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Study cases methodology in process dynamic and industrial plants control subject

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Abstract

Dynamic simulation has been incorporated into Chemical Engineering Master at the University of Castilla-La Mancha as a teaching tool together with working cases. Concretely, this study presents the activities, evaluating criteria and a set of case of studies performed by master students in the process dynamic and industrial plants control course. It is described in detail, the Aspen HYSYS® simulations carried out to study the influence of main tuning parameters of proportional, integral, and derivative controllers (gain, integral time, and derivative time) and other relevant parameters such dead-time, amplitude, or period of sine wave disturbances. The dynamic simulation helps the students to understand the previously mentioned concepts, analyzing their effect in the realistic behavior and control of simple processes. Finally, anonymous online surveys were conducted to evaluate the effectiveness of the proposed training activities and methodology. Students felt that Aspen HYSYS enhances the control theory understanding from a chemical engineering perceptive, eliminating the tediousness and time-consuming aspect of process calculation. Thus, this learning methodology promotes a successful achievement of learning outcomes.

KEYWORDS

dynamic analysis tool, master chemical engineering, process control tuning, sine wave disturbances, study cases

1 | INTRODUCTION

The development of chemical process simulators in the last years has been remarkable and lead to a widespread utilization of them both in the academia and industry, as nowadays they have become a very useful tool to understand and predict the behavior of chemical plants. In this way, the chemical engineering curricula usually include some subjects related to the use of these programs, as they can offer to chemical engineering students the opportunity to make fast and complex calculations and to apply to one problem the knowledge acquired in different subjects, giving a complete overview of the chemical engineering field. Nevertheless, it is important for the students to understand the limitation of this kind of applications, as they need assumptions, restrictions, and cannot always replace the manual calculations [7].

The Chemical Engineering department of the Castilla-La Mancha University has a long teaching experience in chemical process simulators, starting in 1999. Recently, we published a paper [3] reporting an analysis of the achievements of the project-based learning technique applied to the chemical process simulators in terms of competencies gained and the satisfaction of the students. Analyzing the marks obtained by the students and the results of the surveys conducted, it was concluded that the followed methodology allowed an important success in terms of learning progress. In addition, the student satisfaction with the subject was higher than average for the chemical engineering degree and average for the whole University.

This experience in the use of chemical process simulators has been applied to the course of the Chemical Engineering Master at the University of Castilla-La Mancha entitled “Process Dynamic and Industrial Plants Control” to improve the students' understanding of the control theory applied to chemical plants by the introduction to dynamic simulation.

Control theory is a fundamental part of the degree plan for chemical engineering. Many companies in the chemical industry field have separate control and instrumentation departments, where the chemical background of the engineers is low. It implies that they treat the chemical process as mere transfer functions making great assumptions. However, understanding the chemical engineering principles is necessary to assess the modeling error, which is a requirement in designing robust controllers [16]. The importance of the control theory in the chemical engineering curricula has been pointed out by several authors like Shinskey [14], who provided a detailed analysis of the discrepancies found in the field and what is being taught in academics; and G. Stephanopoulos [16], who also defended the importance of the control of the chemical process and its specificity compared with other engineering fields.

Practical work in laboratories is usually part of the control courses. They are useful but have some weak points, as they cannot provide fast controller response analysis because of the real-time constraint; it is not easy to modify the setups for different processes and it is not possible to reach extreme conditions to check the controller robustness [16]. Owing to the abovementioned issues, many graphical programming tools such as MATLAB® and LABVIEW® are being used for the virtualization of the control laboratory [5,11]. However, they also suffer some drawbacks related to the complexity of the programming, the lack of pre-programmed modules of chemical unit operations, and the predominant point of view of the electrical, electronic, and mechanical engineering in this kind of software.

An alternative to them is the use of chemical process simulators with the capability to deal with dynamic systems. In this sense, Aspen HYSYS® offers the possibility to work not only with steady-state simulations but also to perform dynamic simulations, where the application of control theory to different chemical modules can be evaluated [16]. Furthermore, statistical process charts can also be obtained from the simulation, which are used to diagnose and troubleshoot the processes [4] and are also a valuable tool for laboratory demonstration. The continuous increase in the capacity and power of computers has allowed the possibility to resolve complex problems in a very short time with conventional computers, making it easier to resolve dynamic simulation problems, what some years ago was very demanding. Dynamic simulations are extensively used to maintain standard operation and for SP tracking [2]. They can also predict the ultimate response of any system in the event of an emergency failure. As a result, the dynamic responses of real systems can be estimated and utilized for control applications. Dynamic simulation has now made significant inroads in both industrial and research area [8,12,18]. Despite its advantages, dynamic simulation is still much more demanding when compared with steady-state simulation. It requires some more parameters, which are usually optional in case of steady-state simulation, for the simulation of the transient conditions of the plant [19]. As it is well-mentioned in References [1,10,15], steady-state modeling and simulation in chemical process simulators environment are fairly common today, and despite its extensive use in the industry only little is known about the dynamic simulation in the open literature.

The present study reports the pedagogical methodology followed in the process dynamic and industrial plants control course of the Chemical Engineering Master of the University of Castilla-La Mancha related to the application of chemical process simulators to dynamic systems, concretely, the use of Aspen HYSYS simulation study cases. Furthermore, the evaluation of the feedback from the students concerning this learning methodology in the last three academic years has been evaluated.

2 | PROCESS DYNAMIC AND INDUSTRIAL PLANTS CONTROL COURSE DESCRIPTION

The process dynamic and industrial plants control is a mandatory six European Credit Transfer System (ECTS) credits course of the first semester of the Chemical Engineering (ChE) Master at the University of Castilla-La Mancha (UCLM, Spain). The students of the ChE Master at the UCLM must accredit to have the competencies corresponding to the ChE degree. Thus, they are already able to carry out conceptual design of industrial processes, to propose process control strategies and to work with commercial simulators like Aspen HYSYS for simulating steady-state processes.

2.1 | Motivation

As commented before, the normal operation of chemical processes is in dynamic regime, although stabilized or controlled around a constant average value for the main process variables, thanks to the application of different control strategies. Thus, a complete course related to the process dynamic and control of industrial plants is essential for the integral formation of any ChE Master.

In contrast, simulation programs can significantly facilitate the study of the dynamic behavior and process control in industrial plants and the optimization of procedures [17].

Therefore, half of the course program is dedicated to provide the students the ability to simulate industrial processes in dynamics state and to design the best control strategy with the commercial program Aspen HYSYS.

2.2 | Objectives or learning outcomes

The process dynamic and industrial plants control course complete the students' knowledge about process control and industrial plant simulation. The main objectives or learning outcomes of this subject are:

- To acquire the knowledge for the dynamic characterization of open- or closed-loop systems in time, Laplace and frequency domains.
- To be able to design the control, instrumentation, and automation of a chemical process.
- To handle the commercial program Aspen HYSYS for the dynamic simulation and control of complex industrial plants.

Other general learning outcomes that are expected to reach are knowledge and capacity of technical management and design of the main industrial facilities, processes, and systems in the field of ChE; ability to solve problems with initiative, decision-making, and creativity; ability to communicate and transmit knowledge and results; capacity for critical thinking and decision-making; capacity for the direction and organization of the activities object of the engineering projects; and ability to learn and improve their skills autonomously along their professional career.

2.3 | Covered topics

To achieve the previously mentioned objectives and learning outcomes, the topics covered by the process dynamic and industrial plants control subject are the following ones:

- Unit 1: Advanced dynamic of process. General concepts of time and Laplace domains. Frequency domain.
- Unit 2: Local control. Continuous or sequential control.
- Unit 3: Industrial plants control. Digital communications and distributed control architecture. SCADA systems. Model predictive control (MPC). Control architecture of real chemical plants. Control architecture of experimental systems for R+D+i studies.
- Unit 4: Dynamic simulation of chemical processes. Fundamentals. Simulation of processes regulated with PID controllers. Dead-time and gain effects. Study cases.
- Unit 5: Advance process control and controllers tuning in Aspen HYSYS simulators.
- Unit 6: Dynamic simulation of automatically controlled chemical processes. From individual units to global industrial processes. Study cases.

3 | IMPLEMENTATION AND IMPACT

3.1 | Methodology

The subject methodology has two main different blocks of practically the same weight. The first three units are developed with a more traditional methodology while Units 4–6 are mainly taught by the study cases method combined with simulation-based learning. The activities and methodologies with their corresponding ECTS credits and learning or study hours are listed in Table 1.

This study focuses on the methodology implemented for Units 4–6, which aims to enhance the learning experience of ChE students in the process dynamics and control of industrial plants by the simulation with Aspen HYSYS of growing complexity working cases. These working cases starts with the dynamic simulation and control of individual operating units where the influence of the main tuning parameters of proportional, integral, and derivative (PID) controllers (controller gain [K_c], integral time [T_i], and derivative time [T_d]) on the system response is analyzed. Other relevant concepts such as the dead-time or the amplitude or period of sine wave responses are analyzed. Finally, the students must propose control of a more complex system with several operating units.

TABLE 1 Training activities, methodologies, ECTS credits, and learning or study hours of process dynamic and industrial plants control subject

Units	Training activity	Methodology	ECTS credits	Hours
1–3	Master class	Theoretical concepts description	0.6	15
	Workshops or seminars	Problem-based learning	0.6	15
4–6	Computer practices	Simulation based on study cases learning	1	25
	Group tutorials	Problem-based learning	0.12	3.0
1–6	Test preparation (Project work)	Autonomous work	3.6	90
1–6	Final test	Evaluation tests	0.08	2.0

Abbreviation: ECTS, European Credit Transfer System.

3.2 | First case of study: Influence of tuning parameters

In this subject, students are expected to become complete process simulation experts available to apply extensive simulation knowledge (both steady state and dynamic modes). To that aim, process simulation skills are transferred to the students through the combination of a set of working cases.

It is known that the first-order with delay and second-order processes are widely used to simulate many dynamic processes. In the last case, the response depends on whether it is an overdamped, critically damped, or underdamped second-order system. It should be also taken into account that the choice of a proper controller structure and tuning methods are key in the design of a control system. A "feedback" control structure works in many of the first control systems. It is required to track set point (SP) changes and to suppress unmeasured disturbances (a change in the controller output) that are always present in a real process. In this sense, there must be an error before corrective actions are taken. However, the use of "feedforward" combined with feedback control structure can significantly improve the performance over feedback control alone whenever there is a disturbance that can be measured before it influences on the process output. The effect of the disturbance is, thus, reduced (or even entirely eliminated) by measuring it and generating a control signal that counteracts it [9].

Hence, to learn how to tune and simulate a control structure, the first working case proposed to the students allows them to establish the fundamentals of dynamic simulation and control of a regulated process, where the influence of the main tuning parameters of PID controllers are explored.

In a first session, taking into account that PID controllers are designed to automatically manipulate a certain variable (OP) to hold a process variable (PV) (e.g., measured pH, flow rate, temperature, composition, or pressure) at a pre-established SP, the type of actions are shown to depend on the value of K_c, T_i, and T_d parameters through the following control algorithm [6]:

$$y(t) = K_c\left[u(t) + \frac{1}{T_i}\int u(t)dt + T_d\frac{du(t)}{dt}\right],$$

where $y(t)$ and $u(t)$ refers to the output and input variables evolution over time. However, it is explained to the students that the PID equation is usually converted to a "transfer function" (defined as the input to output representations of the dynamic system) by performing a Laplace transform on each of the elements in the s domain:

$$G(s) = \frac{Y(s)}{U(s)} = K_c\left(1 + \frac{1}{T_i s} + T_d s\right).$$

Students are then reminded that the "proportional" action of a PID depends on K_c or "controller gain," which is the key process parameter that influences on the extent of a process response to a change in the controller output (in terms of sensitivity). Defined as the ratio between the change in the variable input and that in the output, a high gain in a controller is found to result in a faster loop response to the output change but it is also related to the existence of an offset except for not self-regulated first-order control systems.

The "integral action" is complementary to the proportional one and, although this action does not control by itself, it allows to diminish the offset and its effect depends inversely on the integral time parameter (T_i). Therefore, its use slows down the response and tends to do it oscillatory, which may destabilize the system.

The "derivative" action (also called "rate") is also complementary to P action and is applicable to processes with high time constants. Its effect depends directly on the derivative time parameter (T_d) and allows to anticipate the response based on the rate of change of the measured process variable or error. However, it should not be used in case there is noise in the process, since it tends to amplify it.

Therefore, a P controller is best-suited for integrating processes, while PI or PID controllers are more suitable for nonintegrating ones.

Once PID fundamentals are reviewed, in a second session, performance testing of the proposed control structures is carried out by dynamic simulation using Aspen HYSYS environment (8.0 version). To that aim, a first working case is presented to make students put in practice the acquired knowledge. To achieve this implementation the following steps have to be completed: building a steady-state process, tuning of the controllers, and evaluating the control structure.

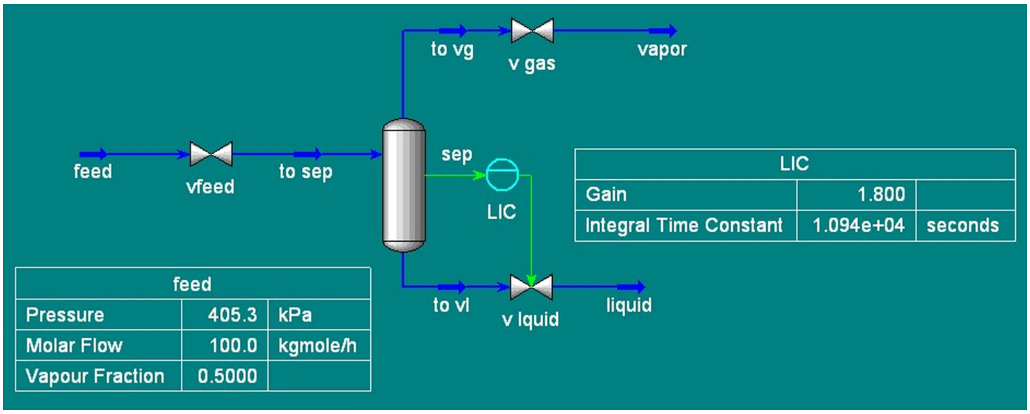
Therefore, for this first working case, the first step helps students to create a simple and well-known steady-state flowchart of a sudden distillation of an equimolecular methanol–water solution as the basis for building the dynamic case where a level controller (LIC) is acting upon it. Figure 1 shows the closed-loop PI controller for dynamic process in Aspen HYSYS.

Before transitioning from steady-state to dynamic-state simulation, a specification of pressure and flow rate is required for each process stream. Moreover, sizing of the equipment (valves and separator) is carried out based on the control objectives. To size a valve, the type (quick opening, linear or equal percentage), normal opening position, current flow rate and pressure drop across the item should be stablished. In this sense, students are recommended to assume that the pressure drop is 35 kPa for v_{feed} and v_{gas} and 10 kPa for v_{liquid}, respectively. Then, the three valves related to feed, vapor, and liquid streams should be dimensioned with the “size valve” button in the “sizing” section of the “rating” tab. They should also consider a volume of 0.4128 m^3 (50% occupied by the liquid) for the separator unit. In this study, Peng–Robinson package is used for the simulation of the separation of the aqueous alcohol solution.

The control objective of the LIC is to attain specifications of liquid/vapor products (i.e., requested mole fraction) by manipulating the liquid stream flow rate. The PI controller is used to directly control the liquid level on the separation unit by acting a valve on the output stream, which is known as a direct-acting “backwards” loop. Proportional gain (K_c) and integral time (T_i) are determined by “manual” tuning method on the Aspen HYSYS online dynamic system. In this case, as $T_d = 0$, the transfer function for the controller is simplified as

$$G(s) = K_c \frac{T_i s + 1}{T_i s}.$$

Hence, to identify the best values for the closed-loop control parameters, the next step starts with inserting the level controller and add a stripchart (from tools-data book) including the liquid percent level in the separator unit as PV, the SP of the level controller (LIC-SP), and percentage open related to v_{liquid} valve, as OP (manipulated variable). Then, students are asked to analyze the evolution of the selected variables over time for a series of disturbances such as a pressure change in the feed stream (3.9–4.1 atm) or the variation in the SP level of the separator unit (i.e., 40–60%), which differs from the established starting point. To that aim, the “sample interval” (T_s), which is the rate at which a controller samples the process variable is set to 3 min. Moreover, axes scales of the datalogger should be put in “Automatic Autoscale” and the corresponding “faceplates” should be opened to correctly visualize the disturbances. From this point on, to study the response behavior of the PI controller, students are encouraged to play by widely varying both gain (K_c: 0.1–10) and integral time (T_i: 0.1–100,000 min). Even more, they are required to calculate control parameters



LIC		
Gain	1.800	
Integral Time Constant	1.094e+04	seconds

feed		
Pressure	405.3	kPa
Molar Flow	100.0	kgmole/h
Vapour Fraction	0.5000	

FIGURE 1 Dynamic configuration flowchart of a closed level controller (LIC)-controlled loop

by using the "Autotuner" tool in the "parameters tab" and compare them with those already applied in the controller.

From results obtained in this working case (see some examples in Figure 2), students should conclude that the gain controls the response speed of the system but the higher the value of the gain, the faster the response evolves and the larger the offset. They should also notice that the integral time reduces or totally eliminates the system offset. However, if its value is excessively high or small, it can destabilize the system. They can even evaluate which gain value leads to a constant amplitude oscillation system response.

Therefore, once students have acquired the skills for the dynamic characterization of control loop systems, Laplace and frequency domains, they learn that for tuning PI controllers, a consensus must be reached between K_c and T_i values.

3.3 | Second case of study: Influence of dead-time, amplitude, and period

As commented above, the most commonly used model to describe the dynamics of chemical processes is the First-Order plus Time Delay Model (so called First-Order and dead-time transfer functions, FOPDT) [13], which can be expressed as

$$\tau_p \frac{dy(t)}{dt} = -y(t) + K_c u(t - \theta_p),$$

where $y(t)$ and $u(t)$ are the output and input variables, K_c is the process gain, τ_p is the time constant, and θ_p refers to the dead-time, respectively. However, one advantage of working in the Laplace domain is that differential equations become algebraic and thus, the last expression is often written with Laplace transforms as follows:

$$Y(s) = K_c \frac{\Delta u}{s(\tau_p s + 1)} e^{-\theta_p s}.$$

Moreover, taking into account that the effect of dead-time is usually induced by the inclusion of a transfer function block in the simulation environment, the final transfer function is given by

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_c e^{-\theta_p s}}{\tau_p s + 1},$$

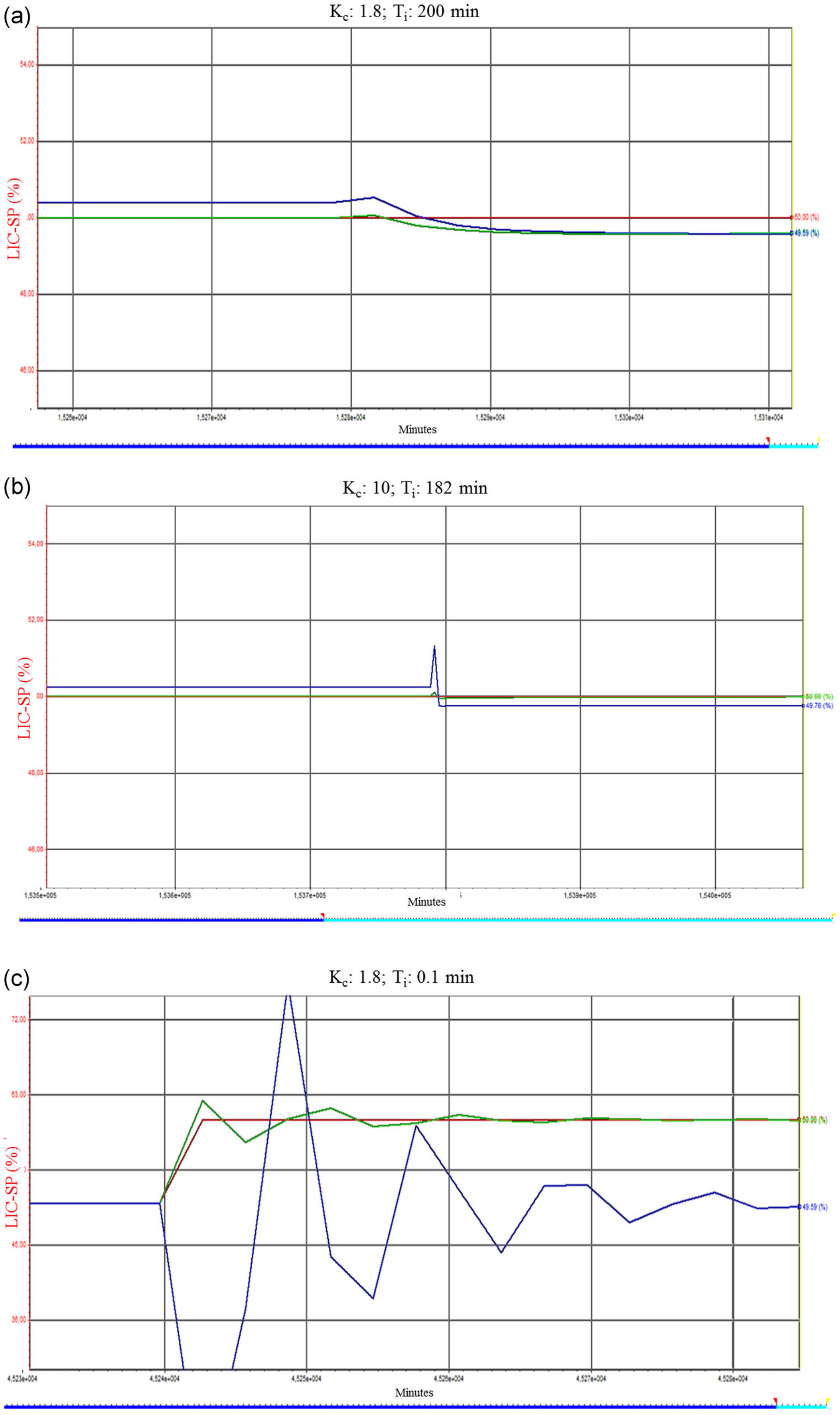
where $U(s)$ is $\Delta u/s$.

Therefore, once students are able to understand PID control features, it is important to introduce them that the dynamic response of self-regulating processes can be described reasonably accurately with a simple model consisting of process gain, time constant, and dead-time.

Thus, in the first session, all these concepts are presented. Both the disturbance period and amplitude are shown to determine the amount of attenuation of a disturbance (see Figure 3). Moreover, although capacitance is good for disturbance rejection, high capacitances can result in very long response times. Dead-time (θ_p, so called delay), in contrast, is exposed as a key dynamic parameter to hold a proper tuning and control of the system since it limits how fast a controller can react to disturbances, expressed as a time shift in the input variable ($u(t - \theta p)$). It is often reported as a reason for increased loop variability within the industrial processes and might appear by computation and communication delays or when a higher order model is approached with a low order one. Students are requested to note that null dead-time would lead to a perfect control of the system and the controller gain could be theoretically infinite. However, negligible dead-time only occurs in simulations and even if the process dead-time is extremely small (due to automation) it must be dealt with. The effect of this parameter should be thus minimized or compensated to fulfill design specifications. In addition, "time constant" (τ_p), also denoted as "lag time, capacity element or a first-order process," is shown to determine the amount of time after the dead-time that the process variable takes to move 63.3% of its final value after a step change in the valve position. Even more, it is presented as the key parameter to determine its ability to reject, or attenuate disturbances.

Therefore, to get an idea about the importance of these control parameters to reject, or at least minimize, the effect of disturbances, the dynamic characteristics of processes with capacitance, and appreciable dead-time are studied (in the following session) through the working case depicted in Figure 4. To go one step further, the challenge proposed to the students, which is illustrative of a real plant situation, is based on the tuning and analysis of three different controllers plus two transfer function blocks, simulating dead-time and capacitance effects.

The flowsheet in steady-state mode is similar to that studied in the first working case although includes a cooler unit where the feed stream, which is composed of a mixture of *n*-hydrocarbons is pretreated prior entering into the separator unit (SEP). Again, three valves regulating the feed, gas, and liquid streams flow rates are present (e.g., V1, VG, and VL, respectively). Note that in this case, three controllers complete the process: (a) temperature indicator and controller (TIC) to control the temperature of the liquid stream (liq) through the energy


(a) K_c: 1.8; T_i: 200 min

(b) K_c: 10; T_i: 182 min

(c) K_c: 1.8; T_i: 0.1 min

FIGURE 2 Stripchart plot of level controller at different K_c and T_i. Blue line, v_{liquid} percentage open (%), Green line, Sep-Liq percentage level (%), red line, LIC-SP (%)

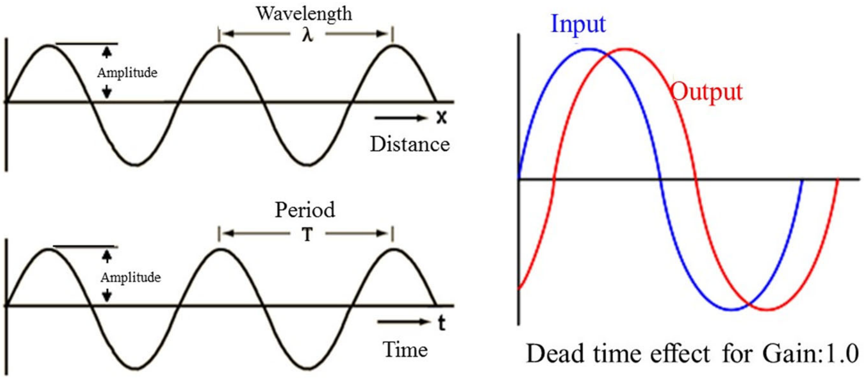


FIGURE 3 Different control parameters tools

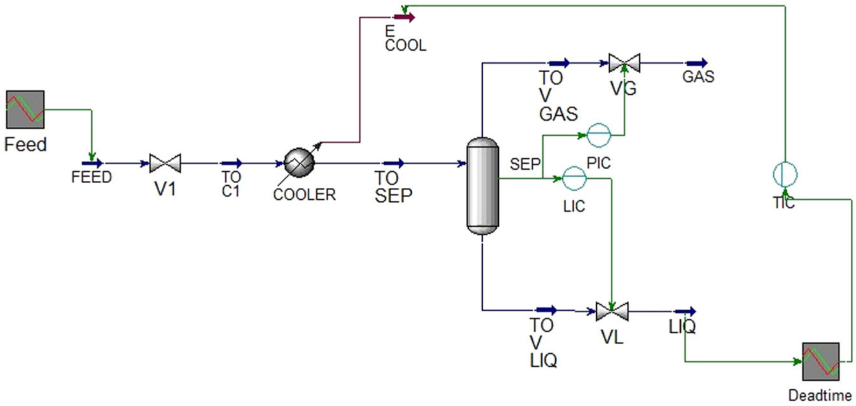


FIGURE 4 Flowsheet of dynamic-state configuration with transfer function blocks for dead-time and capacitance analyses

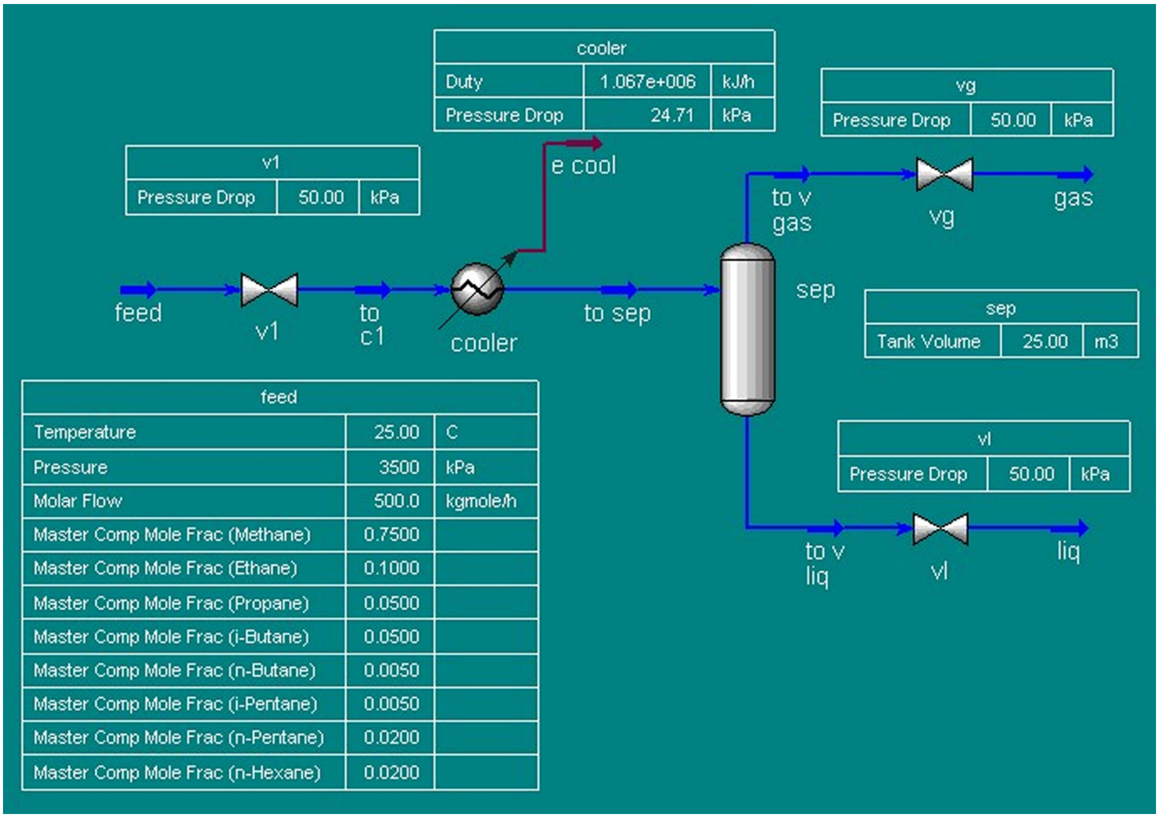
stream of the cooler (by means of the flow rate of cooling water supplied to this unit); (b) LIC: the level of the separator is controlled by acting on the valve that regulates the "LIQ" flow rate, and (c) pressure indicator and controller to control the pressure on the separator unit by acting on the valve located in the gas stream. Fluid package used as an activity model is Peng–Robinson.

After sizing the cooler (Min-Max direct Q: 0–2 × 10^6 kJ/hr), separator and valves following operation conditions are depicted in Figure 5, and considering those control parameters summarized in Table 2, controllers can be added to the flowsheet using the same procedure followed in the first working case. Once controllers have been included, students should make the necessary connections for PV onset and OP targets, select the minimum and maximum PV values, the controller action (direct in this case), and input tuning parameters. Finally, they should choose the control mode (manual or automatic).

Then, the students are recommended to generate a stripchart including the SPs of the three controllers and controlled variables to be able to observe the selected simulation variables in real time as the dynamic simulation runs. They should also insert a controller Face Plate for monitoring by pressing the Face Plate button on the property view. The sampling interval is set to 2 min and the datalogger in "Automatic Autoscale." At this point, students are encouraged to play with dynamics by means of changing the TIC SP from −10°C to 10°C analyzing the system response.

Figure 6 shows an example of the dynamic evolution of the selected variables. Students can observe that the response of both the output temperature of the liquid stream and the heat flow rate are underdamped, which indicates that the oscillatory character is preserved but its amplitude decreases over time, resulting in the cessation of the disturbance. They should also note that destabilization (in terms of amplitude of the fluctuation) increases with a higher SP change. Fluctuations in the liquid level of the separator unit should be also recorded.

Then, a transfer function is added to the outlet liquid stream to generate a delay in the time response of the closed-loop system (as-referred dead-time). To that aim, students should select the "transfer function block" from the main simulator builder (or through the process flow diagram). On the "Connections" page they must attach the output of the transfer function block to the feed "Object" and select the process variable as "Temperature." Then, they should move to the "Parameters page" and set the SP at 0°C and the PV/OP ranges to vary between −50°C and 50°C. Students must select the



cooler		
Duty	1.067e+006	kJ/h
Pressure Drop	24.71	kPa

vg		
Pressure Drop	50.00	kPa

v1		
Pressure Drop	50.00	kPa

sep		
Tank Volume	25.00	m3

vl		
Pressure Drop	50.00	kPa

feed		
Temperature	25.00	C
Pressure	3500	kPa
Molar Flow	500.0	kgmole/h
Master Comp Mole Frac (Methane)	0.7500	
Master Comp Mole Frac (Ethane)	0.1000	
Master Comp Mole Frac (Propane)	0.0500	
Master Comp Mole Frac (i-Butane)	0.0500	
Master Comp Mole Frac (n-Butane)	0.0050	
Master Comp Mole Frac (i-Pentane)	0.0050	
Master Comp Mole Frac (n-Pentane)	0.0200	
Master Comp Mole Frac (n-Hexane)	0.0200	

FIGURE 5 Flowsheet of steady-state configuration. Operation conditions for sizing

"Delay" option in the "Dead Time Model" transfer function, set a delay of 5 min, and activate the integrator.

It is important to note that students are instilled that the controller has to be always connected to the transfer function and not the other way around (see Figure 7).

Once the settings have been properly filled, to analyze the system response and check the effect caused in the controlled variable, students are required to add both PV and "Temperature" of the "Liq" stream to the stripchart and to define the limits (from −20°C to 20°C in this case) in the datalogger (which is set as Automatic Autoscale). Moreover, students are suggested to change the controller SP (to 10°C) and, if necessary, to modify TIC parameters (to 0.54 for gain and 20 as integral time, respectively). In this way, students are able to observe that the selected variables follow the same trend, for example, an underdamped response until settle down at the stablished SP and, the expected delay in the system response produced by the dead-time function (see Figure 8a).

TABLE 2 Control parameters for LIC, PIC, and TIC

	LIC	PIC	TIC
Min/max PV value	0–100%	3,000–3,500 kPa	−50 to 50°C
Gain	1	2	2
Integral time constant (s)	300	600	120
Control action	Direct		
SP	50%	3,425 kPa	0.147°C

Abbreviation: LIC, level controller; PIC, pressure indicator and controller; TIC, temperature indicator and controller.

The last step in the proposed working case deals with the analysis of the influence of the capacitance (frequency response) through the introduction of a transfer function block (named Feed), which is used to generate a second-order sinusoidal disturbance in the temperature of the input stream (FEED; see Figure 4).

Following the procedure detailed before for including a transfer function block, students are requested to add the specified one by selecting "Temperature" as the process variable and setting an input PV of 25°C along with PV and OP ranges from 0°C to 100°C. A "2nd order" and "sine wave" type must be selected in this case from the page labeled "Lead/2nd Order." An amplitude of 10 and a period of 30 min are then specified to start with. However, both, the amplitude and disturbance period will be varied depending on the dynamic test being run to explore their influence on the evolution of the system (e.g., process responses). In addition, they are proposed to

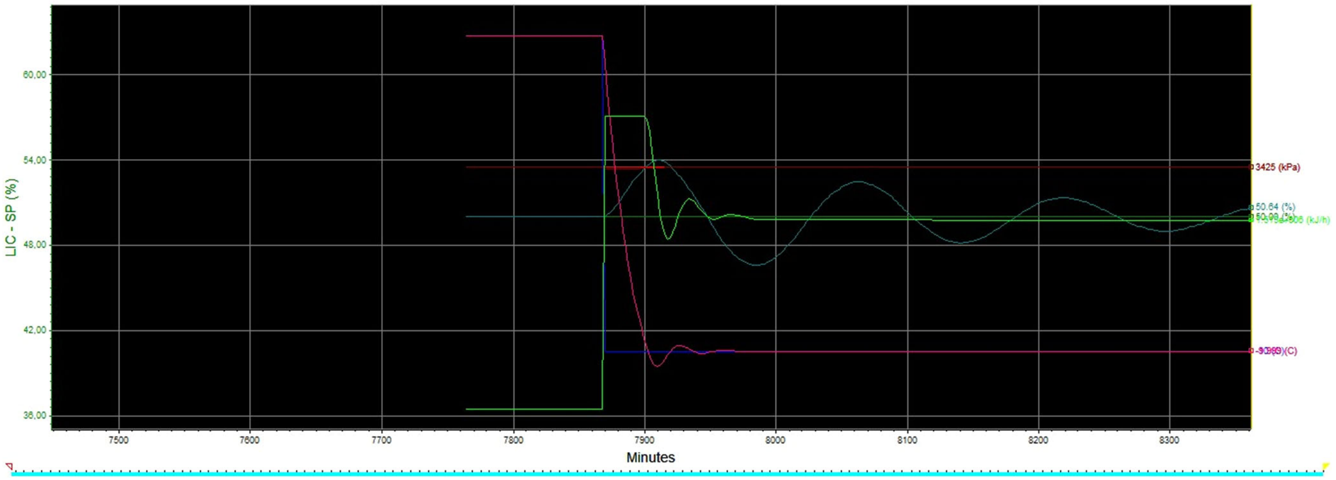
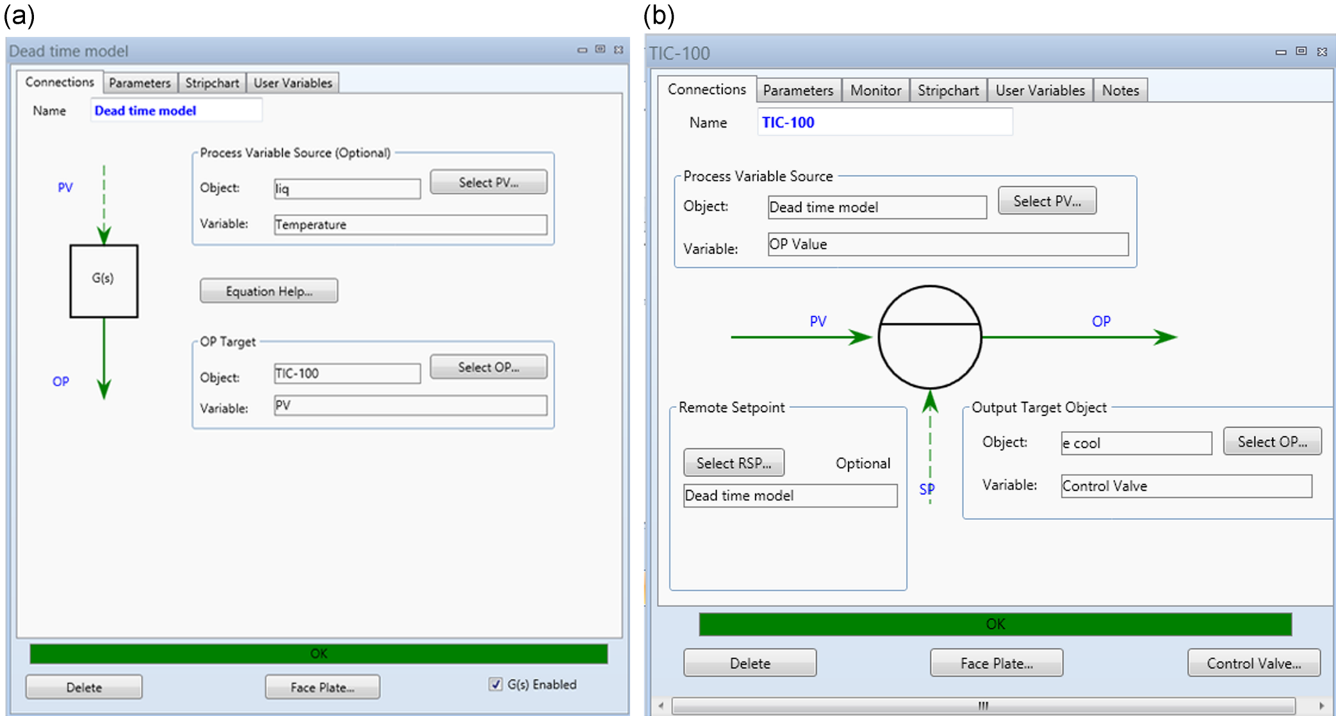


FIGURE 6 Sep liquid level (%), cooler flow rate (kJ/hr), T_{output} liquid stream (°C), pressure on Sep (kPa). Dynamic plot of TIC SP: −10°C. Blue line, Sep. liquid level (%). Green line, cooler flow rate (kJ/h). Pink line, toutput liquid stream (ºC). Wine colour line, pressure on Sep (kPa)

play combining those effects with higher dead-time values.

From frequency responses are depicted in Figure 8b,c and data collected in Table 3, students can observe that the disturbance in the temperature of the input stream causes a sinusoidal oscillation in the response, that is, in the temperature of the liquid stream leaving the separator unit. However, those values corresponding to both pressure and liquid level in the separator PV variables are kept almost constant being 3,427 kPa and 50.08%, respectively.

Students can also observe that if Step 1 is repeated modifying the amplitude of the sine wave (e.g., 20), the amplitude of the response is proportional to this change. In contrast, an increase in the period for the same amplitude is found to result in quite similar variation ranges



(a)

Name: Dead time model

Process Variable Source (Optional)
Object: liq
Variable: Temperature

OP Target
Object: TIC-100
Variable: PV

☑ G(s) Enabled

(b)

Name: TIC-100

Process Variable Source
Object: Dead time model
Variable: OP Value

Remote Setpoint
Dead time model

Output Target Object
Object: e cool
Variable: Control Valve

FIGURE 7 Transfer function connection

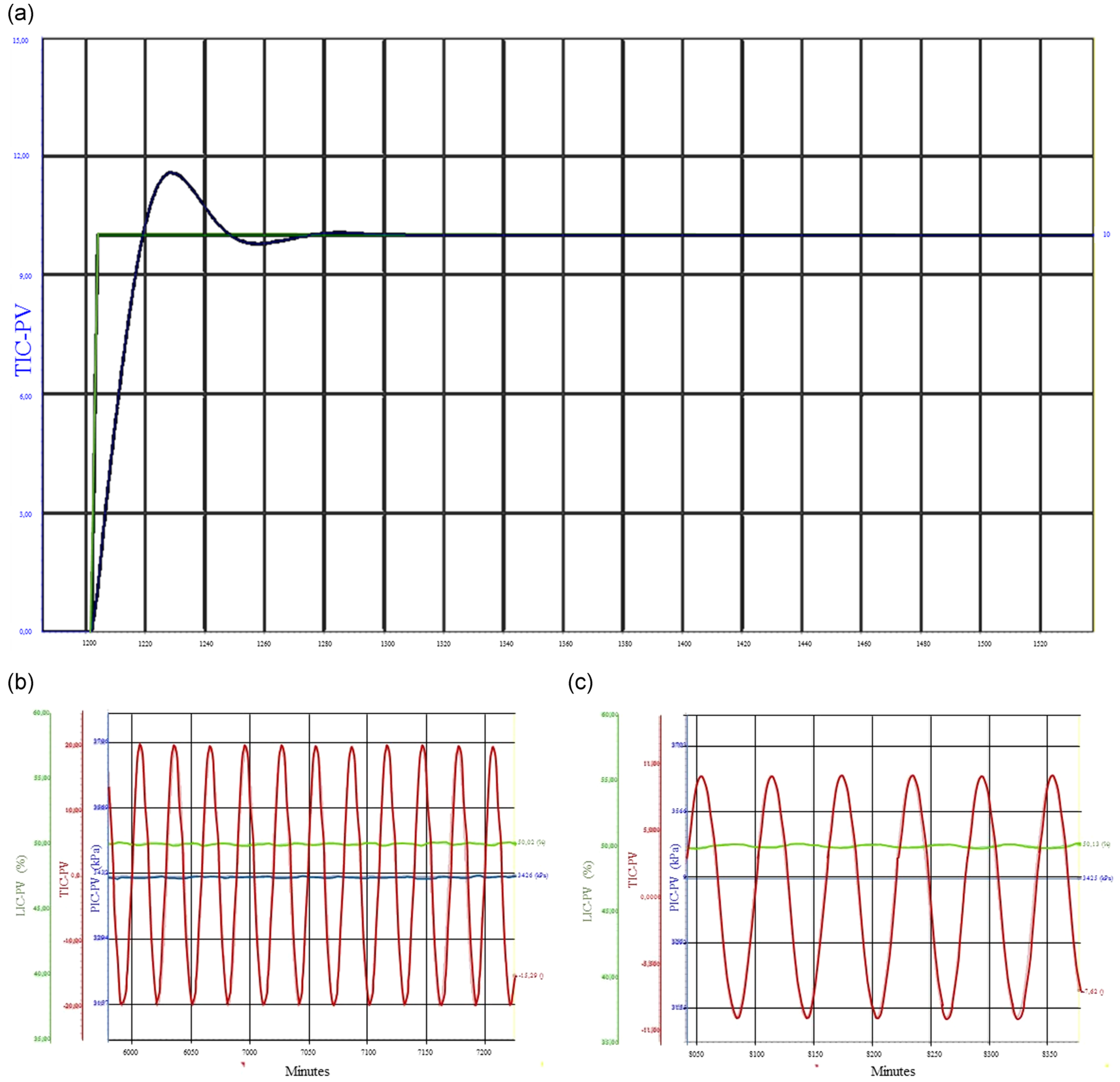


FIGURE 8 (a) TIC dynamic controller response. TIC, LIC, and PIC dynamic response to changes in (b) the amplitude or (c) period of the sine wave transfer function. LIC, level controller; PIC, pressure indicator and controller; TIC, temperature indicator and controller

TABLE 3 Influence of amplitude and period of oscillation on different PV

Amplitude	Period (min)	Temperature (°C)		Liquid level (%)		Pressure (kPa)	
		Min.	Max.	Min.	Max.	Min.	Max.
10	30	−0.77	0.97	49.82	50.17	3,424.05	3,425.68
	60	−1.04	1.25	49.77	50.35	3,424.10	3,425.65
20	30	−1.78	1.93	49.63	50.30	3,422.46	3,429.21

Abbreviation: PV, process variable.

TABLE 4 Survey questions regarding the general assessment of the subject

No.	Question/statement
1	The teaching methodology and planning allow to acquire the predicted competences
2	The contents of the program have been developed during the course
3	The bibliography, the information sources, and the recommended teaching materials are useful for the subject follow-up
4	The distribution of the student's workload is balanced

to those in Case 1 but it takes longer to repeat each oscillation cycle.

It is important to note that apart from the two working cases exposed in this study, more challenges are proposed depending on the specific content of each unit to ensure the implementation and understanding of the principles of dynamic simulation, control design, and automation of a complex industrial process. It is also worth it to mention that students are requested to complementary submit a report summarizing each proposed study working case, performed during the computer practices, along with the sequential tasks and the corresponding analysis of the obtained results for their evaluation.

4 | RESULTS

Effectiveness of the training activities and methodology used in process dynamic and industrial plants control subject were assessed by an anonymous online survey for the last three academic years. This survey was divided in two parts, with one part the students give their opinion about the general assessment of the subject (Table 4) and the other providing their opinions and feeling concerning the use of study cases using simulation software to acquire skills and knowledge (Table 5). To collect qualitative feedback on their experience, the survey was rated on a scale of 0–5: *strongly disagree*, *disagree*, *neutral*, *agree*, and *strongly agree*. In addition, the response rate was higher than 75% of the total students. The responses to the survey for questions shown in Tables 4 and 5 are shown in Figures 9 and 10, respectively.

Figure 9 shows that ChE master students agreed with the general assessment of the subject, valuating all the statements reported in Table 4 with marks >3.5 in the studied courses (last three academic years). Specifically, the program content (Question No. 2) has been very positively valued with the highest mark (4.8), as all the years lines are between the diamond lines corresponding to scores 4 and 5. Therefore, students expressed that the amount of material introduced, the recommended learning materials, and the time allocated to develop training activities have been correct.

TABLE 5 Survey questions regarding learning methodology based on study cases using simulation software

No.	Question/statement
1	Appropriate assigned time and theoretical deepening of the simulation fundamentals of regulated processes with PID controllers
2	Learning to set up a dynamic simulation
3	Definition of controlled and manipulated variables and the installation and tuning of control loops through study cases
4	Testing the dynamic resiliency of different process through study cases
5	Observing the importance of selecting the appropriate manipulated variables for optimization
6	Learning to use the simulator to set up and solve an optimization problem
7	Observing the impact of process constraints
8	Design of study cases are well-designed
9	Process simulation software helps students to understand the control, instrumentation, and automation of chemical processes

Abbreviation: PID, proportional, integral, and derivative.

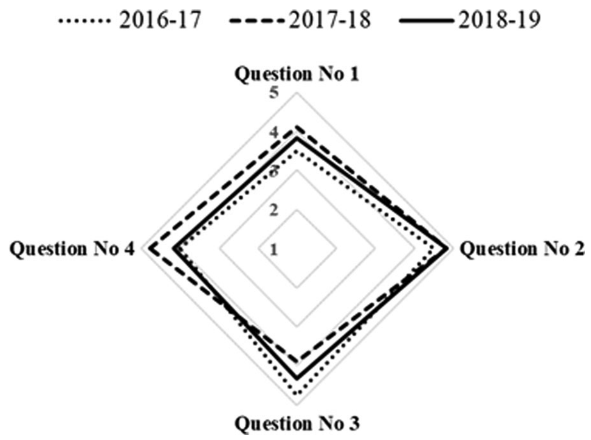


FIGURE 9 Survey results for questions described in Table 4

Regarding the evaluation of the methodology implemented using simulation software study cases for Units 4–6, students generally agreed that all the aims indicated in the survey were satisfactorily achieved since the lowest score was ≥3.5 (Figure 10). According to student responses, the statement nos. 2, 4, 5, and 9 were the highest valued with average marks of 4.5. It indicated that students felt that the use of Aspen HYSYS enhances the control theory understanding from a chemical engineering perceptive. Thus, the combination of theory and the use of such a simulation software led to a better understanding of the process dynamics and control of industrial plants. This fact mainly attributed to simulation software allows to visualize on time the response of regulated chemical processes with PID controllers. In addition, the study case format can support this objective efficiently and spare instruction, eliminating the tediousness and time-consuming aspect of process calculation. In addition, it can be observed in Figure 10 that the academic year 2016–2017, the first year when this teaching methodology was implemented, showed low marks in almost all statements. This fact is associated to the adjustment of the new teaching methodology by students and teachers. Thus, this learning methodology promotes a successful achievement of learning outcomes. In fact, more than 95% of master students pass this subject every year.

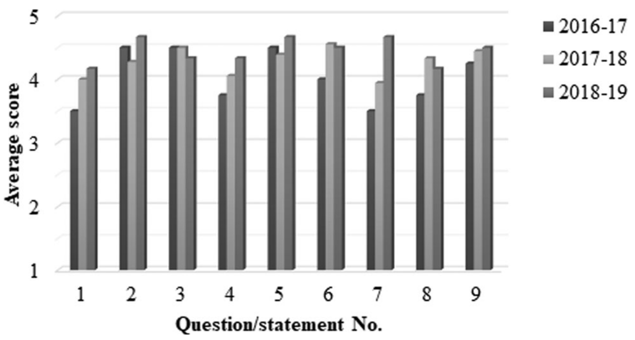


FIGURE 10 Survey results for questions described in Table 5

5 | CONCLUSIONS

The developed cases of studies combined with simulation-based learning using Aspen HYSYS in dynamic mode, allowed to evaluate the influence of the main tuning parameters of PID controllers and relevant concepts such as dead-time, amplitude, and period of sine wave disturbances. This methodology enabled to reach a significant success in the achievement of learning outcomes more easily compared with traditional methods as >95% of master students passed this subject each year. Thus, Aspen HYSYS has been demonstrated to be a powerful tool for the simulation and comprehension of the dynamic behavior and process control of basic operating units commonly used in chemical industries. Besides, according to the survey conducted over the last three academic years, master chemical engineering students feel that study cases format and the use of simulators eliminates the tedious and time-consuming aspect of process calculation, allowing to visualize on time the response of regulated chemical processes with PID controllers.

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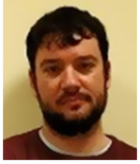

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