Developing the computational thinking process in Physics courses, an empirical study for the learning of the rigid body concept in engineering students

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***Abstract*— In the present Research-to-practice Full-paper, the learning, reasoning, and problem-solving processes, in engineering students, have been analyzed from different approaches, one of them is the computational thinking process, where most of the activities must be performed as a computer does and the reasoning is developed with the well-oriented activities realized by them. In many of the engineering career programs, the Physics courses are fundamental, and because of the diversity in contexts, they have not been seen as a subject where students can develop the computational thinking process. Present work describes an empirical study based on the learning of the rigid body concept in physics, with the use of spreadsheets as an electronic tool for promoting the learning with the programming of all the dynamical system, describing the evolution, generating, and analyzing graphics, and explaining the physical phenomena with a high comprehension and transfer of knowledge. At the end, students identified where the concept can be applied in their professional context with the use of a simulation. The learning sequence was implemented in three sessions of *1.5* hours each one, two diagnostic tests were applied, one for identifying the previous knowledge and use of electronic spreadsheets, the second one used as a pretest and post-test, it was focused on the main concepts of the rigid body system, like forces, kinematics, and circular movement. The sequence was implemented with $N = 77$, students. *Session 1*, started with the introduction of electronic spreadsheets for their use in science and engineering, some examples in Physics and Mathematics were described with their respect feedbacking for students. For *session two*, the rigid body concept was described with the support of electronic spreadsheets, all the dynamics, equations, plotting of the results and the relationships of all variables were described; for reinforcing the concept learned, students were asked to solve two more similar exercises with the use of the spreadsheets as homework, and finally they were asked to record, in groups of three students, a video with the solution of the problem assigned. In the video, they must present the problem description, equations and dynamics involved in the solutions and explaining all the programming steps needed to perform the solution in an electronic spreadsheet with its graphical representation and interpretation of the variables, and a description of implications in the changing values of the variables in the mathematical model. At the end of the sequence, in *session three*, a virtual simulation related to their professional context was used for the reinforcement of all the concepts learned. For analyzing the impact in their learning process, the Normalized Conceptual Gain was used in the pre-test and post-test, results showed a $g = 0.85$, which represents a high learning and normalized conceptual gain. Finally, the results showed that the computational thinking process can be developed by students, as they must program equations, analyze data, understand it, and identify graphically the variables involved, linking the learning of a physical concept with a computational tool that let them understand in a more clear, specific, and ordered thinking.**

Keywords*— *Computational thinking, engineering students, electronic spreadsheets for learning, physics courses in engineering, professional skills.

I. Introduction

The learning process, at any level, requires some elements that let the student to acquire knowledge, internalize it, and apply it, presenting, in some cases, mistakes during the first time that the learner tries to reproduce the knowledge acquired, it is a human and natural condition, even for many species. For majors in an engineering or science career program, the learning process requires many skills to perform a more complex understanding of the things to be learned and applied, they must work with abstract and physical representations of the world, combining all the topics and concepts learned for the creation of new knowledge or engineering solutions.

A. Computational thinking process in engineering and science education

Since the first mention and definition, of the Computational Thinking (CT) in [1], many research work has been done since 2006 [2–6], for the research in how to integrate and adapt, the computational thinking process and facets, like in problem solving and thinking in different students' age and cognitive level states. These facets are *decomposition, abstraction, algorithm design, debugging, iteration, and generalization*, it is necessary to consider how them can be extrapolated in other related disciplines, like Physics.

One can analyze the learning process and put forward activities for create a pathway for this CT development, combined with the learning of other concepts that are necessary for the instruction in a career curriculum for engineering and sciences [7]. In the Physics Education Research (PER) area, there have been many works that are related with the use of computers as an additional tool to help students in their learning and understanding of the different concepts they must comprehend in their subjects.

The use of programming languages and simulations were, probably, the first use of computers in teaching some Physics' concepts, the versatility of computers for handling, programming, and manipulating data could be considered a core stone in the digital information science work. With the evolution of computers, in software and hardware, and new digital devices, like sensors, they were more adopted and used by the scientific communities. Here we can see the relationship that computers and science have generated over the past eight decades (beginning around *1940's*, approximately).

Some initiatives for the learning of Physics with the use of computers started the combination of commercial software, like electronic spreadsheets. In almost the last three decades, the science community, have used computers for teaching complex concepts. The work in [8], described the use of electronic spreadsheets for complementing information andas a support tool for the learning of Physics, it described some examples of how using the electronic spreadsheets can help to understand some physics concepts. For [9], mentioned how the aid of computers in the Physics Education area was an opportunity for implementation in the classroom and laboratories, they also pointed out many potential scenarios like tutorials, use of artificial intelligence, simulations, etc.

In [10], is described the *Physics Workshops Methodology*, using electronic spreadsheets as a tool for simulating physical phenomena and stimulating the information analysis obtained by the students' laboratory work. It is interesting that they preferred the use of electronic spreadsheets because of its simplicity for non-programming users, as example in the beginning of the methodology they tried using the Pascal programming language, but the learning of the programming language generated a lack of time for the students in the adoption, implementation, and low results in their studies of Physics. Here we can see one of the opportunities for continuing using electronic spreadsheets as a versatile tool for learning Physics, Science and Engineering, pointing out the facility for using them and not requiring previous knowledge of programming.

Finally, other authors have mentioned how to design examples using electronic spreadsheets directly in the classroom or use them as black boxes for teaching specific concepts [11–19], [22]. The use of spreadsheets can be compared with the early learning in data analysis and manipulation by many students, whereas the manual method using grid and paper often still seems to be the most suitable for teachers in early grades. The merit of this technique is the active mind participation in students because they must work through all the steps in calculating via formulas and plotting the results in the paper, similarly, the spreadsheet presents this kind of "flavor", letting the student feel comfortable with a previous method for instruction and the possibility for plotting all the data generated by the electronic spreadsheet.

The negative part of using electronic spreadsheets can be the difficulty for debugging as the amount of data generated and macros programming, it requires specialized teacher knowledge in manipulating the electronic spreadsheet, the precision data generated by the software, graphical visualization of complex systems or mathematical models and not enough materials available for teaching some specific topics.

A research question appears with the use of electronic spreadsheets and the Computational Thinking process: *How to design a learning sequence that promotes the development of CT skills and help students in their learning of complex concepts in Physics?* For answering this question, we designed an active learning sequence that promotes the learning activation in students, focusing on their participation and collaboration with the teacher and other peers.

Preset work, describes an empirical study in the design and implementation of a learning sequence that use, as a digital learning tool, spreadsheets for the learning of physical concepts, using the rigid body concept in a Mechanics course, for describing how a well oriented learning sequence can help to students and teachers in the learning process of acquiring disciplinary concepts and developing Computational Thinking skills, like data manipulation, basic programming, mathematical modeling and graphical creation and interpretation, in first year students of an engineering career program.

For evaluating the impact of the learning sequence, the statistical tool called Normalized Conceptual Gain (NCG [27]) was applied. With this concept we could see if the activities promoted by the learning sequence really had a positive or negative impact during the learning sequence.

II. METHODOLOGY

For the development of the Computational Thinking (CT) in engineering students, we propose a learning sequence that includes all the facets of the CT for an efficient and effective learning cycle, we consider that it can be implemented in any science and engineering program, with or without a computer laboratory, because the activities can be done in a computer laboratory with the guidance of the teacher or can be done with the teacher exposing the activities in a classroom. The steps and stages in the learning sequence that we proposed, let students to have a smooth pathway for the development of the CT's skills necessary for their instruction, like mathematical modeling understanding, numerical and data manipulation, abstract and critical thinking, physical comprehension of the phenomena observed and graphical interpretation of any physical system with their variables, also the transfer of knowledge is present, because students can see similar examples with software simulations, where they have to interpret and reasoning in a particular example for the applications of concepts related to their engineering program, like a robotic arm simulation.

For designing the learning sequence, we chose the *rigid body* concept, as an example of how the CT can be developed in engineering students, this because it is considered by students as one of the *most difficult* concepts to learn in a Physics course, but some relevant points are that the concept uses different mechanics principles and applications like kinematics, dynamics, and circular movement. The following activities described, can be implemented in similar scholar contexts and the ages of the students can be between the *15* to *21* years-old with algebra fundamentals as previous knowledge.

A. Learning sequence methodology description

The learning sequence methodology implemented was in three sessions of *1.5* hours for online class and *3* hours in extra-class activities. The steps in the learning sequence are:

1) *Characterizing the students' knowledge of electronic spreadsheets and standardizing the use of them.*

For the first session (*90* minutes), students started with answering an online test related to the knowledge and use of electronic spreadsheets, they were assigned *25* minutes for answering, and the items are related with the knowledge and use of electronic spreadsheets, they were asked if knew how to use an electronic spreadsheet basically and what kind of software, commercial or open access, they knew it. Finishing the online test activity, the teacher initiated with the explanation and description of the electronic spreadsheets, the goal in this class was for standardizing knowledge, in students, for the use of electronic spreadsheets, they were explained about the use of the electronic spreadsheets and, numerical, mathematical, and graphical manipulation based on the facets of decomposition, abstraction, algorithm design, debugging, iteration, and generalization proposed by the CT process.

Five activities were carried out: *a. Explaining the basic function of an electronic spreadsheet, b. Spreadsheet for solving numerical and mathematical exercises, c. What are the data in an electronic spreadsheet? d. How to plot in an electronic spreadsheet from tabular data? And what kinds of graphics can be done in an electronic spreadsheet? and e. Graphical interpretation and description of data in a plot.* For activities *a* and *b*, the time assigned was *25* minutes for both, for activities *c* and *d* were assigned *15* minutes for both, and for the activity *e*, it was assigned *25* minutes. This session required that students must learned the manipulation of numerical series, programmed the equations, and generated the graphics in the electronic spreadsheet. The concepts viewed in this session were related to kinematics, forces, and circular movement.

Two results were obtained in this session, the first one, was to help students to remember and reinforce the previous mechanics concepts needed for the learning of the *rigid body* concept and the second one was for the CT skills with the use of the electronic spreadsheet by programming the equations of the kinematics' example, generating the numerical series of all variables and, plotting and interpreting the graphics generated by the software, it is important to mention that students were faced with questions related to the use, interpretation and visualization of the physical phenomena that must be learned, during the description of the exercise, the feedback from the teacher was relevant because after this session students have to solve another exercise as a homework activity, all based in the use of electronic spreadsheets for solving a physical problem, in Figure *1*, it can be seen the online session.

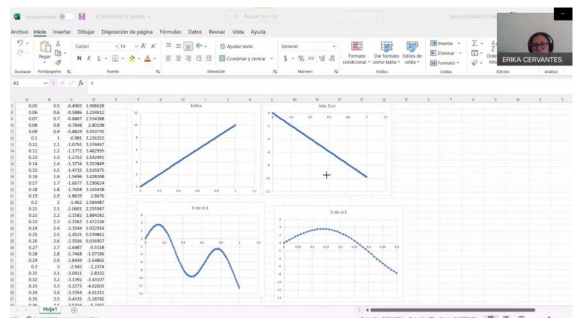

Fig. 1. Online session with students for introduction to the use of spreadsheetsin Physics.

2) *Learning the **rigid body** concept with electronic spread-sheets.*

For the second session (*90* minutes), it starts with a pretest related to concepts of force, motion and graphical understanding, the test was proposed and conformedwith items taken from two standard test: the *Force Motion Conceptual Evaluation (FMCE [25])* and the *Test of Understanding Graphics in Kinematics (TUG-K [26])*, the time assigned for answering the online test was *30* minutes. Finishing the online test, the teacher did a fast feedback, based in the previous class, were students learned how to work with an electronic spreadsheet, the time assigned for this activity was *15* minutes, for the rest of the session, the teacher described and explained in detail, the *rigid body* concept, with an example, to all students, she described the step-by-step process for solving the *rigid body* example, here students were asked to following the same steps she did, using their computers, tablets or cell phones.

The feedback by the teacher was fundamental, for this activity a *45* minutes time was assigned, in this partof the session, we consider that the teacher needs to have a good knowledge of both areas, for one side the use of electronic spreadsheet, and for the other side the physical concept to be taught, because the students' learning process had to work with two different things, by one way the use and manipulation of an electronic spreadsheet and by the other hand the learning of acomplex physical phenomena. We have to point out, that for this session, most students showed a good knowledgeof electronic spreadsheets, they learned the basics in previous courses and, a few of them, about 5 students, had low or no knowledge of the use of electronic spreadsheets, but their peers help them to explain the use of the digital tool, this is a little example of the interest in the students for the learning of Physics with the use of digital tools in a collaborative way. Figure *2* shows part of the online session for the description ofthe *rigid body* concept.

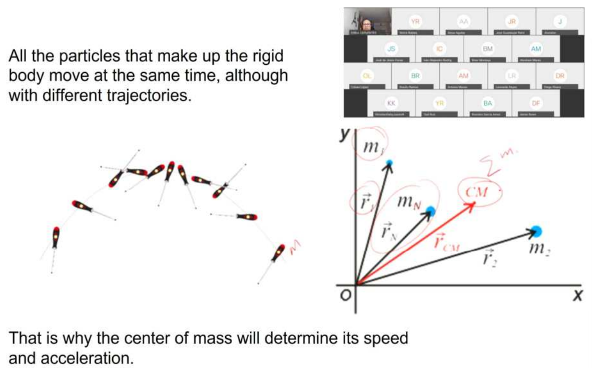

Fig. 2. Teaching online the *rigid body* concept with the use of spreadsheets.

Finally, students were required to conform groups of three or four peers for solving a *rigid body* exercise, it was assigned similar, but with a little more complexity, respect to the one viewed during the online the session. They must create a video describing the solution of the exercise and, deliver the exercise solved to the teacher.

Both products, the exercise and the video recorded, had the goal to promote the collaborative learning in students, the reinforcement of the facets from the CT process and, the learning and comprehension of the physical phenomena learned by students.

Figure 3 shows an example of the video generated by students. In the results for the videos, most of the students recorded the video and described, with their voice in 'off', how to solve the assigned exercise, a positive point for these videos were that they can be reused for future interventions, first because the concept never change in the curricula for future courses and, second because the language for the description of the problem is affordable to their peers for future viewing.

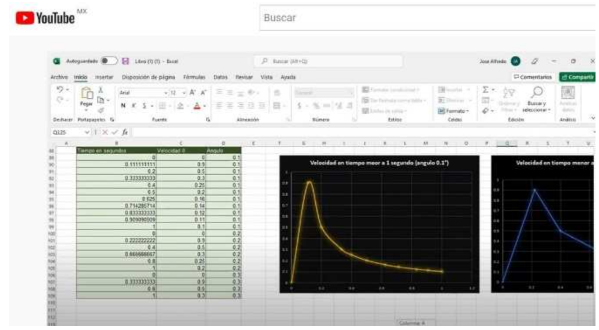

Fig. 3. Students' video for solving a *rigid body* exercise with electronic spreadsheets.

3) Using a simulation for the reinforcement and integrationof all the physical concepts learned.

For the last session (*90* minutes), students were faced with the use of a free software for learning with simulations, the Webots (*https://cyberbotics.com/*) software, it has many examples for engineering and physics simulations, they were asked to download the software previous the session and install it in their computers, tablets or cell phones, a specific example (that comes integrated with the software) was viewed, we chose the simulation of a robotic arm as an example (see Figure *4*, for reference), because it allowed the students to see how the motion and dynamics of the *rigid body* concept can be applied in a similar scenario related to their professional activities after finishing their undergraduate program in engineering.

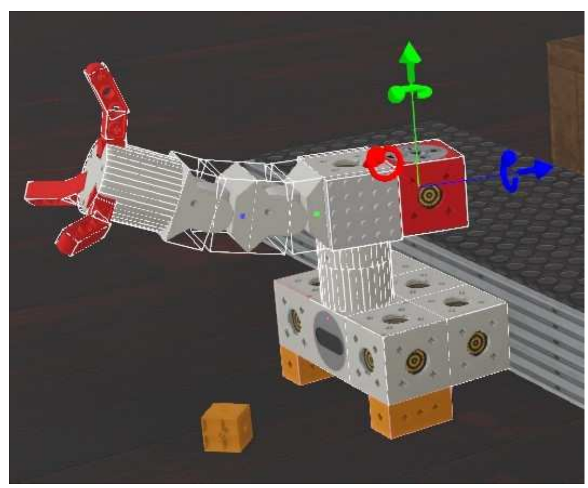

Fig. 4. Webot software: Robotic arm simulation example, for the reinforcement of the *rigid body* concept.

The graphics and data generated by the simulation let students to reinforce the learning on the graphical interpretation and the numerical manipulation of data generated by the robotic arm. In this session, the goal was that students could see that the same behavior, of the *rigid body* concept learned, can be seen in another platforms and from a different software than the electronic spreadsheets, the time of *50* minutes was assigned for this activity, finally and for closing the learning sequence, a post-test (being the same as the pretest) was applied online to students, with this information all data were collected for being analyzed in the whole learning sequence, the same time that the pretest was assigned (*30* minutes) for answering this final activity.

The last *10* minutes remaining of the session, were for an informal interview to the students with the use of electronic spreadsheets and what did they think of using this kind of digital tool in their learning process.

B. Students' characterization and context of the learning sequence implemented.

The learning sequence was applied in $N = 77$ students,the group was mixed, with *55* male students and *22* female students, the range of ages was between *18* and *21* years-old, for the *85 %* of students, this was their first course of Mechanics, and for the *15 %* of students, it was the second or third time that took the course.

The Mechanics course, where the learning sequence was implemented, is situated in the second semester of an Industrial Engineering career program for a university level, this is the first course in Physics. Previously, in the first semester, students should take a semester of Superior Algebra and, Differential and Integral Calculus courses, instead the Mechanics course must be taught in a calculus-based content, the level must be adjusted to an algebra-based course, because of the abstraction of the concepts that the curricular program has and, the diversity in knowledge of the new first year students that took the course, must of them didn't have calculus knowledge, and in the previous course of Differential and Integral Calculusthey didn't approved in a *95 %*, being this a handicap for teaching a calculus based physics course.

The course is coordinated by the Physics Academy, and the academic career program, had a curricular redesign recently, where all departments and academies must be involved, in this process the professors, that teach at the final semesters, described and pointed out, that students need to develop the skills for using electronic spreadsheets, because of the professional context for the Industrial Engineer, where the data manipulation, interpretation and transformation is basic for many of the activities that a professional in this area must to perform. The learning sequence proposed can be extended to any engineering program, because most of them, have at least one Physics course and the CT process can be developed as a basic skill for professional activities in the early years of the career program.

III. Results and Discussion

For analyzing the results and impact of the active learning sequence proposed, we used the Normalized Conceptual Gain (NCG), proposed in [27], with this information we are able for describing how was the impact of the learning sequence in students and interpret the efficiency and efficacy of the activities realized for students.

A. Results from the quantitative evaluation of the learning sequence

For evaluating the impact of the learning sequence implemented, we used the Normalized Conceptual Gain (NCG) [27], as the conceptual test have *thirty-five* multiple-choice items, taken from the FMCE and TUG-K tests, [27] describes the way for calculating it, the Equation 1 for obtaining it is:

$$g = \frac{[Post-test\ (\%)] - [Pre-test\ (\%)]}{100\ \% - [Pre-test\ (\%)]} \qquad (1)$$

Where the *[Pre-test (%)]* variable is the percentage obtained from the pre-test applied to students, the *[Post-test (%)]* variable is the percentage obtained from the post-test applied to students and the one hundred value corresponds to the percentage of all the items.

The NCG has some ranges for gain *'g'*, in [27], the levels that can be obtained in a learning sequence, are in Table I:

TABLE I
NCG
LEVELS

Level (g)	Range (%)
Low-g	$0.00 < g < 3.00$
Medium-g	$3.00 \leq g < 7.00$
High-g	$g \geq 7.00$

Table II presents the percentage results obtained from the application of the pre- and post-test in the learning sequence:

TABLE II
PRETEST AND POST-TEST
RESULTS

Pre-test (%)	Post-test (%)
18	88

Substituting the results in Eq. 1, the NCG obtained is:

$$g = \frac{88\ \% - 18\ \%}{100\ \% - 18\ \%} = 0.8536 \approx 0.85 \qquad (2)$$

Based on the results and according to [27], where g is greater than *7.0 (according to the third range Table I)*, we obtained a *High-g* value, the result can be considered fare and demonstrates that the impact in the learning sequence was effective and efficient for students. This result demonstrates that the learning sequence obtained a positive impact in the learning process in students, and they get benefit from both approaches the CT development skills and Physics learning concepts.

B. Discussion of the results

With the high value of NCG obtained, we can consider that the learning sequence could achieve the goal proposed at the beginning of the research: To develop in students the Computational Thinking process and skills related to this thinking and the learning of physical concepts. The sequential and timing activities proposed, let students to learn and perform, in a smooth pathway, the acquisition of new knowledge and concepts in two areas, one relates to the facets in the CT process and another for the learning of a *complex considered* concept, like the *rigid body in physics*.

Students' participation in the proposed activities was considered like an active learning scenario, because all the students participated in at least one activity, showing interest, and working collaboratively with their peers. The videos and homework done by students also demonstrate the pertinence of the learning sequence, promoting group and individual work. A hole cycle can be seen during the instruction, since the use of an electronic tool for data manipulation, passing from the learning of a complex concept like the *rigid body*, and acquiring the skills for supporting their learning with tools and by the guidance of the teacher.

Particularly, and in many learning engineering or physics, research works, the use of a control group is considered for comparing the outcomes between a pure lecture instruction versus an active learning sequence group as mentioned in [16], [20–24]. For the present active learning research work, it only has an experimental group, because it was the only group assigned during the semester and with the possibility for controlling all the variables during instruction. Additionally, the literature review that used the same multiple-choice test (FMCE and TUG- K) and compared some active learning proposals respect to a lecture intervention, reported quite similar values of the pre-test like this research work, being around or less than 30 %, reporting that the post-test and the NCG, after the lecture activities were with values of *g* less than *0.3* [21–24], this can partially support the absence of a control group and we consider that more research work must be done, possibly using a control group for comparing the sequence outcomes.

IV. Conclusions

Using electronic spreadsheet (ES) as a digital learning tool can help students and teachers in their learning process, this because the ES presents an intuitive way for numeric manipulation, nor previous programming skills necessary, basic mathematical knowledge in an algebra level for using it. Also, graphical representation of data with only using a few links in the ES software are some of the advantages in using them. Finally, the use of a complementary digital learning tool for the reinforcement of the concepts viewed during the learning sequence is recommended, this can be substituted or complemented with a laboratory activity, where students can see and experiment a real phenomenon and recollect, possibly with sensors, the physical data generated in the experiment, with the advantage that these data obtained can be seen as the ES uses it.

We consider that the research question at the beginning of present work was answered, and we can conclude that is possible to develop the Computational Thinking (CT) process in students, combining the facets of the CT, with a well-designed learning sequence that requires the learning of Physics. The advantages of developing the CT in first year students is that they can develop the digital skills in the early career semesters, reinforce them and having a solid knowledge of data manipulation, understanding how information can be acquired and transformed for their application in another context, different from science and promote efficient and efficacy solutions to engineering problems.

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