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Impact of Jupyter Notebook as a tool to enhance the learning process in chemical engineering modules

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ABSTRACT

Jupyter Notebook (JN) is an example of an innovative and efficient digital tool that can be used effectively in higher education. In this work, a set of JNs was developed and implemented in the module "Chemical Processes" of the Master's in Industrial Engineering at Universidad Politécnica de Madrid (Spain) to strengthen key Chemical Engineering concepts and enhance the learning process of students. Specifically, five interactive JN activities related to mass balances, reactor design, and separation operations (i.e., distillation, absorption, and extraction) were created, including a set of self-assessment tests to measure the effect of this tool on the knowledge and understanding of students. In addition, the final grades obtained by the students were used to evaluate the impact of the interactive activities proposed in the learning process. Finally, the opinions of the students were collected through an anonymous questionnaire containing closed and open questions. The results obtained are discussed in terms of numerical indicators and student feedback to assess overall performance and engagement. In summary, this innovative teaching approach based on JN was considered a successful initiative to promote student motivation and learning experience in Chemical Engineering-related modules.

1. Introduction

The continuous development of new technologies and digital tools has led to a drastic change in the teaching-learning process, where books and conventional didactic materials, on paper or PDF, have been gradually transformed into much more interactive materials, using the advantages of the Internet (Lorandi Medina et al., 2020).

Nowadays, numerous digital tools and software packages are available, both commercial and open-source; hence, educators need to select the most suitable ones to be used in their modules. In this way, four relevant factors were proposed to evaluate a tool: availability, ease of use, scalability, and learning objectives (Inguva et al., 2021). Many of these digital tools and technologies have been embedded in chemical engineering education in the last years, ranging from coding programs to game-based application or augmented/virtual reality (Bhute et al., 2021; Bodnar et al., 2021; da Silva Júnior et al., 2021; Inguva et al., 2021; Kumar et al., 2021). Inguva et al., 2021; Kumar et al., 2021). An interesting example of a digital tool for innovative teaching is the so-called Jupyter Notebook (JN), which can be defined as an interactive framework that contains text, equations, interactive graphs, and video. It is an open-source web-based environment for interactive computing that can handle various computer languages, such as Python, R, LaTeX, Javascript and many others. It allows including theoretical explanations, computer codes, simulation results and plots in a single file, leading to a workspace where students can learn the concepts through watching and playing, even if they are not familiar with programming languages. Moreover, this is a practical tool for instructors to monitor the progress of the students, as information is gathered in a single network document (Golman, 2016; Suárez et al., 2018). Another important feature of JN is that students can access and edit the code, unlike other commercial tools that present an interface that does not allow viewing and editing the mathematical models, becoming "black boxes" (Henrique et al., 2018; Sawaki et al., 2020). The JN can be used online but also offline if desired (Boukouvala et al., 2020), and they can be easily shared with other users by email, through a cloud storage service (e.g., Dropbox or Google Drive), by an Internet hosting service for software development such as GitHub™, or using directly the Jupyter Notebook Viewer ("Project Jupyter | Home," n.d.).

In recent years, the use of JN has increased considerably due to their simplicity, active support community, and the availability of numerical and plotting libraries, being widely used for teaching purposes, especially in higher education (Zúñiga-López and Avilés-Cruz, 2020).

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Science, Technology, Engineering, and Mathematics, also known as STEM disciplines, are areas where JNs are widely used in last years (Cañas et al., 2020; Cardoso et al., 2019; Gajdos et al., 2022; Ochkov et al., 2022; Suárez-García et al., 2021). In fact, millions of notebooks are available on GitHub ™ covering different fields of technology and science ("Jupyter Notebook Viewer," n.d.), and a growing network of professors develop and implement these tools in higher education (Menke, 2020; Ruiz-Sarmiento et al., 2021; Tang, 2021; Zúñiga-López and Avilés-Cruz, 2020). Zúñiga-López and Avilés-Cruz, 2020).

In the Chemical Engineering field, several case studies concerning the use of JN as an educational tool have been published in the last years. Usually, these works include a general description of the developed JNs, their application in a specific course or subject, and a feedback section in which the opinions of the students are analyzed and discussed. Some examples are given as follows. In 2016, Golman published an educational module using the IPython software package (former name of JN) for the application of transient response method to the kinetic analysis of multipath reactions; with such tool, students were able to perform the simulation and analyze the results by visualizing the response for various parameters (Golman, 2016). The pedagogical effectiveness of this teaching approach was evaluated through an anonymous questionnaire, with results showing student satisfaction. Two years later, the same author published a new set of JNs for the analysis of transport phenomena and reactions in porous catalyst pellets (Golman, 2019). In this case, students were able to explore a large variety of reactions and analyze the effect of operational conditions and model parameters from concentration and temperature distributions in the porous pellets. The student feedback was very positive, highlighting the effectiveness of the tool in providing a better understanding of the theoretical concepts in chemical reaction engineering.

Recently, another educational approach, named REAJA, was developed for simulating three ideal reactors (continuous stirred-tank reactor, plug flow reactor, and batch reactor) under various conditions, such as isothermal, adiabatic, and with heat exchange (Sawaki et al., 2020). The software was based on the Python programming language using JN to support mathematical modeling. It was implemented in two different courses (minicourse and optional undergraduate course), and its usefulness was validated from an online questionnaire, with results confirming the success of this resource as a complement to the subject. The same year, another study (Boukouvala et al., 2020) also reported five case studies for the use of JN in the Chemical Engineering curriculum at several institutions. Specifically, the authors described how the notebooks were implemented at different instructional levels (undergraduate, junior, etc.) and several courses (e.g., optimization, chemical reactors, process control), as well as the impact on students and instructors. These authors concluded that computational notebooks are powerful and versatile tools for improving the students' understanding of physical, chemical, and biological phenomena that chemical engineers apply daily. Moreover, some students also highlighted that "the use of JNs is by itself a skill that can be beneficial in other aspects of their careers".

Based on JN, Domínguez et al. (2021) have recently published a paper containing several problem generators and lecturing tools for standard exercises in chemical engineering (or other related BSc/MSc degree programs). The main advantage of these problem generators is that they provide an "unlimited" number of exercises (with certain restrictions) to practice with different numerical values. In this article, the problem generators are classified into three types (fixed problem, case-based, and random problem generators) according to the unknown variables in each exercise. Considering this tool as a starting point, additional lecturing materials have also been designed for teaching support and e-learning. As in the above-mentioned articles, an anonymous questionnaire was also used to evaluate student feedback, concluding that these new resources are helpful and reduce the studying time.

While the use of Jupyter Notebook in Chemical Engineering is not new, in many cases the modules available in repositories are mostly demonstrations, examples and lecture notes. Conversely, the high level of interactivity offered by tools produced in the present work is novel, in comparison with similar resources, offering the user the ability to manipulate different parameters and get immediate feedback on the results of the simulation. In this way, experimentation by the students is promoted.

It is important to highlight that a major challenge identified in the module where the proposed JNs activities were implemented was the fact that most students do not have a Chemical Engineering background, as they come from a variety of undergraduate engineering programs (e.g., electrical, mechanical, or industrial organization engineering, among others). Therefore, JNs were introduced as an interactive tool for the students to learn the basics of chemical engineering unit operations and understand their impact in a chemical process context. It should be noted that this tool can be operated at a user level with no previous knowledge of programming; however, if desired, it is also possible for the students to open the codes and interface with them, learning at a deeper level. Therefore, the learning approach proposed herein can be used as a flexible and versatile teaching methodology to enhance understanding and knowledge at different levels depending on the student background, while promoting motivation and engaging through the module.

The aim of the present work is to develop new teaching materials based on JN to enhance the learning process in Chemical Engineering modules. Specifically, in this work, five interactive activities based on JNs related to unit operations were implemented in the module "Chemical Processes" of the Master's in Industrial Engineering at Universidad Politécnica de Madrid (Spain). Herein, a general description of the computational methodology followed and the JN activities created is provided. Afterwards, different indicators to assess the impact of this tool on the students' learning are presented and discussed. In particular, a collection of tests related to each JN was provided for the students to complete before and after the interactive activities. Moreover, the final grades obtained by the students were used to evaluate the effect of such JN activities on the learning process. Finally, feedback from students was collected through an anonymous questionnaire. Overall, the results obtained, both in terms of numerical indicators and student feedback, were very encouraging, demonstrating the effectiveness of using software applications to enhance learning chemical engineering concepts.

After the general context provided above, the manuscript is organized as follows: Section 2 "Materials and Methods" presents the set of JNs developed to create five interactive activities related to mass balances, reactor design, and separation operations (i.e., distillation, absorption, and extraction) as well as the evaluation methodology followed in this work. In particular, Subsection 2.1. details the general computational methodology used to create the JNs, Subsection 2.2 provides a description of the various interactive activities created, and Subsection 2.3. presents the anonymous questionnaire prepared to collect student feedback. Section 3. "Results and Discussion" details the number of students participating in each activity, analyzes the marks obtained by the students in each test and their correlation to the performance in the final exam, and evaluates the student feedback. Finally, Section 4. "Conclusions" highlights the main findings along the main challenges and opportunities.

2. Materials and methods

The set of JNs developed in this work was implemented in the module "Chemical Processes" delivered in the Master's in Industrial Engineering. Each year, around 300 students enroll in this module with a diverse engineering background (electronic, mechanical, industrial organization, etc.); however, it is worth highlighting that few students have prior knowledge of Chemical Engineering, which means that their understanding of concepts related to chemical reactors and unit operations is limited. Therefore, the proposed approach can be regarded as a

valuable tool to ease the learning process of students and strengthen basic concepts in the Chemical Engineering field.

For that purpose, five interactive activities based on JN related to mass balances, reactor design, and separation operations (i.e., distillation, absorption, and extraction) were created and implemented in the module. In all cases, the main theoretical concepts are first reviewed and included in the JN, and then practical interactive examples are proposed. A PDF document with instructions for accessing JupyterHub (server where JBs are hosted) was also provided to the students. To promote student motivation and engagement, an extra credit was awarded upon completion of the interactive activities to those students who passed the final exam (minimum of 5/10). To evaluate the learning progress of the students, specific tests related to each JN were created for the students to answer before and after completing each interactive activity (see Tables S1-S4, available as Supplementary Material). In addition, the grades obtained in the final exam by those students who completed the JN-related tests were compared with those obtained by students who did not complete the interactive activities. Moreover, an anonymous questionnaire was provided after completing the five JNs to assess student satisfaction regarding the new learning approach implemented.

In subsequent sections, the general computational procedure used to create the JNs, and a brief description of them, including their main objectives and structures, are provided.

2.1. Computational methodology

Chemical engineering problems related to balances, reactors, or unit operations can be solved using analytic mathematical tools, numerical solvers, or graphical diagrams. Python provides tools to allow using any one of these three approaches, via libraries such as *SymPy* (Meurer et al., 2017), *SciPy* (Virtanen et al., 2020), *NumPy* (Harris et al., 2020), or *matplotlib* (Hunter, 2007), which have been used intensively in this work. The activities developed in this work are not designed to teach programming, and as such, students are exposed to minimal Python code. Thus, each interactive activity consists of a JN, which contains text and equations explaining all the theoretical concepts, and a companion Python code file that implements the mathematical and graphical methods, and provides the solutions, which are again shown in the JN. Students do not need to inspect the content of the Python code to complete the activity. This approach allows the students to focus more on the physico-chemical principles that govern chemical engineering operations and not on the computational algorithms used to solve each problem. However, the same activities could also be used in a more advanced chemical engineering or programming course, but this time focusing on the algorithms and methods rather than on the principles.

The structure of all the JNs is very similar. Each JN contains an introductory section with a general description of the activity and instructions on how to explore and interact with the page. Then, a series of exercises of increasing complexity follows, each one containing interactive controls, such as buttons, sliders, and dropdown lists (implemented with the help of the *ipywidgets* library ("Jupyter Widgets — Jupyter Widgets 8.0.2 documentation," n.d.), which allow students to explore different aspects of several chemical engineering processes by selecting different chemical substances, or specifying different flow rates, temperatures, or compositions. Each time the value of an interactive element is changed, the corresponding Python code is invoked, and the solution is shown in the JN. Depending on the complexity of the problem, the response time can range from milliseconds to a few seconds, which gives the student the impression that he or she is controlling the chemical process in real time. A link to access the developed JNs is provided in the Software availability section.

2.2. Jupyter notebook description

In this section, a brief description of the five created JNs is presented. Each activity has an associated test, which is included in the Supplementary Material (Tables S1-S4).

2.2.1. Mass balance

This JN contains two simple examples related to mass balance with chemical reaction. Firstly, the concepts of conversion, extent of reaction, selectivity, and yield are practiced through a set of two parallel reactions (A→2B; A→C), where A is the limiting reactant and B is the desired product. The molar feed can be modified introducing either pure A or mixtures of the different compounds (including D as inert) to analyze its effect on the studied parameters.

Subsequently, a chemical process for methanol production from CO and H_2, presenting reaction and separation steps with recycle and purge, is simulated to evaluate the effect of purge flow rate (mol/h) on different variables such as global conversion (%), reactor inlet flow rate (mol/h), and CO content at reactor inlet (%) (see Fig. 1). The students can change the flow rate of the purge stream and observe how all the other streams are affected. The feed flow rate is 100 mol/h, and the purge flow rate can be modified between 2.60 and 82.40 mol/h.

2.2.2. Reactor design

In this interactive exercise, Levenspiel plots are employed to select the best ideal reactors association (Continuous Stirred Tank Reactor, CSTR, and Plug Flow Reactor, PFR) to minimize the total volume, for a target yield, through a simple A→B reaction. The activity enables the user to represent seven different kinetic laws in terms of velocity, r_A, and conversion, X_A, where the values of the kinetic constants can also be modified. Firstly, the dependence of velocity (r_A or $1/r_A$) with conversion can be employed to analyze the different shape plots and the effect of the kinetic constant value on them. Then, Levenspiel plots for associations of up to three reactors can be explored for calculating the total volume by selecting the reactor type (CSTR or PFR), the desired conversion for each reactor, the kinetic law, and the kinetic constant (see Fig. 2). To simplify the problem, feed flow rate (F_{A0}, in mol/h), volumetric flow rate (in L/h) and initial A concentration (C_{A0}, in mol/L) were considered equal to unity. The kinetic constant and conversion can be varied between 0.1 and 5 and 0.01–0.99, respectively.

2.2.3. Distillation

In this activity, basic concepts related to vapor pressure, pure substance volatility (i.e., Antoine equation) and ideal binary mixtures (i.e., Raoult's law) are first reviewed. Next, these concepts are applied to solve two illustrative distillation problems involving flash distillation and fractional distillation.

In the case of flash distillation, the shapes of *T-xy* (temperature – liquid composition – vapor composition) diagrams are explored for a variety of ideal mixtures that can be selected by the students (including compounds such as acetone, acetonitrile, acetic acid, water, ethanol, phenol, or isopropyl alcohol) as a function of the column operating pressure and mixture characteristics. Specifically, the parameters that can be modified are the following: feed molar fraction, x_F (between 0.05 and 0.95), feed temperature, T_F (between 0 and 200 °C), operating pressure, p (between 0.1 and 5 atm), and feed flow rate, F (between 1 and 100 mol/s). By varying these parameters, students can observe the phases present in the selected system.

As for fractional distillation, *x-y* (liquid composition – vapor composition) diagrams can also be plotted for binary mixtures of the compounds mentioned above as a function of the column operating pressure, which can be varied from 0.1 to 5 atm. Then, McCabe-Thiele method is introduced as a simple, intuitive, and instructive graphical method for column design; the basic steps for graphical construction, including equilibrium curve, construction lines, feed location, number of stages and reflux ratio are explained. Afterwards, once the students have understood the effect of the different variables and specifications on fractional distillation problem solving, the McCabe-Thiele method is practiced through an interactive example as illustrated in Fig. 3. Such

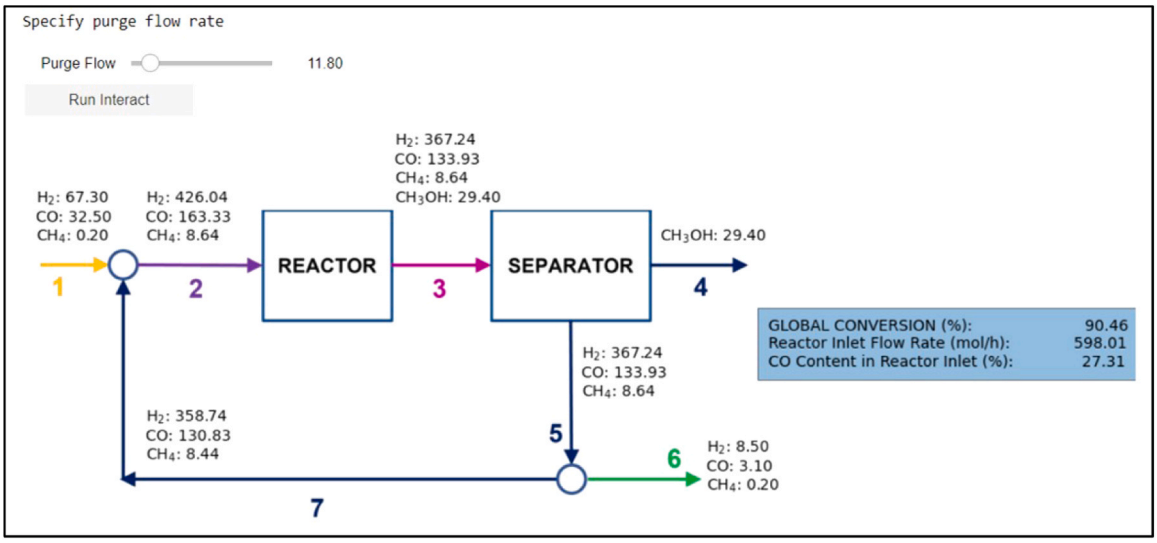

Fig. 1. Snapshots of the Jupyter notebook for exploring the mass balance in a process with recycle and purge.

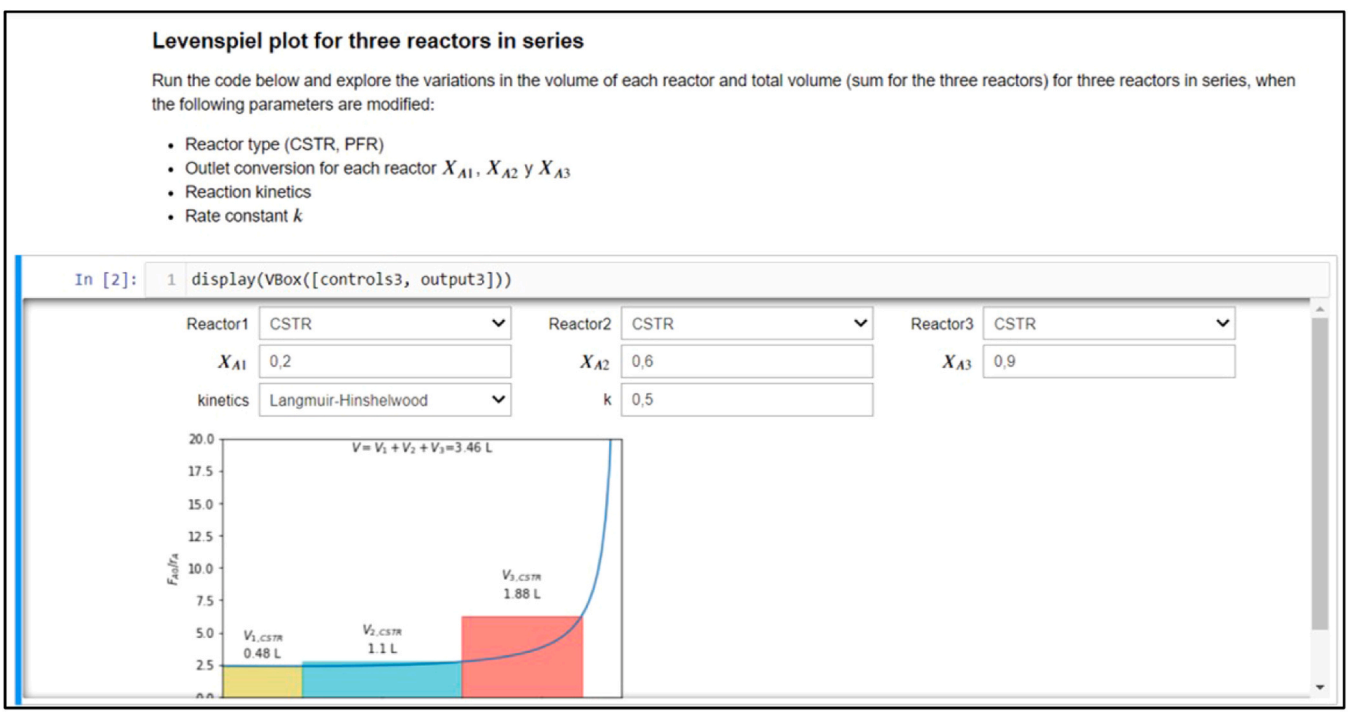

Fig. 2. Snapshots of the Jupyter notebook for exploring the Levenspiel plot model for the study of serial reactors.

activity allows the user to explore the effect of the different distillation parameters on the number of stages. To do so, students should select the compounds that constitute the binary mixture to be separated, feed composition specifications, external reflux ratio, feed temperature and column pressure, to analyze how these variables determine the distillation column design in terms of minimum reflux ratio and number of stages. In this case, students can change the following parameters: feed molar fraction, x_F (between 0.1 and 0.9), distillate molar fraction, x_D (between 0.51 and 0.99), bottom molar fraction, x_B (between 0.01 and 0.49), feed temperature, T_F (between 30 and 300 °C), operating pressure, p (between 0.1 and 5 atm), and external reflux ratio, R_{ext} (between 0.1 and 5), and the number of trays (up to 50). A McCabe-Thiele plot is shown with the solution to the distillation up to the selected tray, and diagrams are shown detailing the composition and position of the selected equilibrium plate in the column, as can be seen in Fig. 3. Also, a schematic diagram of the column is shown, depicting the number of trays, the selected tray, and the position of the feed, which divides the column in enriching (top) and stripping (bottom) sections.

2.2.4. Gas-liquid absorption

In this activity, a review of basic concepts related to gas solubility in liquids, including Henry's law and Van't Hoff equation, is firstly provided. In addition, the concept of molar ratio is introduced, and the procedure to build the solubility curve and express mass balances in terms of such molar ratios is explained. Afterwards, this information is applied to solve problems involving the design of columns to absorb gases in liquids.

To do so, the graphical method for absorption column design based

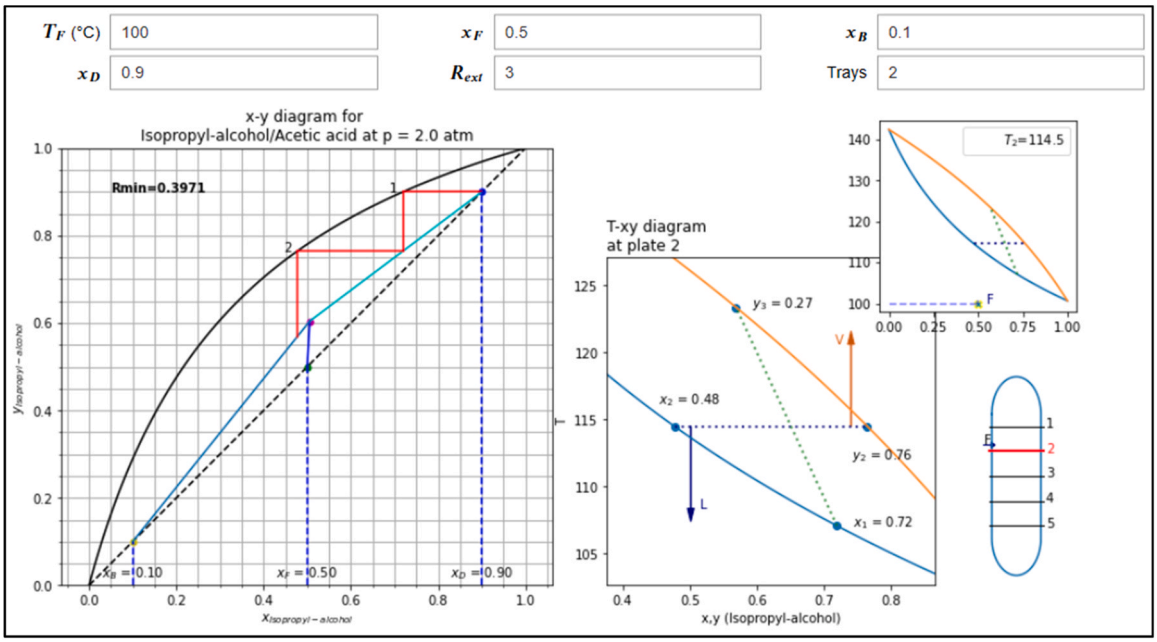

Fig. 3. Snapshots of the Jupyter notebook for exploring the fractional distillation of an ideal binary mixture.

on the equilibrium curve and different construction lines is illustrated step by step to determine the minimum and actual liquid/gas ratio (L′/G′, where the flow rates of the solvent and carrier gas are expressed in a solute-free basis), and the number of stages required for the absorption process. After explaining the effect of the different variables and specifications on absorption column design, this activity allows exploring how the different absorption parameters determine the number of stages required for the process, as shown in Fig. 4. In particular, students should select the gaseous compound (O_2, H_2, CO_2, N_2, He, Ne, Ar, CO) to be absorbed in water, the operating temperature and pressure in the column, specifications of the inlet and outlet gas streams (composition expressed as molar ratio), composition of the absorption solvent, and factor relating minimum and actual L′/G′, to analyze how these variables affect the number of stages needed for absorption. In this case, the following parameters can be modified: inlet molar ratio for gas, Y_L (between 0.05 and 0.2), outlet molar ratio for gas, Y_0 (between 0.001 and 0.05), inlet molar ratio for liquid, X_0 (between 0 and 0.00001), factor F by which the minimum slope will be multiplied (between 1.1 and 5.0), temperature, T (between 273.15 K and 373.15 K), and pressure, p (between 0.2 and 10 atm). Once these parameters are set, students can observe if operation is possible and under which conditions (number of steps, and actual and minimum liquid/gas ratio).

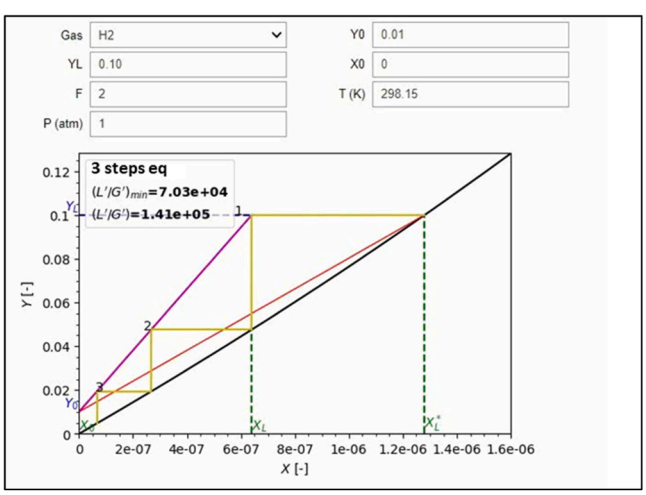

Fig. 4. Snapshots of the Jupyter notebook for exploring the absorption unit operation.

2.2.5. Liquid-liquid extraction

In this activity, basic concepts regarding the construction of ternary diagrams are reviewed, including explanations of the solubility curve, tie lines, and the lever rule to solve liquid-liquid extraction problems. Afterwards, this information is practiced through a graphical case study illustrated in Fig. 5, consisting of a single-stage extraction to separate a mixture of ethanoic acid in water using ethyl ethanoate as extraction solvent. In particular, the interactive exercise allows selecting the composition and the molar flow rate of the feed, F (in mol/s), and the molar flow rate of the extraction solvent, S (in mol/s), to explore the effect of these variables on the molar flow rates and compositions of the extract and raffinate streams. In this exercise, the molar flow rates of feed and extraction solvent can be modified from 10 to 300 mol/s. An

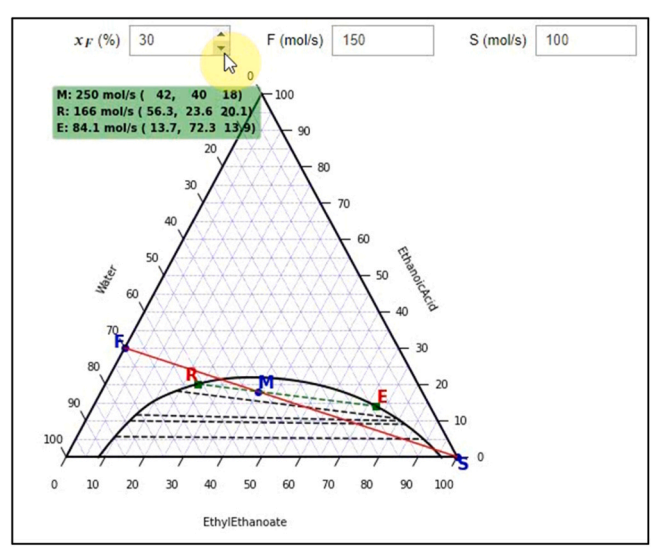

Fig. 5. Snapshots of the Jupyter notebook for exploring the liquid-liquid extraction operation.

alert is displayed if the selected parameters lead to a mixture point, M, located outside of the binodal curve, indicating that extraction is not possible.

2.3. Anonymous student feedback

Finally, an anonymous questionnaire was provided after completing the five JNs to assess student satisfaction with the new learning approach implemented. As can be seen in Table 1, the questionnaire consisted of six closed questions (measured between 1 - strongly disagree - and 5 - strongly agree -) and one open question for the students to give their honest opinion about the JN activities implemented in the module. The results obtained in this questionnaire, along with the tests and final grades, were used to discuss the effect of these activities on the performance and motivation of the students.

3. Results and discussion

The resources presented in this work have been implemented in the teaching of the "Chemical Processes" subject, part of the Master's in Industrial Engineering. Students were given the option to voluntarily choose whether to participate or not in the interactive activities. To promote student participation in the interactive activities and to avoid any sampling bias, we used the test as a continuous evaluation tool; specifically, the students were able to increase their final grades by simply participating in the proposed JNs, regardless of their overall score in these activities. Therefore, this could help to work with a representative population of students. To evaluate the impact of these activities on the learning process, the students who used them were asked to undergo a self-assessment test before and after each one of the activities (Test 1 and 2, respectively), and the marks obtained were analyzed. The questions for each activity are reported in Tables S1-S4, available as Supporting Material. The results for each interactive activity are shown in Fig. 6, as scatter plots of the marks obtained by each student in Test 2 as a function of the mark of the same student for Test 1. It should be noted that in these graphs, individual points may represent a varying number of students who have attained the same results; the histograms shown on the axes in each panel provide the distribution of marks corresponding to both tests. In addition, Table 2 indicates the number of students who participated in each one of the activities. As can be seen, the number of students completing the JNs tends to decrease as the course proceeds. This could be explained by the increasing content complexity and workload in their overall academic activities, that may limit their time availability to perform the tests.

Inspection of the plots in Fig. 6 reveals that most of the points are above the diagonal line, revealing that an overall improvement in the marks is achieved after completing each activity (scores in Test 2 are generally better). This is also observed in the distributions of marks: the horizontal histograms (Test 1) are usually broad distributions covering most of the scores, while the vertical histograms (Test 2) are clearly populated in the upper range of marks.

Interestingly, the number of points below the diagonal decreases with each successive activity. This trend might be ascribed to the decreasing number of students who participated in the activities, according to the numbers reported in Table 1. Being a non-mandatory activity, students that participate are likely to be more actively involved in the learning process, so these values may just reflect the degree of motivation of the alumni.

Table 1
Questionnaire to assess the activity.

Number	Question
Q1	The content of the proposed activities can be easily understood.
Q2	The way the contents are presented in the activities is attractive.
Q3	The activities helped me to understand the theoretical contents.
Q4	The activities help me to study for the exams.
Q5	Working with the activities, my interest in the module increases.
Q6	The time allotted for the activities was sufficient.

To get a better insight on these results, the last panel in Fig. 6 displays the average values of the learning ratio, defined as the ratio between the scores obtained by each student in Tests 2 and 1 respectively. The standard deviation is also shown (due to the large dispersion in the results, the deviation in the plot is divided by half for the sake of visual clarity). For the five activities, the average learning ratio is above 1 (above 1.5 in three of them), again indicating an overall improvement in the results of the students after using the interactive resources. This demonstrates that the activities induced some immediate learning in the students, since they managed to better understand and answer the questions related to each activity after doing the activity, with respect to the understanding that they had prior to the activity.

Apart from the immediate learning acquired by the students after doing the activity (as shown in Fig. 7), it is interesting to investigate how the JN activities impacted on the performance of the students in the paper-based final exams, which is more related to the long-term learning acquired. To this end, we analyzed the score obtained on the exam questions directly related to each of the activities by the students who did each activity and compared them with the scores obtained by the students who did not do the activity (the number of students is reflected in Table 3).

The distributions of the exam marks are shown in Fig. 7, for the students who did (in color) and did not do (in white) each activity. First, it is important to visually notice how the fraction of low (high) marks is lower (higher) for students that did the activity. Also, it is possible to view how the marks distribution shifts to the right when the students worked on the JN activities, so that the mean score increases, and more students get better marks. To quantify both effects, in (Fig. 7.f) the skewness of the distribution is plotted as a function of the mean. The skewness is a statistical measure of the asymmetry of a probability distribution with respect to its mean. It can be positive (for distributions shifted to the left of the mean, with tails on the right), zero (for a symmetric distribution, such as the normal), or negative (for distributions shifted to the right with respect to the mean, with tails on the left). Here, we use the Fisher-Pearson definition of skewness (Abramowitz and Stegun, 1972):

$$\text{skewness} = m_3/m_2^{(3/2)}$$

where m_i is the ith moment of the distribution, defined as:

$$m_i = \frac{1}{N}\sum_{n=1}^{N}(x_n - \bar{x})^i$$

In (Fig. 7.f) it can be observed how, for each one of the activity-related exam questions, the colored point, which describes the distribution of scores obtained by students who did the activity, is shifted to the right (better mean) and to the bottom of the plot (less skewness), with respect to the white point, which describes the distribution of scores obtained by students who did not work with the activity. A higher mean value is already an indicator that the students acquired some long-term learning after working with the JN activity. In addition, a smaller skewness indicates that the tail of the distribution is on the left of the mean, which is an indicator that overall, students significantly improved their understanding of the topics described in the JN activities by spending some time working with them.

Finally, to assess the pedagogical effect of the JNs, the students were asked to respond to an anonymous questionnaire about the activities (see Table 1), as well as to provide their opinion on them. Students were asked to respond using a 5-point Likert scale. The distribution of student answers is shown in Fig. 8. The feedback from the students was very positive, showing very strong satisfaction with respect to all practical aspects of the activities (Q1, Q2) as well as with respect to their own impression of how the activities helped them to understand the concepts, prepare for the exams, and increase their interest in the module

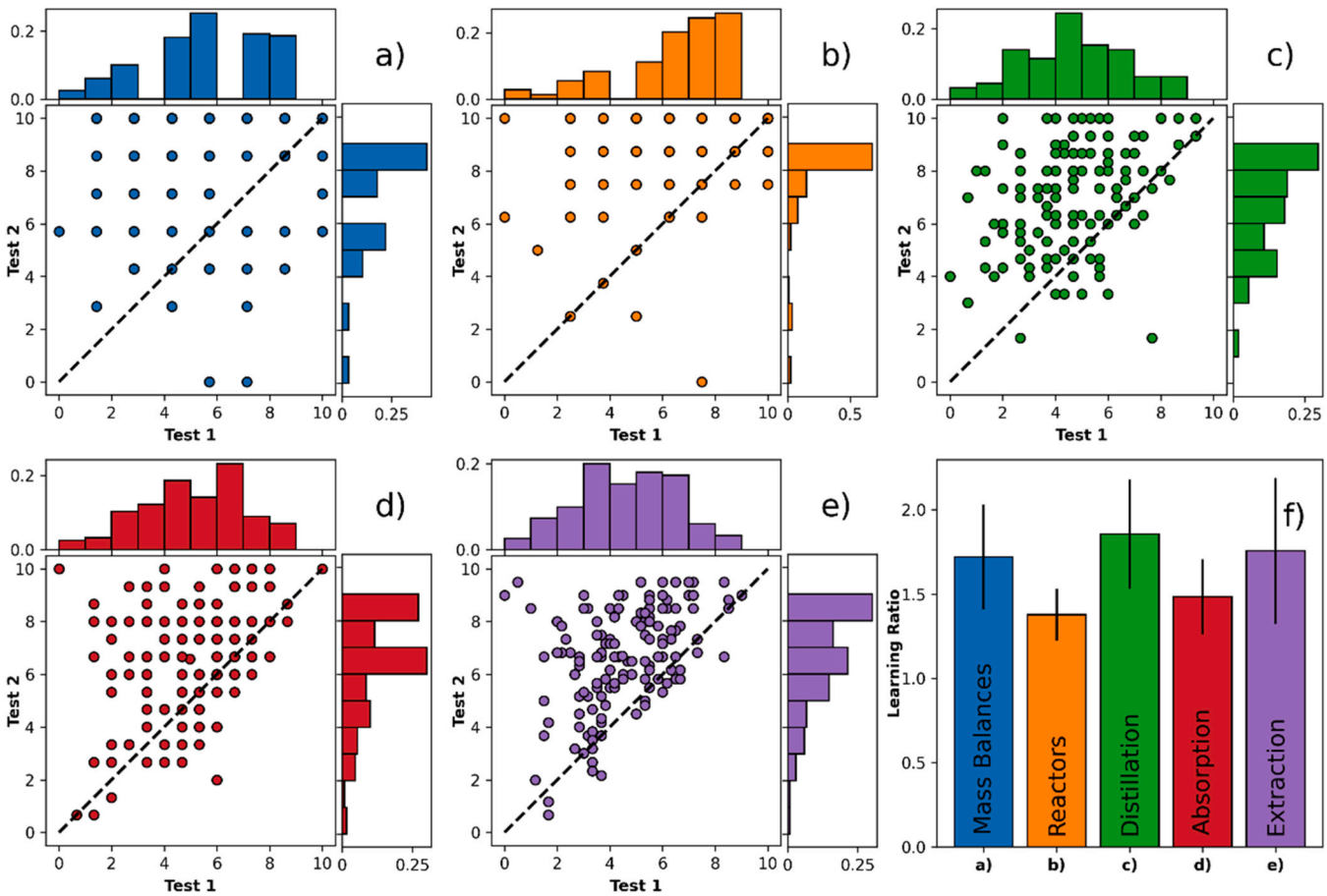

Fig. 6. Scatter plot of the marks obtained by individual students in Test 2 vs those obtained in Test 1, along with the distribution of marks in each of the tests, for all the activities developed in this work: a) mass balances (89.3% of students improved their score, and their corresponding dots are above the diagonal), b) reactors (95.2%), c) distillation (88.1%), d) absorption (80.7%), and e) liquid-liquid extraction (88.6%). In panel f), the mean and standard deviation of the learning ratio (see main text) obtained by each individual student are shown as colored bars and error bars, respectively.

Table 2
Number of students who participated in each of the proposed activities. The total number of students enrolled in the course was 298.

Activity	Participants
Mass Balances	216
Reactors	168
Distillation	137
Absorption	150
Extraction	146

(Q3-Q5). However, their feedback regarding the time required to complete the JN activities (Q6), although still very positive, was not so enthusiastic. There is a non-negligible fraction of students who believed that they spent too much time working with the JNs.

In addition, as expressed in the open comments section of the questionnaire (see Table 4), some students felt that the effort and time spent doing the activities was not reflected in their final marks in the module. Authors believe that this is the reason why the feedback about the time required to complete the activities (Q6) was not as positive compared to the feedback about other practical aspects (Q1-Q5).

Lastly, from the perspective of the instructors, it is worth mentioning that the experience has been very positive, as many students have improved their motivation and engagement with the module. Moreover, the students requested to have the possibility to access the JNs to prepare for the final exams, as they found them very useful to clarify key concepts. Therefore, the instructors were very satisfied with the overall educational experience and the student feedback.

4. Conclusions

In the present work, a set of different interactive JN modules have been developed and implemented in the teaching of the "Chemical Processes" course for students of the Master's in Industrial Engineering, covering topics on mass balances, chemical reactors, and separation operations. The impact of these tools on the learning process of individual students has been analyzed in terms of the results attained in both self-assessment tests and the final exam, as well as through the feedback provided in a questionnaire completed by students.

In general, the results of the analysis are very encouraging. Students not only improve their short-term knowledge and understanding of the topics, as shown by the value of the learning ratio, but they also significantly improve their marks in the final exam. These results suggest that the use of JN helps students to assimilate the contents of the module. Moreover, the feedback received from students has also been very positive. It is worth mentioning that JN not only appears as valuable tool to support autonomous learning but can also be used for interactive lecturing activities to promote student engagement and active participation during the classes.

It should be highlighted that a major challenge identified was the fact that most students do not have a Chemical Engineering background, as they come from different undergraduate engineering programs. Therefore, introducing JN as an interactive tool to learn the fundamentals about chemical engineering unit operations at their own pace is an

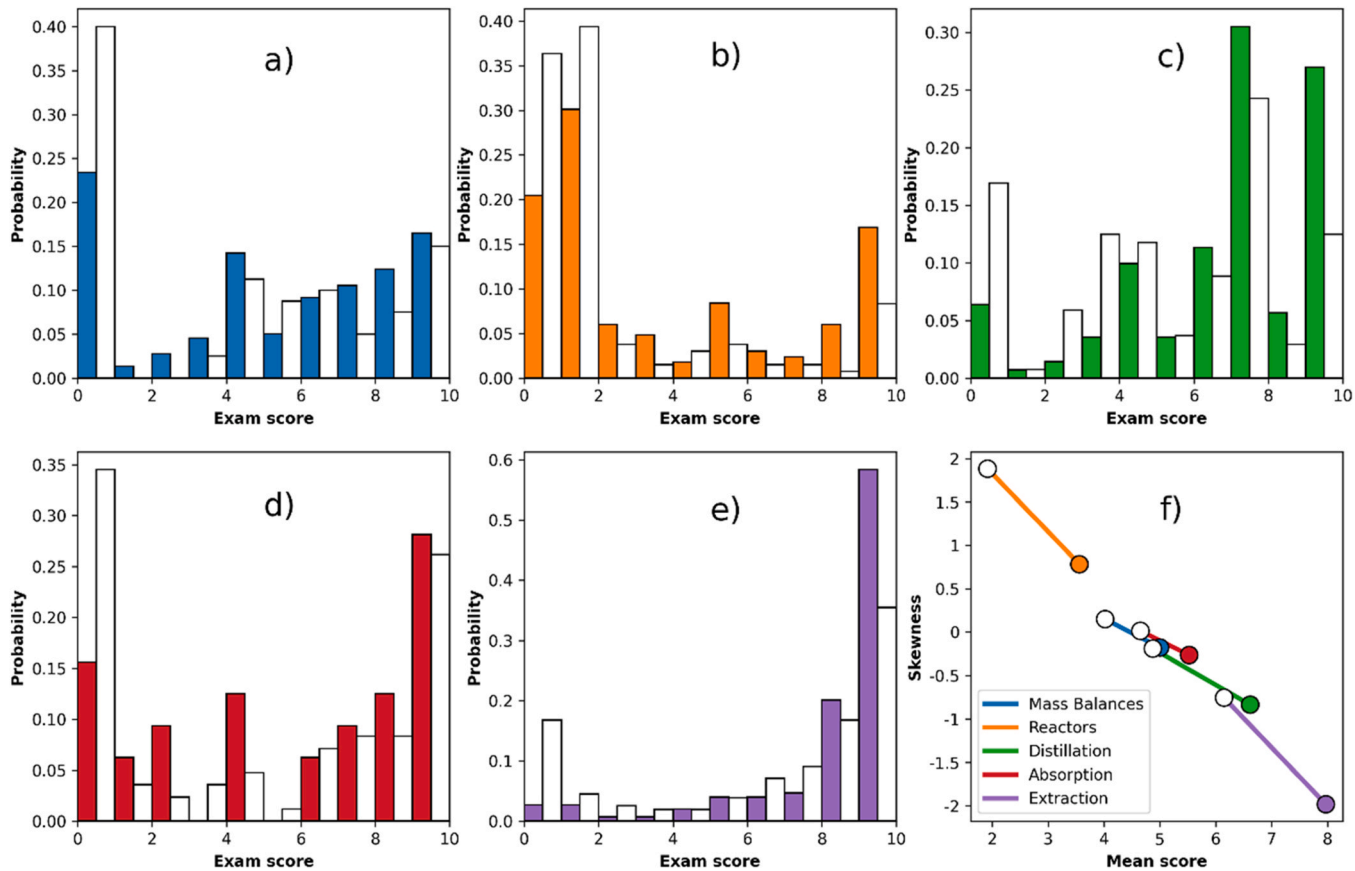

Fig. 7. Probability distributions of the scores obtained in the relevant question on the final exam by the students that did the activity (with color) and those that did not do the activity (grey color), for all the activities developed in this work: a) mass balances, b) reactors, c) distillation, d) absorption and e) liquid-liquid extraction. In panel f) the skewness versus the mean score is shown for all exam questions, taken from the distributions of scores of students that did the activity (with color) and those that did not do the activity (in white).

Table 3
Number of students who answered the questions related to each of the proposed activities and who had (or had not) participated previously in the activity. The total number of students in the course was 298.

Activity	Did the activity	Did not do the activity
Mass Balances	216	80
Reactors	168	128
Distillation	137	161
Absorption	150	148
Extraction	146	152

opportunity to engage students, and enhance their motivation and performance through the module. It should be noted that JNs are implemented to be operated at a user level, but the codes can also be opened by the users if desired. Thus, the teaching methodology proposed herein based on JNs entails a versatile approach to improve student learning in Chemical Engineering courses.

Software availability

The Jupyter Notebook and Python codes developed in this work can be accessed and downloaded from: https://github.com/jorge-ramirez-upm/PQ-Jupyter.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

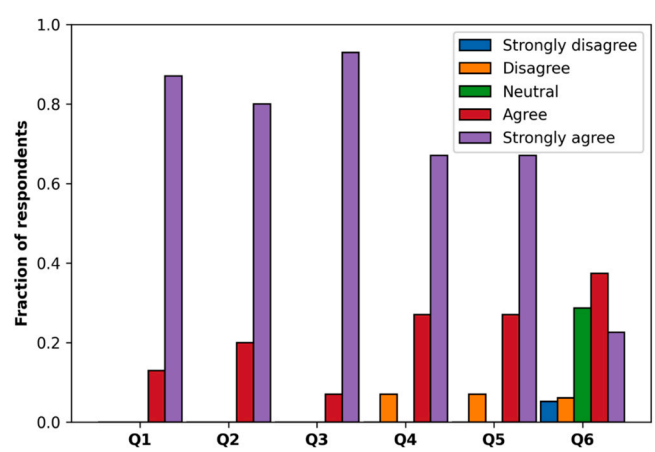

Fig. 8. Results of the student questionnaire about the Jupyter notebook activity. The colors reflect the level of agreement with each of the questions (see Table 1).

Table 4
Representative personal comments about the activity expressed by students.

They help to better understand the theoretical concepts of the module.
The module becomes clearer when you are allowed to play with an interactive tool.
It helps to clarify and expand some basic concepts.
It has helped me to keep up with the module on a daily basis.
It is a pity that they are not directly assessed and counted for the final mark.
It is possibly the best didactic resource I have ever used.

the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ece.2023.06.001.

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