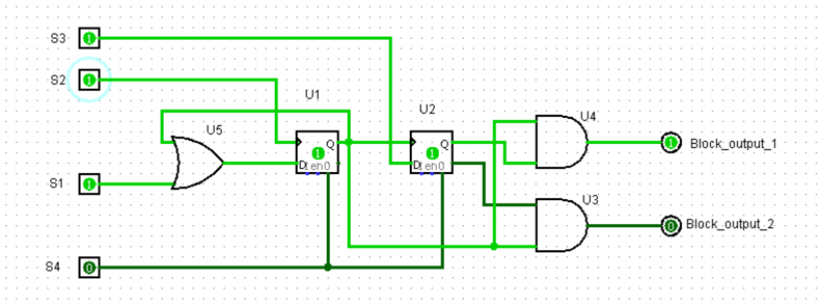

Figure A1. Block circuit (Logisim).

Player circuit is shown in Figure A2. There are eight two-input XOR gates (U6–U13), which are connected to each other and receive the input values and produce information about the player’s turn. If it is player_1’s turn, the number of switches with the value 1 is even, player_output has the value 0 where the LED is off, and it means that player_2 played last. If it is player_2’s turn, the number of switches with the value 1 is odd, player_output has the value 1, where the LED is on, and it means that player_1 played last.

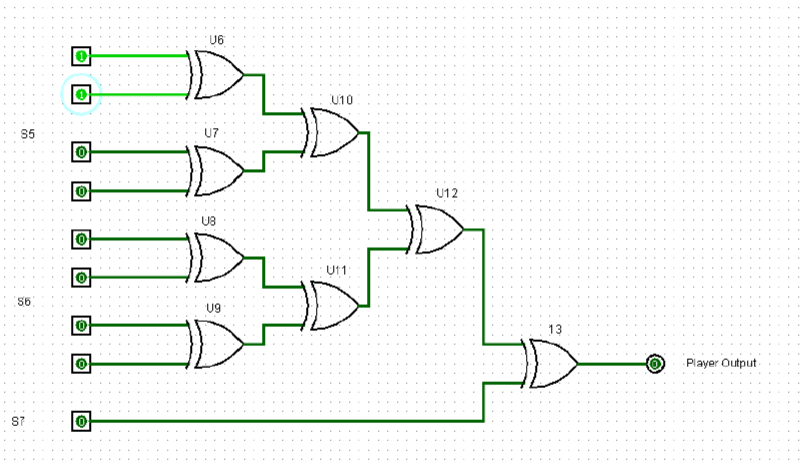

Figure A2. Player circuit (Logisim).

The winner circuit is shown in Figure A3. There are eight three-input AND gates (U14–U21) that receive the input values connected to each other appropriately in a circuit and produce as winner_output the value 1 in case all three specific switches have the value 1; otherwise, they produce as winner_output the value 0. There are seven two-input OR gates (U22–U28), which have as input the outputs of AND gates (U14–U21) and in case even one AND gate (U14–U21), corresponding to the cases ABC, DEF, GHI, AEI, CEG, ADG, BEH, or CFI, produces as output the value 1, the LED is on; otherwise, it produces as output the value 0, where the LED is off.

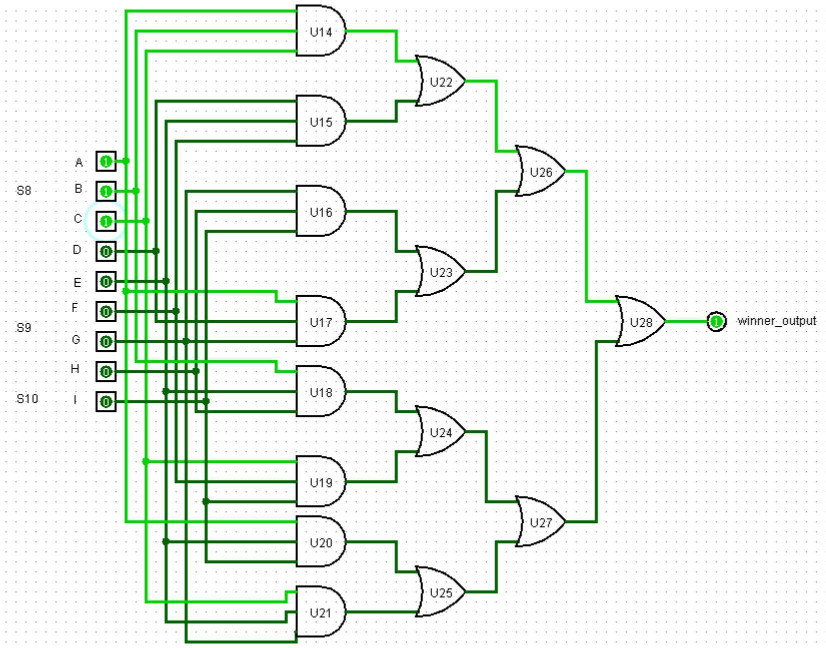

Figure A3. Winner circuit (Logisim).

The Draw/Win circuit is shown in Figure A4. There are eight two-input AND gates (U29–U36), which have as input the previous values connected together in a circuit, which produces as all_switches_pressed the value 1 in case all the switches have the value 1 where the LED is on and all_switches_pressed the value 0 in case not all switches have the value 1 where the LED is off.

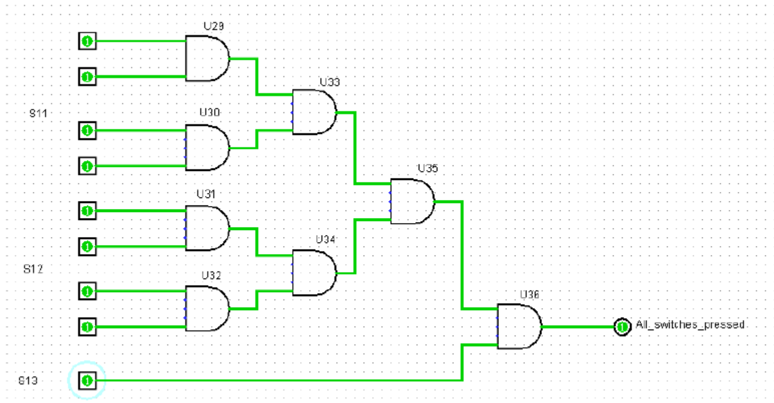

Figure A4. Draw circuit (Logisim).

The result circuit is shown in Figure A5. D flip flop (U37), which receives as input the inverse output of D flip flop (U38), is triggered by the winner_output of player_1 and produces as final_winner_output1 the value 1 in case player_2 has not won where player_1's LED is on. Respectively, the D flip flop (U38), which receives as input the inverse output of D flip flop (U37), is triggered by the winner_output of player_2 and produces as final_winner_output2 the value 1 in case player_1 has not won where player_2's LED is on.

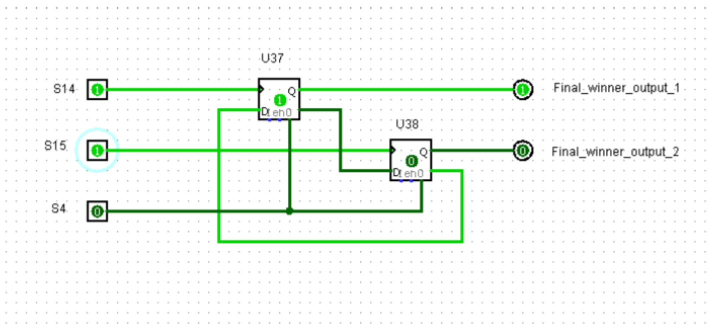

Figure A5. Result circuit (Logisim).

Appendix B

Table A1. Questionnaire 1.

	2017			2018		
Questions	**Opt1**	**Opt2**	**Opt3**	**Opt1**	**Opt2**	**Opt3**
Q1. Have you understood the difference between a digital system and an analog one?	10.7%	60.7%	28.6%	10.5%	47.4%	42.1%
Q2. Have you understood the operation of transistors?	10.7%	71.4%	17.9%	31.6%	52.6%	15.8%
Q3. Have you understood Boolean algebra?	3.6%	14.3%	82.1%	0.0%	10.5%	89.5%
Q4. Have you understood the conversion of numbers into different number systems?	0.0%	14.3%	85.7%	0.0%	21.1%	78.9%
Q5. Have you understood whether logic is objective or subjective?	14.3%	57.1%	28.6%	36.8%	36.8%	26.3%
Q6. Have you understood the importance of the logic expressions?	3.6%	42.9%	53.6%	10.5%	42.1%	47.4%
Q7. Have you understood how a digital circuit is designed?	0.0%	39.3%	60.7%	0.0%	15.8%	84.2%
Q8. Have you understood the TTL logic family?	57.1%	39.3%	3.6%	63.2%	36.8%	0.0%
Q9. Have you understood in how many ways a circuit can be designed?	0.0%	64.3%	35.7%	0.0%	21.1%	78.9%
Q10. Have you understood the logic gates?	0.0%	10.7%	89.3%	0.0%	5.3%	94.7%
Q11. Have you understood the equivalent logic gates?	7.1%	32.1%	60.7%	0.0%	15.8%	84.2%
Q12. To what extent can you design the truth table of a circuit?	0.0%	17.9%	82.1%	0.0%	5.3%	94.7%

Table A2. Questionnaire 1.

	2017			2018		
Questions	**Opt1**	**Opt2**	**Opt3**	**Opt1**	**Opt2**	**Opt3**
Q13. Have you understood the usefulness of the Karnaugh map?	0.0%	17.9%	82.1%	0.0%	0.0%	100%
Q14. To what extent can you distinguish the minterms from the maxterms?	0.0%	10.7%	89.3%	0.0%	5.3%	94.7%
Q15. To what extent can you simplify a circuit using the Karnaugh map?	0.0%	21.4%	78.6%	0.0%	10.5%	89.5%
Q16. Have you understood what sequential circuits are?	10.7%	57.1%	32.1%	0.0%	52.6%	47.4%
Q17. Have you understood the function of Half-Adder/Full Adder?	10.7%	50.0%	39.3%	15.8%	57.9%	26.3%
Q18. Have you understood the function of the Decoder/Demultiplexer?	14.3%	53.6%	32.1%	0.0%	52.6%	47.4%
Q19. Have you understood what the synchronous circuit is in electronics?	25.0%	46.4%	28.6%	26.3%	42.1%	31.6%
Q20. Have you understood the function of the clock in a circuit?	25.0%	53.6%	21.4%	21.1%	63.2%	15.8%
Q21. Have you understood how frequency is related to the clock?	32.1%	53.6%	14.3%	31.6%	57.9%	10.5%
Q22. Have you understood what memory circuits are?	39.3%	35.7%	25.0%	26.3%	57.9%	15.8%
Q23. Have you understood the function of Flip-Flop?	39.3%	53.6%	7.1%	21.1%	73.7%	5.3%
Q24. Have you understood the finite-state machine?	39.3%	50.0%	10.7%	52.6%	47.4%	0.0%
Q25. Have you understood the process of detection and self-correction in a finite-state machine?	42.9%	53.6%	3.6%	57.9%	36.8%	5.3%

Appendix C

Table A3. Questionnaire 2.

	2017			2018		
Questions	**Option 1**	**Option 2**	**Option 3**	**Option 1**	**Option 2**	**Option 3**
Q1. Did you find the games interesting?	0.0%	35.7%	64.3%	0.0%	66.7%	33.3%
Q2.To what extent did the games help you to understand the concepts of the course?	0.0%	64.3%	35.7%	0.0%	83.3%	16.7%
Q3. Do you think that the games motivate you to spend more time on the lesson?	78.6%	21.4%		66.7%	33.3%	
Q4. Would you like to have a variety of games?	92.9%	7.1%		83.3%	16.7%	
Q5. Would you like this educational approach to be integrated in other subjects as well?	100.0%	0.0%		100.0%	0.0%	

Appendix D

Table A4. Questionnaire 3.

Questions	**Cronbach's Alpha**
Attention	
Q2. There was something interesting at the beginning of the lab that caught my attention.	0.915
Q8. The virtual lab was enjoyable for me.	0.924
Q11. The lab was well designed and helped me maintain my focus.	0.912
Q12. This lab is so confusing that it was difficult for me to keep my attention on it	0.914
Q15. I did not like the activities of this lab.	0.913
Q17. The way the lab is organized helped me to keep my attention.	0.914
Q20. This lab has things that piqued my curiosity, e.g., what other games I could implement.	0.915
Q22. Repeating some things in this lesson made me bored sometimes.	0.916
Q24. I learned some things that were unexpected.	0.918
Q28. The pictures, the interaction with the circuits, and the instructional videos helped me to keep my attention in the lab.	0.912
Q29. The presentation style of the circuits (using Tinkercad and Loom web application) is boring.	0.920
Q31. There is a lot of information and texts that are annoying.	0.915
Relevance	
Q6. It is clear to me that the activities of the lab are related to what I already know.	0.914
Q9. There were pictures and videos that helped me understand that what I learned was important.	0.924
Q10. The successful completion of this lab was important to me.	0.914
Q16. The content of this lab is related to my interests.	0.920
Q18. There are examples of how someone can use his knowledge, e.g., Tic-Tac-Toe implementation.	0.920
Q23. The content of the lab gives the impression that it is worth knowing.	0.915
Q26. This lab was not relevant to my needs, because I already knew most of it.	0.915
Q30. I could relate the content of this lab to things I have seen, done, or thought about in my life.	0.919
Q33. The content of this lab is useful to me.	0.913
Confidence	
Q1. In the first contact I had with the lab, I had the impression that it would be easy for me.	0.916
Q3. The simulated circuits in the Tinkercad application were more difficult for me than I would like them to be.	0.922
Q4. After reading the introductory information of the lab, I felt confident about what I needed to learn in it.	0.917
Q7. The activities had a lot of information and it was difficult to choose and remember the important points.	0.919
Q13. As I was performing the activities in this lab, I was sure I could implement them on a board.	0.921
Q19. The activities in this lab were very difficult.	0.915
Q25. After working for this lab, I was sure I could pass a test in it.	0.914
Q34. I could not really understand many things in this lab.	0.912
Q35. The good organization of the lab helped me to be sure that I can implement the circuits.	0.913

Table A4. *Cont.*

Questions	Cronbach's Alpha
Satisfaction	
Q5. When I completed the activities of the lab, I felt satisfaction.	0.916
Q14. I really liked this lab and I would like to learn more about Digital Design.	0.914
Q21. I really enjoyed studying in this lab.	0.912
Q27. Watching educational videos helped me feel rewarded for my effort, e.g., the verification of the truth tables.	0.915
Q32. I felt I would successfully complete this lab.	0.913
Q36. It was a pleasure to work with such a well-designed lab.	0.913

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