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Redesign and Implementation of the Electromagnetism Course for Engineering Students Using the Backward Design Methodology

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Abstract: In this study, the redesign and implementation of an electromagnetism course for engineering students are presented using the methodology of backward design (BD), recognized for its attributes for the development of active learning and its possibility of specifying the fundamentals and principles of engineering education in the development of higher education syllabus. The purposes of this study were as follows: (1) to implement the backward design (BD) methodology to develop argumentative, purposeful, and interpretive skills in an electromagnetism course; (2) to design and apply rubrics to evaluate tests and laboratory reports and determine the level that best suits the knowledge, skills, and competencies of students; (3) to assess the perception of students regarding the use of the methodology and their contributions to the development and understanding of the concepts of the course. The results of this educational research experience showed that the BD teaching approach was pedagogical and significantly superior to conventional models for improving knowledge and skills of electromagnetism based on Hake's statistic (h) of 0.73, which led us to conclude that there was a learning gain in the students. This paper focuses on Sustainable Development Goal 4 (SDG 4) of the United Nations Agenda, which is aimed at "Quality education". The study's results reveal that fully integrated and sustainable solutions can be envisioned for higher education entities via the implementation of BD methodology, which can support the educational transformation of the higher education sector based on SDG 4, which promotes inclusive and equitable quality education for all. This can mitigate the risk associated with university dropouts due to subjects that are highly complex for many students like electromagnetism.

Keywords: backward design; virtual learning; ecosystem; design; thinking

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1. Introduction

Some organizations like UNESCO and the Organization for Economic Co-operation and Development (OECD) have been responsible for the implementation of SDG 4. Both entities explored effective learning strategies and identified active learning as a key approach. In this sense, they have provided practical guidance for educators to integrate sustainable development principles into teaching practices and emphasize the importance of active learning methodologies, such as inquiry-based learning, active learning, and project-based learning, in addressing the SDGs [1,2].

In addition, in recent decades, technologies have evolved vertiginously to facilitate human life, including tools that facilitate the implementation of new pedagogical strategies for the improvement of educational systems [3–5]. Accessibility to the use of laptops and mobile devices from any place and time, including access to network computers, provides remote communication options that have promoted changes in the curriculum of the programs of the Faculty of Engineering of the Universidad del Magdalena, allowing leaps in learning and teaching models emphasizing the evolution of appropriate professional skills for students. In that direction, both this and many universities and educational organizations at the international level are choosing and promoting active learning strategies for their versatility to prepare students in competitive scenarios, where they manage to qualify in order to address the main problems of society once they enter the world of work or entrepreneurship [6–10].

A brief review of references allows the identification of different types of learning that enable students to connect with real-world problems [11]:

- Cooperative learning is the instructional strategy of using small groups in which students collaborate to optimize both their own and each other′s learning, as described by the authors in [12]. These authors indicate that cooperative learning has a connection to collaborative learning, which highlights how the community has an impact on learning.
- Collaborative learning allows students to negotiate the boundaries between the knowledge communities they belong to and the professors′ community via collaborative activities [13].
- Problem-based learning (PBL) is a teaching strategy that allows students the freedom to conduct independent research, combine theory and practice, and apply their skills and knowledge to come up with a solution to a problem [14]. In fact, PBL is very commonly employed in higher education across a variety of subject areas, from those relating to the health sciences to those pertaining to engineering [15,16].

According to a study by [5], the main benefits of active learning are in agreement with the analytical and reflective understanding of concepts in all subject areas, leading students to higher levels of understanding [6,7] (see Table 1). But, there is also enthusiasm and deeper understanding of concepts by students and more time working with teachers [7,8,17]. Additionally, students discuss, listen, learn from their peers, and even contribute to interesting discussions [9], increasing their motivation and positive attitudes towards learning [10–12,18]. Active learning is highly recommended for the development of higher order thinking skills (HOTS) [4], which are essential for engineering projects and related disciplines in the field of engineering education [13,14].

Table 1. Benefits of active learning.

All the Activities	Description	Benefits
Think about sharing the couple	Students are given a problem and asked to analyze it individually (Think). Next, they compare their results with those of their closest neighbors (Couple). Finally, the pairs present their conclusions to the whole class (Share).	It allows the teacher to determine students' understanding of a topic and clear up misconceptions. Classes are more interactive and dynamic, increasing participation. In addition, this promotes student reflection on concepts and problems.
Group assignments	Students perform specific tasks collaboratively.	Promotes team and interpersonal skills
Roleplay	Students adopt a character to do a performance related to a certain situation. Participants then switch characters so that they all have a chance to take on all the roles.	Understanding of concepts and theories is enhanced.

Source: Own elaboration, adapted from [9,19].

The motivation of this study was centered on the students who obtained low grades in electromagnetism in Electrical Engineering, but we know that this is a general behavior in all careers that involve physics subjects; therefore, we look forward to offering our colleagues a redesigned course of electromagnetism to help raise student grades and learning outcomes.

The present study's novelty derives from the fact that this methodology has been used in prestigious universities worldwide, but it has not yet been implemented in physics subjects belonging to engineering careers. Therefore, this study examines the effect of redesigning the Electromagnetism Course on students' understanding.

In the opinion of [20,21], the learning strategies developed in backward design include the principles of active learning, regular practice of skills in these activities with direct feedback from the teacher, and demonstration of knowledge and skills in real-world tasks, such as discussions, exhibitions, experiments, and performances [20–24]. Hence, the purpose of this research was to redesign and develop the electromagnetism course offered by the Faculty of Engineering of the University of Magdalena, using the backward design (BD) learning approach [20,21,25,26], towards the development of engineering competencies to foster the implementation of their knowledge and skills through the solution of real engineering problems using the concepts studied in the subject.

2. Related Research

To develop this investigation, case study research was used due to its pragmatic, flexible research approach, capable of providing a comprehensive in-depth understanding of a diverse range of issues across several disciplines depending on the approaches, perspectives, and individual interpretations of researchers and their designs. Prominent case study researchers have emphasized that it is an overarching methodology that shapes a case study design and that multiple sources of data and methods (qualitative and quantitative) can be used [27–29], thus providing a distinction between the two. In fact, this work uses both methods to organize the results and changes achieved.

Since this educational research practice proposes a change in the traditional way of designing and developing an electromagnetism course at the Universidad del Magdalena, backward design was chosen as the pedagogical approach for the development of the learning experience. This approach is described in detail below.

2.1. The Backward Design Method

The bibliographic review provides evidence of the robustness of the subject and the extensive list of authors who investigate the various elements that directly and indirectly influence the teaching of cognitive skills, including in the area of science. However, few have focused on the subject of reverse design as a research area in the Latin American context and in the Colombian territory. Hence, one of the fundamental purposes of this educational research is to identify to what level of learning it is possible to develop skills in engineering students at the Universidad del Magdalena by implementing inverse design and how they perceive the usefulness of this model of instruction in comparison with traditional education [30].

Backward design, also called backward planning or backward mapping, is defined as a method of designing curricula and educational activities based on the formulation of learning objectives to define the methodologies or pedagogies and forms of evaluation necessary for the construction of knowledge in a certain area [20,31,32].

According to these authors, the main justification for implementing backward design is that, by starting with the formulation of learning outcomes for a course, instead of starting with the first lesson planned chronologically, it allows the teacher to design a sequence of lessons, problems, projects, presentations, assignments, and evaluations that collaborate with the achievement of the learning purposes, which makes it easier for students to learn what teachers really want them to learn. The method in question involves three stages (Figure 1) [33–35]:

Stage 1 consists of identifying the desired results: it includes the definition of objectives and the review of content standards around the environment (national, local, or other), and the expectations of the respective curriculum. Part of the reflection on questions, such as what students should know, understand and be able to do; and how durable should the knowledge be that will be developed. Likewise, it is suggested that at this stage, the results that will be expected from the students at the end of the activity (fundamental concepts or skills) should be identified. Stage 2 consists of determining the acceptable evidence: it specifies the product(s) that will support the results expected from the students. It is at this stage that teachers will be able to check the students' level of understanding, considering the completion of tasks and various evaluation methods (observations, tests, projects, among others). When developing stage 3, the learning experiences and the pedagogies to be used are designed: it refers to the moment of planning the learning activities that will allow the achievement of the objectives set out in stage 1. Some of the key questions raised by the authors for this stage are as follows: what knowledge (facts, concepts, and principles) and skills (processes, procedures, and strategies) will students require to achieve the desired results? What activities will provide students with the necessary knowledge and skills? What and how should they be taught to meet the specified goals? And what materials, mediations, and resources are the most appropriate to achieve these objectives?

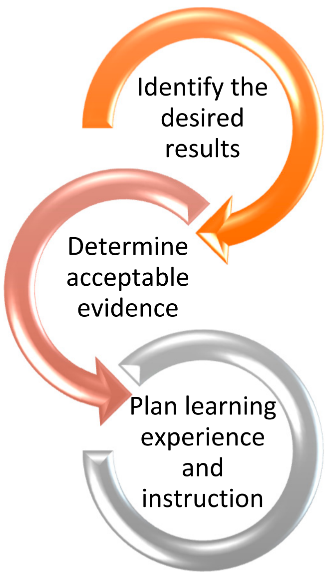

Figure 1. Stages in the backward design process.

Based on these stages, ref. [21] defined a three-ring model to establish curricular priorities (Figure 2). This model indicates that the innermost ring is the knowledge and skills that the student must acquire for the development of their skills, which must remain with them to exercise their professional activity. In the second layer, the knowledge and skills that are important to have as references are indicated, and the outermost layer indicates the issues that are considered familiar to their area of study.

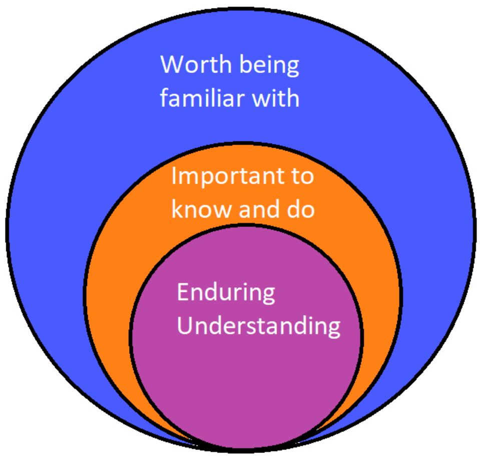

Figure 2. Establishment of curricular guidelines, Reprinted with permission from Ref. [21].

2.2. Definition of Scientific Competence

To understand and put into practice dialogues in science and technology, three specific skills must be kept in mind in these fields, which are as follows: explaining natural phenomena (argumentative competence); interpreting data and evidence scientifically (interpretative competence); and evaluating and designing scientific research (proactive competence) [36]. The first refers to the electronic, technical, and technological elements and how these influence the social sphere. It is obvious that all these elements have their foundations in science, which requires that the individuals have an illustration or knowledge of science and the questions that can be asked to develop their practice to achieve their goals. The second refers to those issues or questions that can be resolved using scientific research; that is, creating a model of how to do science and trying to resolve the questions initially raised. Finally, the third competency refers to interpreting and being able to evaluate the data and what scientific support they have [37–39].

Of course, all these competencies require an epistemic scaffolding, i.e., an epistemological knowledge that makes it possible to understand the foundations on which scientific research practices are developed, the questions that are generated, and the concepts that revolve around them, such as theories, hypotheses, and data, among others [40,41].

The Ministry of National Education of Colombia (MEN) and the tests of the Program for International Student Assessment (PISA) [36] focus on evaluating this type of competence, with other names, but ultimately addressing the same contextualization; that is, students can demonstrate the three competencies mentioned above in different contexts such as work, social and personal, which coincides with the principles of the reverse design.

3. Theoretical Background

3.1. Backward Design Application in an Electromagnetism Course

The electromagnetism course is an undergraduate general physics course for students of the Faculty of Engineering. The original design of the course is planned for lectures and face-to-face laboratories; some virtual laboratories were developed by the authors of this article and some were taken from the web.

The results for each of the backward design stages are as follows:

Stage 1—Identify the desired results: To identify the desired learning results of the electromagnetism course, the following aspects were analyzed according to the suggestions of [42]:

- Explain the causes that give rise to the laws that describe electrostatic and magnetostatic phenomena both in a vacuum and in matter;
- Formulate hypotheses about the known effects of electric and magnetic fields on electric charges for the construction and elaboration of simple and complex electric circuits;
- Apply the basic concepts of electromagnetism to propose alternative solutions to engineering problems;
- Reflect on the results of laboratory practice, carrying out an analysis of the implicit physical phenomena and presenting them with the standard criteria followed by the IEEE (Institute of Electrical and Electronics Engineers).

Stage 2—Determine the acceptable evidence: To materialize this stage, the following learning evidence associated with the learning outcomes specified in the previous stage was defined:

- The generation of laboratory reports that show skills in the interpretation of graphs, argues in response to questions about electromagnetic phenomena, and alternative solutions to problems;
- The solution of tests and resolution of problems elaborated by competencies according to the guidelines of the MEN (Ministry of Education, Colombia);
- The conceptualization of tests about the proposed problems at the end of the forums.
- The elaboration of scientific reports using IEEE standards;
- Competency-based exam founded on the socialization of the rubric;

- Videos showing the development of homemade electromagnetic experiences.

To exemplify, some of the evidence provided by the students are presented as follows:

- IEEE article-type laboratory reports;
- Essays according to the topics addressed in the forums;
- Short videos of homemade electromagnetic experiments;
- Written exams on the thematic axis;
- Conceptualization test results.

Stage 3—Design the learning experiences and the pedagogy to be used: In this stage, the methodologies and some of the most important contents required to achieve the learning results are described (see Table 2).

Table 2. Learning outcomes, methodology, content, and resources for the implementation of BWD.

<table>
<tr><th>Learning Outcomes</th><th>Methodologies and/or Pedagogies Proposed for Its Development</th><th>Main Contents to Develop</th><th>Resources</th></tr>
<tr><td>Explain the causes that give rise to the laws that describe electrostatic and magnetostatic phenomena both in a vacuum and in matter.</td><td>- Group seminars on the subject under study.
- Short experiment related to the subject being studied.
- Individual and group educational workshops on the subject being studied.
- Laboratory guides developed cooperatively.
- Troubleshooting guides for electricity and magnetism.</td><td rowspan="3">1. Gauss's Law and its Applications.
2. Properties of Materials: Conductors, Insulators and Semiconductors, Convection and Conduction Current.
3. Current Densities of Convection and Conduction.
4. Ohm's Law. Polarization in Dielectrics.
5. Electrostatic Boundary Conditions: Dielectric-Dielectric, Conductor-Dielectric and Conductor-Free Space.
6. Fundamental Equations of Magnetostatics in Free Space.
7. Magnetic Dipole. Magnetic Moment. Magnetization of Materials, Magnetostatic Boundary Conditions, Inductance, and Inductors.
8. Magnetic Energy. Energy in terms of B and H. Magnetic Circuits,
Classification of Magnetic Materials.</td><td>Virtual laboratories developed at the Universidad del Magdalena and the University of Colorado (USA)</td></tr>
<tr><td>Formulate hypotheses about the known effects of electric and magnetic fields on electric charges for the construction and elaboration of simple and complex electric circuits.</td><td>- Group seminars on the subject under study.
- Short Experiment related to the subject being studied.
- Construction of conceptual and mental maps on the concepts being studied.
- Laboratory guides developed cooperatively.
- Construction of conceptual and mental maps on the concepts being studied.
- Troubleshooting guides for electricity and magnetism.</td><td>Real and home laboratories.</td></tr>
<tr><td>Applies the basic concepts of electromagnetism and proposes alternative solutions to engineering problems.</td><td>- Short experiment related to the subject being studied.
- Individual and group educational workshops on the subject being studied.
- Laboratory teaching guides developed cooperatively.
- Troubleshooting guides for electricity and magnetism.</td><td>Conferences and Forums</td></tr>
</table>

Some samples of the learning experiences of the course students are presented below.

3.2. Most Outstanding Learning Experiences Developed in the Course

One of the main learning experiences in the electromagnetism course was the implementation of virtual laboratories (see Figure 3), along with deep learning and previous knowledge, which allowed us to examine factors that favor learning with the use of this tool, in addition to the cognitive demands, and levels required to achieve the proposed competencies and learning outcomes.

Figure 3. Implementation of virtual laboratories where the high degree of attention to the evolution of the virtual experiment added to the high number of concerns raised is highlighted.

These competencies were articulated with a series of terms or verbs that regulate cognitive demand such as "recognize", "interpret", "analyze", etc. Likewise, these verbs did not indicate the degree of difficulty of the activities but rather served as an indicator of the students' competence.

Subsequently, after the declaration of a health emergency unleashed by COVID-19 in the middle of our school semester, it was necessary to use totally remote virtual laboratories, without the presence of the teacher, as shown in Figure 3. This modified learning aspect was initially raised, mainly with the design and implementation of the own virtual laboratories and those available on the web for the development of skills in engineering students. Figure 4 shows some of the virtual laboratories used, including the virtual laboratories developed at our university and the University of Colorado, United States of America (https://phet.colorado.edu/ (accessed on 15 February 2020)).

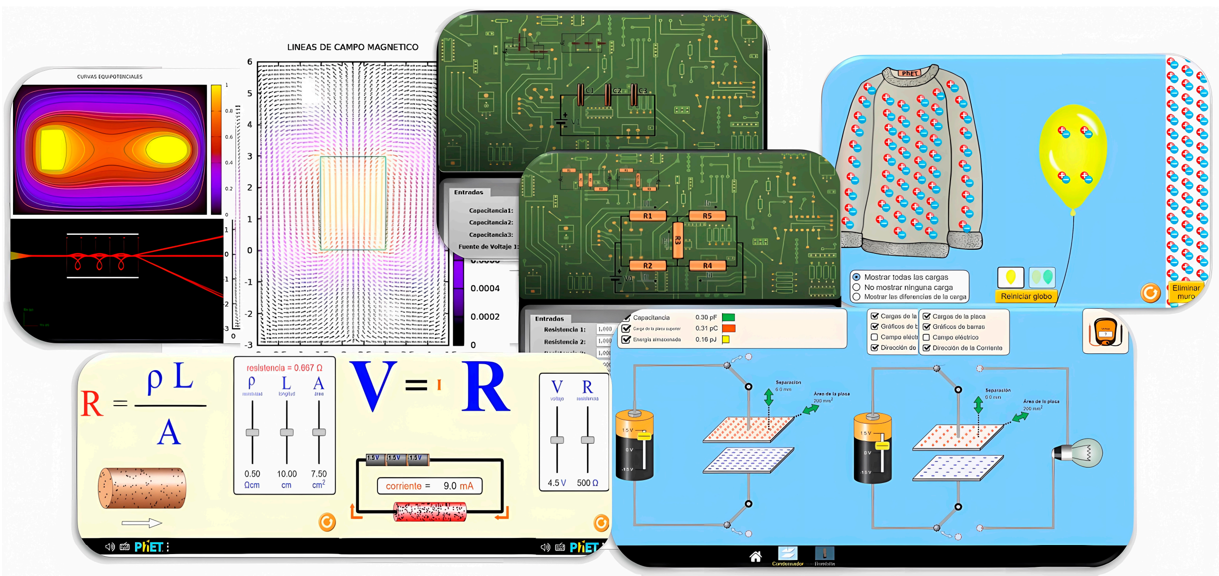

Figure 4. Own virtual laboratories and those available on the web developed for the subject of electromagnetism.

The research showed that the implementation of virtual simulations for teaching physics developed scientific skills, such as interpretive, argumentative, and purposeful skills, which improved the learning of physics; thus, this became a great motivation for understanding natural phenomena related to electricity and magnetism. We highlight the hard work behind the structure of the virtual laboratory guides that accompanied the pedagogical intervention conceived with the following structure: name of the laboratory, standard, competencies to develop, problem question, curricular area, achievement to develop, performance indicators, foundation, simulation, observation of the phenomenon, calculations, results, and analysis.

Another relevant learning experience during the development of the course was the home experiments called short experiments by our group (Figure 5), which influenced their mental processes by activating their commitment to this activity, aided by metacognitive strategies that enable them to adequately develop the problem-solving, interpretative and argumentative competence.

Figure 5. Short experiments introduced by the professor: the students had to make the balloon stick to the ceiling and explain the phenomenon from an electrostatic point of view.

It is necessary to highlight that for the preparation of each learning evidence, the guidelines for the test of the Program for International Student Assessment (PISA) were taken into account; that is, the contexts for the preparation of the questions, the competencies that needed to develop in the students, the learning transfers that they had to develop, the levels of the questions, and the work guides with animations and simulations, especially with their pedagogical structure, were taken into consideration. The reasons for which this was necessary were to adapt the questions of the tests to be applied, to adapt questions where the student could carry out the transfer of their learning in class, the elaboration of rubrics that were known by the students (quizzes and exams always emphasized the development of skills (see Figure 6)), and the preparation of guides adapted to own virtual laboratories and those available on the web.

Additionally, three types of questions were used as follows: those that developed argumentative competence, i.e., the questions of an interpretive nature; and those of a propositional nature. The questionnaire was of the know-pro type, i.e., multiple choice with a single answer, which is characteristic of the test applied by the MEN. For the tests at the end of the period, a structure designed for problem-solving competence was used, and at the end of the tests, a series of questions to develop competency in each unit for the qualification of the tests was devised based on the text by [43] using a rubric.

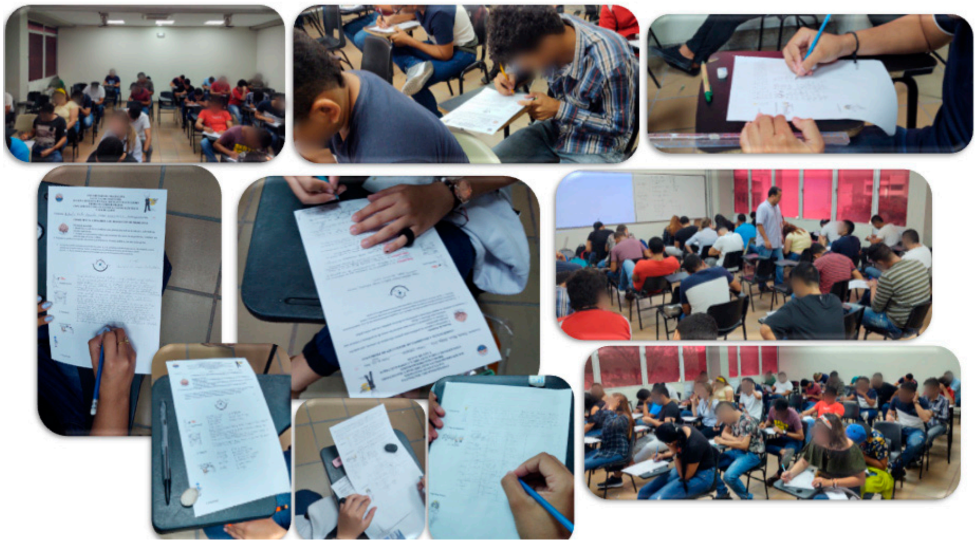

Figure 6. The images show the written test evaluated with a rubric based on the book by the authors Villa and Poblete [43]. This exam design breaks the paradigm of traditional exams.

4. Results

In this article, we present the results of implementing the backward design method and its pedagogical potential in teaching the subject of electricity and magnetism offered by the Faculty of Engineering to its students. Figure 7 shows the first phase of the use of the methodology, applying an entrance test to 94 students, in which levels of learning and development of argumentative, interpretive, and propositional skills were evaluated. The analysis and tabulation of the results obtained were framed according to the evaluation criteria stipulated by the Ministry of National Education, Colombia. According to the results obtained in the tests applied, at the beginning and the end of the course, an improvement in the performance of the students was observed with respect to each of the evaluated competencies, where a low level of competence was observed at the beginning of the course (See Figure 7a), while the final test reflects a significant increase in the development of skills with more than 78% of correct answers (See Figure 7b).

Our parameter to observe is the Hake factor [44], whose formula is a statistical indicator of how much the Physics class students have learned within the context of a particular didactic methodology. The formula to evaluate this is based on the following mathematical expression:

$$h = \frac{\%postest - \%pretest}{100 - \%pretest}$$

The population to which the test was applied were engineering students, the test consisted of 15 questions endorsed by the MEN, which are used in the state test at the national level. This provided more reliability for the application of the test. The results obtained from the pre-test are organized in Table 3, whereas the post-test data are included in Table 4. The entire group was analyzed, taking into account the percentage of correct answers at the beginning and the end of the course. The Hake factor can be easily calculated from the obtained data.

The following general criterion was used to appreciate these quantitative results. The criterion that can be considered is the following:

A low Hake gain is considered to be ≤ 0.3, a medium Hake gain is $0.3 < h < 0.7$, and a high learning gain is $h > 0.7$. By performing our calculations, we obtained:

$$h = \frac{\%posttest - \%pretest}{100 - \%pretest} = \frac{79\% - 21\%}{100 - 21\%} = \frac{58\%}{79\%} = 0.73$$

As we can see from the applied methodology, the learning gain indicated by the Hake factor for learning electromagnetic physics in higher education was medium, and in the Faculty of Engineering of the University of Magdalena, it took one year to develop the investigation.

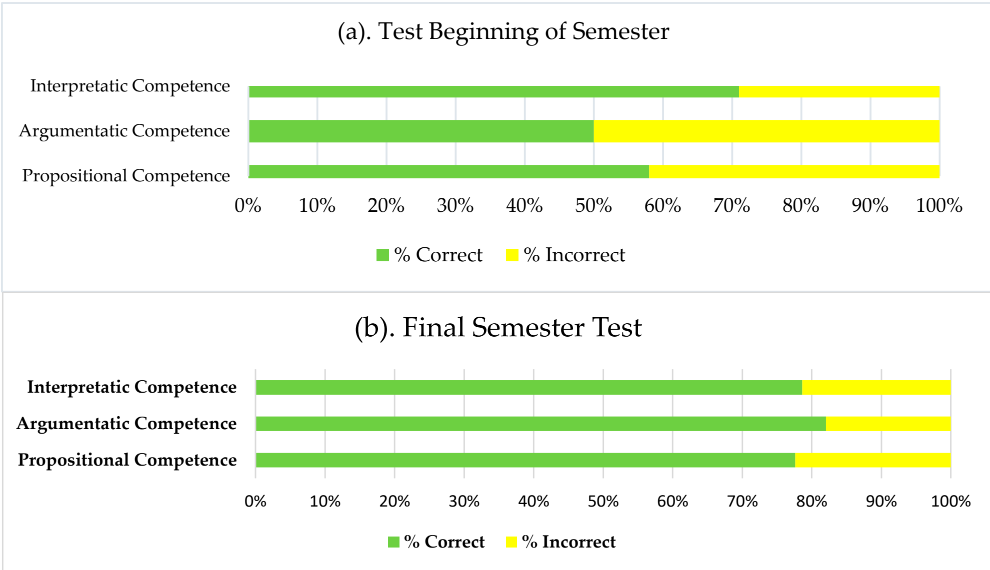

Figure 7. Results of the statistics that compare the scores of the engineering students before and after the test, with questions that contained the style of the Colombian State tests (Saber-Pro).

Table 3. Tabulation of pre-test results.

	Pre Test															
Questions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total %
Correct	31	19	21	18	7	10	19	12	32	25	21	13	21	7	10	266 30%
Wrong	28	40	38	41	52	49	40	47	27	34	38	46	38	52	49	619 70%

Table 4. Tabulation of post-test results.

	Post Test															
Questions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total %
Correct	56	51	49	45	31	51	47	46	48	50	43	48	46	40	50	703 79%
Wrong	3	8	10	14	28	8	12	13	11	9	16	11	13	19	7	182 21%

The results showed that the level of learning achieved by students via the implementation of virtual laboratories developed on the Unity platform at our Universidad del Magdalena (Colombia), as well as the virtual experiences of the University of Colorado (United States of America), have contributed to their academic growth towards the resolution of analytical problems (purposive), understanding the graphs of the results obtained in each virtual laboratory (interpretative), and active participation in discussion forums on electromagnetic phenomena (argumentative). We believe that the students managed to synthesize their analytical and computational skills, becoming better prepared to solve real problems in their training as engineers (see Figure 8).

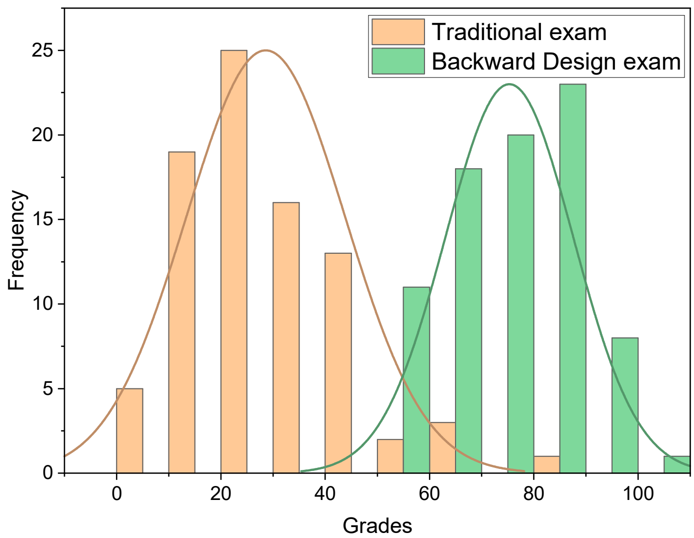

Figure 8. Normal distribution graph of the grades (0–100) obtained by engineering students after solving the traditional electromagnetism exam and the exam designed by our work group using the backward design methodology.

Our course is based on an explicit need to achieve a deep knowledge of electromagnetism that promotes the scope of general and specific skills directed using the backward design method, rubrics, and virtual laboratories. This methodology additionally allows instructors to more clearly identify the difficulties of each student, considering the backward design, but also reveals potentialities in a particular way, given that the evaluation of the course is based on exams and laboratory reports designed in accordance with carefully designed rubrics and discussion forums on real problems where electromagnetism is applied. In addition, creating a set of survey-like micro-tests on specific details prior to each class is useful to obtain an idea of the academic profile of the students and develop motivation before the course begins.

5. Conclusions

The redesign and implementation of the Electromagnetism Course by using BD and the results obtained in this research are directly related to the United Nations Sustainable Development Goal "Quality Education", which promotes inclusive and equitable education. Considering quality in education, the electromagnetic course was redesigned using BD as a response to the low scores of the students of the electromagnetism course carried out in a traditional way and whose foundation was based only on the contents, without delving into the development of skills or the determination of learning outcomes previously established for the subject. Backward design is a methodology with a pedagogical basis in constructivism, and it is an indisputable pillar of engineering careers because it generates tools that allow one to build their own procedures to solve real problems as well as a complementary strategy of the CDIO Initiative (conceive, design, implement, and operate real-world systems and products) whose curricular planning and assessment is results-based. The CDIO approach uses active learning tools, such as group projects and problem-based learning, to better equip engineering students with technical knowledge, as well as communication and professional skills. In addition, the CDIO Initiative provides resources for instructors at member universities to improve their teaching skills [45].

The contributions made by the virtual laboratories, short experiments, discussion forums, experimental videos, and the new competency-based exam proposal allowed the class to become more pleasant, and more students noticed that their learning and understanding of electromagnetic phenomena in the activities carried out in the written tests improved significantly. The results obtained indicate a high favorability, both in the opinion of the students about their learning experience of electromagnetic phenomena, showing a positive attitude and an improvement in the development of skills evidenced in the final assessments. It is necessary to highlight the significant progress in the apprehension about the actions and conceptualizations of the subject being studied. It was also evident that the students presented difficulties in developing and working on each of the competencies via the virtual tool with the pedagogical didactic guides due to the demands of a greater critical and creative value when approaching the problems. It is important to keep in mind that this way of working motivated the students to be more committed when it came to contributing positively to their classes. Finally, it was verified that the virtual simulations mediated with the didactic-pedagogical guides make a perfect combination because they facilitate the teaching and development of cognitive abilities, also favoring other types of competencies.

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Abbreviations

The following abbreviations are used in this manuscript:

CDIO	Conceive, Design, Implement, and Operate real-world systems and products
BD	Backward Design
MEN	Ministry of Education, Colombia
PISA	Program for International Student Assessment
IEEE	Institute of Electrical and Electronics Engineers
HOTS	Higher Order Thinking Skills

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