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Interactive simulations with PhET as a design tool for engineering education: design of an energy integration network

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Abstract

This work describes the use of interactive simulations as learning spaces for digital transformation of engineering education. Students carried out collaborative activities using Matlab-GUI (Graphical User Interface). An interactive simulation was prepared to design an energy integration network that minimizes the use of utilities in a chemical process. Students used the interactive tool to assess the effect of the minimum difference of temperature between the hot and cold streams on the cost of the proposed network and its economic viability. Motivation and academic performance were the variables analyzed in this study. Motivation was measured with the MUSIC model (eMpowerment, Usefulness, Success, Interest, and Caring). Mann-Whitney technique was utilized to measure the differences between the students in the group under study and the control group. Results indicated that the interest of the students in the learning activity and their expectation for usefulness were statistically higher when interactive simulation tools were utilized.

Keywords: *Educational innovation; PhETs; Interactive-simulation; Higher education.*

1. Introduction

Nowadays there are a variety of digital strategies and tools that allow students to be more active and motivated to collaborate, socialize, and share ideas in learning activities (Al Mamun et al. 2022; Motyl et al. 2021). These strategies can merge with each other, looking for students to take a more active role and assume greater responsibility in the construction of their own learning and that of their peers. This competency constitutes the basis of continuous learning, particularly in technical fields. In this study, a learning experience using flipped classroom technique, collaborative learning and interactive simulations is described. The experience consisted in the design and implementation of Matlab-GUI (Graphical User Interface) application aimed to improve the understanding and interest of college students in engineering topics such as energy integration. Its impact on motivation and academic performance of students was measured using the MUSIC instrument (Jones, 2018), which assesses the student perception in terms of eMpowerment, Usefulness, Success, Interest and Care.

In the teaching of science and engineering, the execution of practices in laboratories is essential to facilitate the understanding of physical phenomena and develop specific engineering skills. However, access to these experiences is frequently limited by the lack of space, material and human resources, and even extraordinary situations such as the SARS-CoV-2 pandemic (Vanoye et al. 2020).

Although there are commercial simulators, with applications in the chemical in-dustry, such as Aspen Plus, these simulators are not as readily available to students due to the prior knowledge required for their use, in addition to computational requirements and licensing costs. Few interactive resources have been developed for didactic purposes, focused on illustrating specific concepts within chemical engineering courses. Vanoye et al. (2020) present a compilation of virtual reality applications in chemical engineering. Particularly noteworthy is Learncheme.com, a website that includes video recordings, interactive simulations, Polymath files, short quizzes, and a virtual laboratory (Granjo y Rasteiro, 2020). On the other hand, PhET interactive simulations are educational resources originally conceived for teaching of physics, the use of which has become popular and today is used in multiple educational innovations, including some on chemical engineering concepts (Khatri et al. 2014, Gargallo et al. 2009).

In the area of engineering, the understanding of concepts has been facilitated using computational tools such as Maple and MATLAB. MATLAB is a technical calculation language and programming environment for algorithm development, data analysis, visualization, and calculation developed by the Mathworks company, and with great popularity around the world. Majid et al. (2012) evaluated the effectiveness of its use on students' attitudes and motivation and its impact on learning. Gemechu et al. (2018) found, for example, that the use of MATLAB software can improve students' conceptual understanding, even if their mathematical skills are weak.

In the area of chemical engineering teaching, the use of MATLAB has begun to be explored in material balance applications (Domínguez-Candela et al. 2021), chemical reactors (Molina et al. 2020), heat transfer operations (Lobato et al. 2021), process optimization (Jeraal, et al. 2021), among others. Specifically, Pinch point analysis, also known as energy integration, is an important concept in chemical engineering instruction. The Pinch method is a systematic approach to designing processes, which incorporates techniques to maximize energy efficiency and minimize energy consumption for utilities in a chemical plant.

2. Description of the educational innovation

In this project, graphical user interfaces were created using MATLAB GUI (Graphical User Interface). These MATLAB interfaces or APPS are stand-alone programs that allow the automatization of a task or calculation. Typically, these interfaces include controls such as buttons, toolbars, and sliders. The graphical interface that was created is shown in Figure 1. The elements present in the graphical interface are:

a) A diagram of an industrial chemical process. In this process stream 1 must be heated from 20 to 135°C to be fed to still T1. The distilled product (stream 3) leaves T1 at 80°C and must be heated to 140°C to be fed to still T2. The bottom stream of T2 (stream 2) leaves the equipment at 170°C and must be cooled to 60°C. Finally, the bottom stream of T1 (stream 4) must be cooled from 150 to 30°C. All these heating and cooling processes are carried out in heat exchangers that use external services: cooling water to cool the hot streams and steam to heat the cold streams. These services represent operation costs and contribute to the emission of greenhouse gases.

b) A table with the characteristics of the hot streams (which require cooling) and cold streams (which require heating) in the process. This table specifies the inlet and outlet temperatures for each stream, as well as the amount of heat (Q) that must be added or removed from each stream and the product of the mass flow and the specific heat capacity for each stream.

c) A composite curve that relates the temperatures of the hot and cold streams to the amount of heat exchanged by the streams. As can be seen in Figure 1, the curve of the hot currents has higher temperatures than the curve of the cold currents, in such a way that there can be a flow of heat between both currents. The minimum temperature difference between the curve of hot and cold currents (ΔTmin) is a very relevant parameter for the design of the energy integration network. In the graphical interface, this composite curve has a slider bar that allows the student to define the value that the ΔTmin parameter will have in his energy integration network proposal. Figure 1 shows the composite curve for ΔTmin = 15°C. The effect of ΔTmin on the design of the heat exchangers surface area is inverse, decreasing ΔTmin would increase the surface area of the heat exchanges and consequently the capital cost of the project.

The educational innovation was implemented in the IQ2017 Chemical Process Design course, which is offered during the fifth semester of the Chemical Engineer program (Tec21) at Tecnologico de Monterrey, a private university located in Monterrey, Mexico. The experimental design consisted of a classical experiment with a control group and an experimental group. The population of the control group was 38 students, while the experimental group was 33 students. The variables of interest were "academic performance" and "motivation".

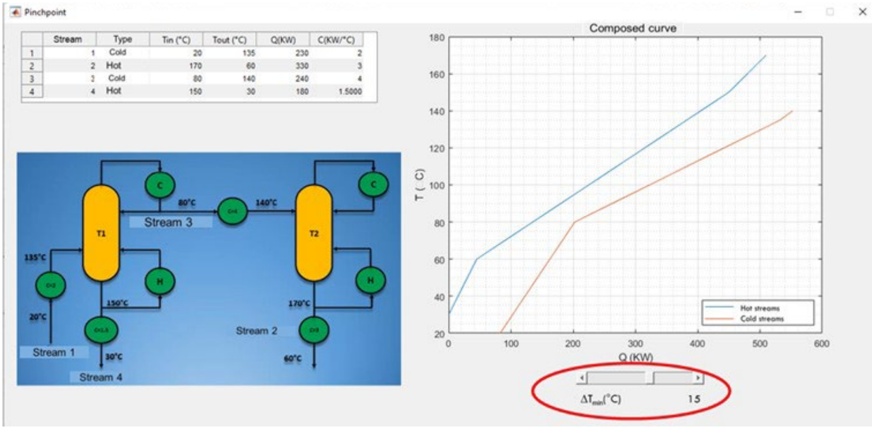

Figure 1. Graphical interface created for the interactive simulation as part of the learning activity in the Chemical Process Design course.

The measurement instrument for "academic performance" was a rubric and to measure the variable "motivation" the MUSIC inventory of academic motivation was used. The MUSIC model of motivation was developed by Dr. Brett D. Jones as a research-based model to explain the relationships between factors that affect people's motivation to participate in activities, such as courses and class assignments (Jones, 2009). The instrument developed for this measurement is composed of 26 items divided into 5 sub-scales: empowerment, usefulness, success, interest, and care. Each item has 6 response options. The English version has been used and validated in terms of reliability by various studies. For example, a publication by Chittum et al. (2019) on 552 college students demonstrated Cronbach’s alpha of 0.85. In a recent study, Bendicho et al. (2018) found that the instrument has a Cronbach's alpha of 0.79 (teacher as instructor) or 0.94 (when another student was used as instructor). Jones (2009) found a Cronbach's alpha of 0.92 in a sample of 201 Spanish-speaking university students.

A scoring rubric was used as an instrument for assessing the students’ achievement of their academic performance. The rubric assessed 6 performance indicators of the learning outcomes: a) Strategy, b) Tools used, c) Analysis, d) Synthesis, e) Solution approach, and f) Report.

Responses were quantified through a Likert-type summated scale, designed to assess students´ demonstration of the competency key actions (0= unacceptable, 1=marginal, 2= acceptable, 3= very good). Validation of the instrument for assessing the students’ achievements was carried out using the technique of expert judgement, which allows identifying inconsistencies in terms of sufficiency, clarity, coherence, and relevance. A total score was calculated with the sum of the assessment ratings of the six performance indicators of the learning outcome.

The learning activity was planned to take place during a two-hour session. Before the session, the professor uploaded the link to the CANVAS platform of the course "Design of chemical processes" to access the description of the activity and complementary information. During the session, the students were divided into small groups, discussed the activity, and clarified doubts with their teacher. Subsequently, they solved the problem presented in the activity and uploaded the result of their work to the CANVAS platform. The purpose of the learning activity is to learn how to use the methodology known as “pinch point” to create an energy integration network in a chemical process. Through a systematic procedure, the network is defined in which the hot streams of the process can be in contact with the cold streams in such a way that the consumption of external services (steam and cooling water) is minimized. Specifically, the learning activity seeks that students evaluate the effect of the minimum temperature difference (ΔT_{min}) on the consumption of external services, and on the cost of the energy integration network. The control group used the traditional approach, where they solve all the system mathematical equations that model the heating phenomena, including heat and mass balances as well as heat transfer equations for each heat exchanger. The experimental group used the PhET app described above.

3. Results and discussion

The MUSIC inventory of academic motivations was used to measure the “motivation” of the students in the learning activity. Each of the 26 items on the instrument has 6 response options, on a scale of 1 to 6, where 1 represents “strongly disagree” and 6 represents “strongly agree”. Student responses were used to calculate motivation on each of the model's 5 subscales: empowerment, usefulness, success, interest, and caring. The statistical analysis of the results was carried out with Minitab version 21, using the non-parametric Mann-Withney test. The p-value < 0.05 was used as a criterion to differentiate results that are statistically significant.

Table 1 and Table 2 show the results of the Mann-Whitney test for the experimental group and the control group. As can be seen, the results indicate that the Interest of the students in the learning activity and their expectations of Usefulness are statistically higher when the interactive simulation tools were used. As can be observed in Table 1, the p-value for the Usefulness category is 0.04, lower than the criterion established for statistical significance (0.05). Also, in Table 2, the p-value for the Interest category is 0.013, considerably lower than the p-value of 0.05. These findings support the idea that the use of this digital education technology has a relevant impact on the motivation of the students.

Table 1. Results of the Mann-Whitney test for the variable "motivation" using the MUSIC model, for the eMpowerment, Usefulness and Success categories.

Group	Samples	eMpowerment		Usefulness		Success	
		Median	p-value	Median	p-value	Median	p-value
Experimental	27	4.6	0.395	5.4	0.040	5.0	0.185
Control	36	4.5		4.9		4.75	

Table 2. Results of the Mann-Whitney test for the variable "motivation" using the MUSIC model, for the Interest and Care categories.

Group	Samples	Interest		Care	
		Median	p-value	Median	p-value
Experimental	27	5.1	0.013	6	0.264
Control	36	4.7		6	

As shown in Figure 2, the 95% confidence intervals for the average academic performance measured in the PhET group do not overlap with the confidence interval for the traditional group measurements, which means that the null hypothesis: "there are differences between the results obtained by the two different learning processes", is accepted. The results obtained by the students in the experimental group are better than the results obtained by the control group.

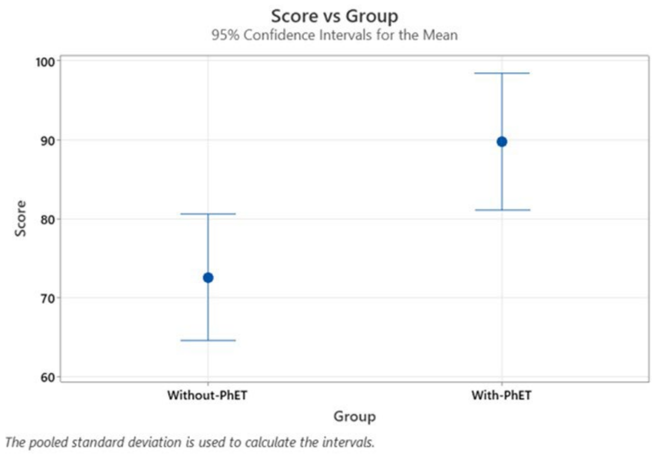

Figure 2. Comparison of the average score of students in the learning activity with PhET and without PhET.

The interactive graphical interface allowed the students to visualize more clearly the effect of the minimum temperature difference ($\Delta Tmin$) on relevant process variables such as the consumption of external services and the temperature differences between hot and cold currents in the different sections of the diagram.

In this project, an interactive simulation digital tool was developed to be used in the design of a heat exchange network proposal that contributes to the efficient use of energy in chemical processes. The digital tool allowed evaluating the effect that some important variables of the network design have on the cost of the energy integration proposal. The variables of motivation and academic performance of the students were evaluated. It was observed that collaborative learning activities with interactive simulators (PhET) are more Interesting and have higher expectations of Usefulness than activities that do not use this digital tool. This improvement in student motivation can be considered as a strength of the project. The difference between the experimental group (with PhET) and the control group (without PhET) was statistically significant at the 95% confidence level. The students in the experimental group that used the PhET tool obtained a higher academic performance than the students in the control group. The students in the experimental group had more time to analyze the effect of the change in the relevant variables of the design of the heat exchanger network than the students in the control group. The latter required a considerable amount of time solving the system of mathematical equations and less time analyzing the entire system. Furthermore, the control group was subjected to miscalculations that could mislead the conclusion. Overall, this work contributes to the continuous improvement process of engineering courses and can be replicated in other schools. In a second phase of implementation, an increase in the number of interactive simulators will be sought to build a virtual laboratory that contributes to the digital transformation of engineering education.

4. Conclusions

This work contributed by providing more insight into the interest of the students in learning activities and their expectations of usefulness, which were statistically higher when the interactive simulation tools were used. The results supports the idea that the use of digital educational technology significantly improved the learning process.

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