Learning electrical circuits for the development of critical thinking

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Abstract. This article presents an articulated proposal of two pedagogical approaches to favor the development of critical thinking from a physics topic. The purpose is to design a didactic sequence for the subject of electrical circuits, using two articulated pedagogical approaches so that students from a school of engineering in Mexico must solve an engineering problem linked to a relevant topic of physics, such as the characteristics of electrical circuits, the problem must be solved methodologically and systematically. The inquiry approach is quantitative, with a quasi-experimental design, a validated instrument is used for data collection. Subsequently, the hypothesis test for differences between means is applied and the results are analyzed. Thus, it is found that the development of critical thinking is incipient; however, the assessment of physics learning products reveals relevant findings such as the promotion of creativity. Likewise, the problem presented to the students allows them to contextualize their learning and recognize the relevance and application of the characteristics of electrical circuits. This inquiry confirms that the development of critical thinking through physics improves the comprehensive training of engineers. Therefore, according to the results, there is empirical evidence that both articulated methodologies can gradually favor the development of critical thinking; In addition, the methodological and contextualized learning of physics through the subject of electrical circuits is applied to a branch of engineering.

1. Introduction

Universities seek to develop different skills in students, among these are higher-order skills, such as critical thinking [1]. Thus, learning physics for engineering is essential, since a high percentage of theoretical content is linked to applications in engineering, however, solving physics exercises is not a guarantee of understanding conceptual topics such as electrical circuits [2] and, making use of traditional teaching, the development of higher-order skills will not be achieved either.

Thus, an identified problem is that critical thinking is not considered important by physics teachers and in a particular way it is not developed in the course: Electricity and Magnetism and it is not measured either. Then, from integrated and robust pedagogical approaches like science, technology, engineering, art, and mathematics (STEAM) and problem-based learning (PBL), the development of critical thinking is stimulated through physics. Both methodologies are characterized because the training is through practice, where the student works in a real way through experimentation, promoting the development of creative and innovative skills for problem solving. According to Botero and Sneider [3] through STEAM it is possible to develop skills that can improve innovative and critical thinking.

Based on the above, the learning of physics should focus on the construction and evaluation of scientific knowledge and eventually it would be contributing to the formation of critical people, capable of evaluating alternatives and generating creative solutions to problems [4]. Therefore, it is necessary to
renew the learning of physics through pedagogical approaches that allow to make the link with the work context, as recommended in Mexico by “Asociación Nacional de Universidades e Instituciones de Educación Superior (ANUIES)” [5]. However, physics teachers do not develop these recommendations in the classrooms due to ignorance of didactic strategies, the foregoing is the motivator for this present inquiry.

So, this inquiry is relevant in the field of physics for engineering since the evaluation of different thinking skills by themselves is not possible if it is not sought to develop them through some methodology or learning strategy. In addition, inquiries for the learning of physics with a STEAM approach have rarely been carried out [6]. Thus, this work aims to design a didactic sequence for the subject of electrical circuits articulating STEAM and PBL and their relationship with the development of critical thinking. In this order of ideas, the following research question is posed: does the articulated didactic sequence based on STEAM + PBL, for electrical circuits, manage to develop individual generic competencies (critical thinking) in engineering students?

The hypotheses that are formulated are: (i) null hypothesis (H0): with the STEAM + PBL methodology it is not possible to develop critical thinking with the experimental group of ESIQIE students. H0: \( \mu_{E} = \mu_{C} \leftarrow \) Null hypothesis, there are no significant differences in scores after STEAM + PBL. (ii) alternative hypothesis (H01): with the STEAM + PBL methodology, critical thinking is developed with the control group of ESIQIE students. H01: \( \mu_{E} \neq \mu_{C} \leftarrow \) Alternative hypothesis, there are significant differences between the scores after STEAM + PBL. Where \( \mu_{E} \) is and \( \mu_{C} \) are, respectively, the score of the experimental and control group.

2. Methodology and materials

The methodology is quantitative, with a quasi-experimental design. Where the independent variable is the proposed methodology based on STEAM and PBL and the dependent variable is the level of critical thinking (score obtained by each student in each group).

The subjects participating in this inquiry are a total of 133 students, they were distributed into a control group (30 students) who worked under the transmission-reception methodology and an experimental group (103 students) who were exposed to the STEAM didactic experience and PBL. The context of the study of this inquiry is the virtual classrooms of the “Escuela Superior de Ingeniería Química e Industrias Extractivas (ESIQIE)” from “Instituto Pedagógico Nacional (IPN)”, Mexico. The ages of the students are in the range of 19 years to 27 years. Likewise, the investigation is part of the Electricity and Magnetism course, which is part of the study plan of the bachelor's degree in Industrial Chemical Engineering, of the 2021-2 cycle.

As an instrument for measuring critical thinking, “Cuestionario de Competencias Genéricas Individuales (CCGI)” test by Olivares and López [7] is used, which is in Spanish; it has the corresponding validation and an acceptable reliability range (Cronbach’s alpha coefficient of 0.790); furthermore, this instrument has already been used to measure critical thinking in engineering students [8,9]. The methodological design was developed in four phases:

- Definition of objectives, selection of the topic.
- Design of the physics problem for engineering in a systematic way using the “Diseño de Programas de Estudio en Carreras de Ingeniería (Dipcing)” methodology, for its acronym in Spanish, with the participation of the teacher and a theoretical physicist; later it was evaluated by three experts: a chemical engineer in service; theoretical physicist and teaching physicist, as suggested [10]. Returning to the problem that is linked to the topic of electrical circuits and was extracted from a chemical plant is adapted for educational purposes, the Dipcing methodology [11] is made up of three linked and continuous stages, the first consists of making a diagnostic evaluation of the students' prior knowledge of physics; the second involves reviewing the contents of the university physics books and the third indicates linking physics with the profession being formed, through supervised visits to the chemical plant and interviews with engineers.
• The STEAM + PBL proposal is implemented for the experimental group, in the ESIQIE virtual classrooms, during three sessions of two hours each.
• The CCGI test is applied using the Google classroom forms after the pedagogical intervention. Post-test results are analyzed with inferential statistics and documented.

Regarding the physics problem for engineering that must be analyzed from the theoretical framework of electrical circuits, it is described below. The ClosoMex Company needs to determine and analyze the operation and maintenance factors that are affecting the high consumption of electrical energy within the cell rooms of this plant, located in the Northeast of Mexico. The plant consists of two electrolyzers (rooms) with electrolytic cells that, together with the brine treatment sections; the handling of chlorine and hydrogen gas, caustic soda, and sodium hypochlorite, produce a total of 80 t of chlorine gas per day with its equivalent in caustic soda at 50%. The cell rooms are in turn divided into two sectors; the first section that has a total of 27 cells of the Do Nert type; and the second section has a total of 19 cells of the Olin type.

Do Nert cells have a cathodic area of 11.5 m$^2$ operating with a maximum load of 50 KA and a total voltage between 115 V and 118 V. Olin cells in turn have a cathodic area of 14 m$^2$ operating with a maximum load of 110 KA and a total voltage between 85 V to 89 V. Guiding questions:

• The way in which the cells are distributed according to the problem posed is inferred: are they in series, parallel or mixed?
• How does charging affect current efficiency?
• What happens to the voltage in each room and why is it? Justify.
• How would you calculate the electrical energy consumption from the load and the number of cells? If the cost of 1 KWh is $2.5, how much does ClosoMex pay per month considering a continuous process (24×7, it considers that a month has 30 days)?

It is observed that the thematic contents related to the characteristics of series circuits are intertwined; for this engineering physics problem, students must infer that the cells are connected in series from the data tables provided and a systematic process of research analysis; peer discussion and teacher guidance, the above is provided by PBL. Likewise, based on guiding questions, students formulate hypotheses about the decrease in current efficiency; the cost of energy consumption of this company is also estimated, and it is analyzed because it is increasing the costs of electrical energy. The problem described above is a problem in a chemical plant whose technology is mercury cells. Thus, our students are exposed to a real and cognitively challenging situation, where their passive knowledge must activate them; first, analyzing and discussing the problem presented; then inquiring, relating to the characteristics of electrical circuits, and finally presenting their conclusions from the questions in the guide, in an infographic.

2.1. Articulation of didactic approaches to learning physics in engineering

Experts and institutions agree that STEAM is successfully articulated with the PBL methodology, with project-based learning, among others, since the solution of a real problem or the development of a project requires both creativity and critical thinking [3,12]. As previously mentioned, the potential of the PBL does not only lie in the methodology itself, but the problem is also key in the process, that is why for the authors of this article the problem is conceived as an instrument that must be carefully designed. Thus, Escobar and Ramírez define contextualized problems “... that difficulty that, extracted from the phenomenal context, links a specific topic of a factual science (physics) with the industry or field of action of a professional, to starting from qualitative information and proposing close quantitative data in its solution” [13].

Then, given that in university physics books the learning of the subject electrical circuits is through a brief theoretical framework and the resolution of exercises [14-16], and the analysis of electrical circuits in the literature is limited to the calculation of resistances, voltages and currents; that although
they promote explicit knowledge, they do not promote tacit knowledge, that is, that acquired knowledge allows the student to develop in contexts alternative to academic [17].

Therefore, for the application of the PBL methodology, eight steps are followed, however, a variant was proposed in the section of presentation of results, traditionally carried out through a report, the variant proposed is that the students present their results through an infographic. This is a novel way of presenting information in a synthetic way, in addition, when creating this learning product, the creativity skill is being developed, linked to art within the STEAM dimension. Because, through the creation of infographics by students, they are developing 21st century skills [18]. Together, their use to replace engineering technical reports has been successfully documented [19,20]. For the creation of the infographic, students are given a rubric proposed by Guzmán, Lima, and Meza [21] for their elaboration. Therefore, with our proposal as indicated in Table 1, the STEAM dimensions are adequately related to both the content and the proposed learning activities.

Table 1. Proposed activities for each STEAM dimension.

| Dimension | Contents                           | Learning activity                                      |
|-----------|------------------------------------|-------------------------------------------------------|
| Science   | Physical                           | Analyze the problem from the conceptual framework of electrical circuits |
| Technology| Software, Excel                    | Process and organize data                              |
| Engineering| Chemical engineering, electrochemical cells | Use the data to understand the data and visualize the information through the graphs |
| Art       | Infographics, complex visual diagrams | Make a scientific infographic, using a rubric as a guide |
| Mathematics| Data and use of graphs             | Use the data to understand the data and visualize the information through the graphs |

3. Results and discussion

It is decided to test whether, in effect, the proposed didactic sequence with the two articulated approaches for the subject of electrical circuits allows the development of critical thinking, using the test for normal populations with known variances and thus establishing whether there are differences between two means with a level of significance of 0.05. Since it meets the criterion that both samples are greater than 30 individuals and are independent samples. According to Devore [22] defines the standard deviation of the difference between two means as indicated by Equation (1).

$$\sigma_{X-Y} = \sqrt{\frac{\sigma_1^2}{m} + \frac{\sigma_2^2}{n}}$$

(1)

and the standardization of the sample mean is calculated by Equation (2).

$$Z = \frac{X-Y-(\mu_1-\mu_2)}{\sqrt{\frac{\sigma_1^2}{m} + \frac{\sigma_2^2}{n}}}$$

(2)

where, $X - Y$, are the averages of the post-test for the experimental and control group respectively and $(\mu_1 - \mu_2)$ represents the hypothetical difference of the population means. In this regard, other studies that measure critical thinking have carried out this type of statistical analysis [23,24]. The data were analyzed with the data analysis function in Microsoft Excel 2013, applying the function “z test for means of two samples” with 95% confidence, see Table 2.

Thus, since the calculated value of $z = -0.8622$ does not lie in the rejection region ($-1.96 < -0.8622 < 1.96$), therefore, the null hypothesis cannot be rejected, it is accepted. Analogous results found, using only PBL [25]. However, the researchers applied the methodology for 5 weeks versus three two-hour sessions that we apply in this proposal. In contrast, other inquiries record improvements in the development of critical thinking, but this is quantified by validated rubrics based
on achievement levels [24,26]. In this sense [27] they refer, that in their study carried out for two years implementing STEAM for the learning of chemistry topics that the development of critical thinking and creativity is stimulated with this approach by asking questions; defining a problem; examine evidence; analyze assumptions and consider other interpretations.

It also agrees with [20]; because it is appreciated in the learning products that the students develop investigative skills, and a congruent handling of variables is observed. For his part, it is agreed with [28] who says that PBL has as an added value the structuring of knowledge that arises from the problem, in our case involving knowledge of circuit characteristics, constituting a contribution to physics with this inquiry, as is the systematic integration of pedagogical approaches and the contextualization of physics in engineering, allowing the stimulation of higher-order skills.

Regarding the elaboration of the infographics, 70% of the students complied with the delivery of this product, showing that the students respond positively to methodologies that involve the connection of physics with the work reality and cognitive processes are reinforced [2,18]. Only 20% reached (three work teams) the outstanding achievement level, these were the most active teams, corroborating that infographic is a tool to acquire refined knowledge of physics; because it allows the representation of ideas, models, and concepts [20].

These results reinforce the idea that students should be exposed to situations that allow them to develop critical thinking and continuously understand physics; because to solve physics problems they must connect previously learned concepts to solve them [29]. But also, there is implicit learning through the effective integration of disciplines where they solve problems posed in a real work context [6]. This is also confirmed by physics teaching researchers such as Becerra [30] who points out that a good pedagogical approach improves knowledge of electrical circuits.

### Table 2. Z-test for two sample means.

|                      | Control group | Experimental group |
|----------------------|---------------|--------------------|
| Means                | 37.1110       | 37.6990            |
| Variance (known)     | 9.1370        | 13.0370            |
| Observations         | 30            | 103                |
| Hypothetical difference of means | 0            |                    |
| Z                    | −0.8620       |                    |
| P (Z <= z) one tail  | 0.1943        |                    |
| Critical value of z (one-tailed) | 1.6448     |                    |
| Critical value of z (two-tailed) | 1.9599     |                    |

### 4. Conclusions

This study described that it is possible to integrate science, technology, engineering, art and mathematics and problem-based learning for learning physics in an engineering training context. Based on the results of the previous section, the objective of this investigation being the design of a didactic sequence integrating contextualized knowledge of physics about electrical circuits with engineering, resulting in a contribution to the gradual development of critical thinking and creativity.

Given that the null hypothesis is accepted, this indicates that there is statistical evidence that indicates that there is no development of critical thinking with this proposal, a relevant factor could eventually be the time of application of the didactic sequence, since other inquiries report the application of active learning methodologies of at least 5 weeks or even a full semester, years inclusive.

Another factor that could influence, it is considered, is socialization among peers, the former being a limitation in this inquiry, since other inquiries report the performance of interventions in non-virtual environments, where students are monitored and directed towards activities Scientific learning, for our case of physics, is effective.
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