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Process Control Laboratory Projects: Technical Training, Team Development, and Global Collaboration

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Process Control Laboratory Projects:
Technical Training, Team Development and Global Collaboration

Abstract

Process Control has been established as a core course for the formation of chemical engineers. Very often, it is the only course dealing with the analysis of transient (time dependent) phenomena and conditions. It relies on difficult concepts requiring intensive mathematical approaches and simulations based on differential equations and Laplace transform. It is commonly criticized for its level of abstraction and mathematical involvement, in contrast to other courses in the career, and for the restricted applicability to industrial jobs. This criticism generally negatively affects the motivation of students. However, the combination with hands-on experiments has proved to enrich the learning and motivation of students, but most colleges face severe restrictions on the investment, maintenance, and operation of process control labs and the addition of new requirements in the curriculum. Some alternatives have been exploring the use of simple modules for classroom demonstrations, theoretical simulations of equipment in unit operations lab, and virtual-lab simulations.

This paper describes the scope of technical training based on process model and synthesis of PID controllers for six experimental set-ups with liquid level and temperature control, using lab equipment fully automated for data acquisition, handling of manipulated and disturbance variables, and selection of parameters for PID controllers. MATLAB codes and Simulink graphical simulations support the processing of data and analysis of results. In addition, the course develops a unique experience in team skills and performance where every team is a combination of two sub-teams. The "office" sub-team oversees research on industrial applications, instrumentation characteristics, and computational modeling. The "lab" sub-team oversees elaborating and testing experimental plans, collecting data, and analyzing results. Every team is assigned two sequential projects; one for process modeling (open-loop) and one for controller synthesis (closed-loop), and the sub-teams switch their roles from one project to another. Detailed analysis of relevant team dynamics is assessed quantitatively and qualitatively based on the experience with 71 students arranged in 12 groups. Based on this experience, a proposal is made to develop a program of institutional collaborations to broaden the accessibility of real lab experience to students worldwide, mainly targeting those without this valuable resource. A preliminary trial showed the potential for a successful global collaboration addressing technical content and team dynamics.

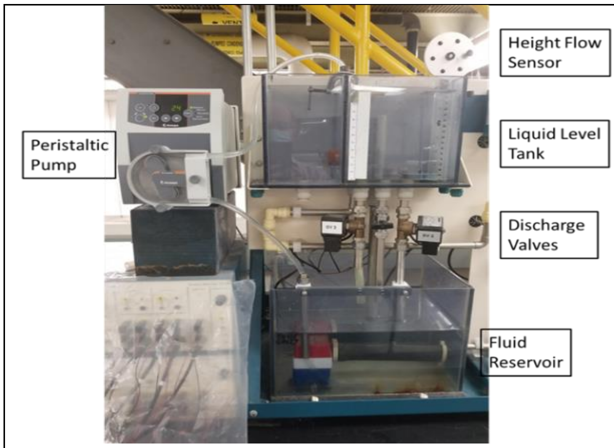
Introduction

The most recent survey on the series of chemical engineering undergraduate education, conducted by the AIChE Education Division on the curricular and pedagogical topics for Process Control, points to an average of approximately 40 hours of lecture, 11 hours of simulation, and 7 hours of experimental laboratory per course [1]. In addition, more than 50% of respondents require no lab reports [1], which can be interpreted as having no corresponding lab, confirming the perception that most process control courses in chemical engineering rely on classroom settings and mathematical content [2]. "Systems Engineering, I: Dynamics and Modeling" is a classical one-semester course in Process Control [3] and one of the two capstone courses for senior students at the University of Pittsburgh. It is a five-credit course where students meet with the instructor three times a week (84 hours of lecture), plus 10 recitation sessions (20 hours of simulation). In addition, a one-credit lab companion course that takes up the remaining day of the week (28 hours of experimental laboratory). This immersive experience heavily enriched with process simulation (Matlab, Simulink) and the experiential learning at the lab provides students with a thorough understanding of the chemical process prototypes they have been encountering during their career.

There has been criticism on traditional process control courses relying mainly on mathematical descriptions and analysis of process control problems, frequently asking for more experiential learning, application to real systems, and knowledge on sensors and control devices, including characteristics, location, and signal processing [1], [4]. It has been proved that lab exercises improve student learning, both as inductive experiences before classroom lectures, and as application experiences to aid in the understanding of more difficult theoretical concepts [5]. Several initiatives have been reported [5], ranging from including some experiments (there are many kits commercially available) during the lectures to adding a 1 semester-hour lab course. The lab experiences, with the identification, operation and functional analysis of sensors, control valves, variable speed pumps, PID controllers, computer operations, can also support alternative proposals for updating chemical engineering education more focused on plant automation design [6]. However, the implementation of process control lab experiments is limited at many institutions by lack of equipment, technical support, and other factors [7]. One interesting alternative is the use of remote or distance labs [2], [7], [8]. A relatively close alternative is the use of virtual-lab simulators [8], [9], [10], [11]. Still another approach has been to use the experience in previous unit-operations lab modules with real equipment and design and analyze theoretical proposals for automatic control of those experimental units with the support of simulation [12].

Technical training

Our lab offers six fully functional process control experiments with automatic PID controllers. One set of experiments deals with three liquid level control systems (1. a small tank with a variable speed pump and two gravity-drain valves, 2. a large tank with a control valve and two gravity drain valves, and 3. two tanks in series with variable speed pumps and gravity-drain pipes). Another set of experiments deals with three temperature control systems (1. an internal coil heating tank with a steam control valve and two plate heaters for recirculating water stream with variable speed pump, 2. a two pass and multi-baffle shell and tube heat exchanger with steam and water control valves, and 3. a 3-hot and 5-cold passes double-pipe heat exchanger with steam, water, and ethylene-glycol control valves) (Figure 1).



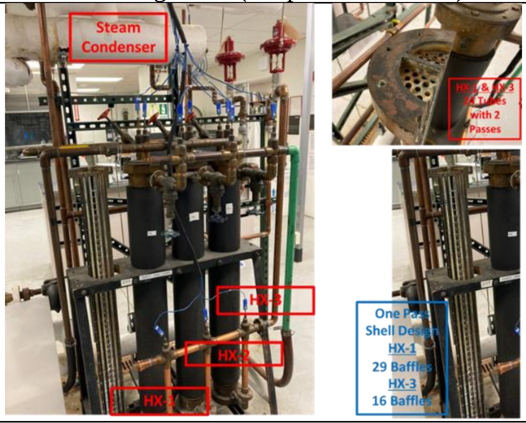
Small liquid tank (level control)

Quad tanks (level control)

Large tank (level control)

Large tank (temperature control)

Double pipe heat exchanger



Shell & Tube heat exchanger

Figure 1. Illustration of the six experimental set ups at the Process Control Lab

The course is structured into two sequential projects conducted by teams of 4-6 members. The first project (open loop) runs for the first 7 weeks of the semester and targets developing a process model. It should be based on first principles derivations (mass and energy balances) leading to ordinary differential equations where characteristic parameters (flow head equation, heat transfer coefficients) are determined by least-squares subroutines fitting lab data, transfer functions derived by linearization and Laplace transform solution, or by approximate methods based on the process reactive experimental curves [3]. The second project (closed-loop) runs for the last 7 weeks of the semester and explores the synthesis and tuning of PID controllers by on-line tuning and various model-based tuning methods (IMC, AMIGO, ITAE, Z-N, and Relay auto-tuning) [3].

Students have available manuals for each experiment with detailed description of the basic principles, equipment, instrumentation, and operational procedures. In addition, they are provided with detailed rubrics on the main deliverables (final report, final presentation, individual assessment). The course starts with an introductory session to explain the scope and dynamics of the course, the assignment of the experiments, and includes team building games to reinforce team skills. In the second session, a tutorial on Simulink is presented. Next, they have three lab sessions to collect data, a fourth session to work out on the report and presentation (lab is available to collect more data if needed) and a final session for delivering the presentations.

Teams switch the experiment from the open-loop project to the closed-loop project to have every team running one level control and one temperature control experiment. For the closed-loop project teams receive the report from the previous group on the corresponding open-loop project. They are requested to criticize the previous report to some extent to justify adopting or changing the approach developed for modeling before proceeding with controller synthesis. The project is introduced with a lecture on instrumentation and Simulink block configuration for closed loop. Teams have up to five lab weekly sessions to collect data, with the remaining session for the presentation of results.

For the open-loop experiments, students manipulate one variable (that will be set as the manipulated variable later in the closed loop project) by step changes to observe the transient behavior of one output variable (that will become the controlled variable in the closed-loop project). In addition, they also manipulate at least one disturbance variable. Some experiments allow for more than one disturbance variable, but it is advised to use only one. Data is automatically collected (every 1-3 seconds) by LabView software over a dedicated computer and saved as EXCEL files. Students generate plots to display the transient behavior at different experimental conditions (Figure 2). Students develop a Simulink block structure, supported with a MATLAB code to solve ordinary differential equations, coupled with a non-linear regression subroutine to derive best parameters to fit the experimental data (i.e., characteristic valve coefficient, power factor in a relaxed Bernoulli's model for gravity drainage, heat transfer coefficients) (Figure 3). Students develop and analyze models using ordinary differential equations and transfer functions derived by Laplace transform [3] (Figure 4).

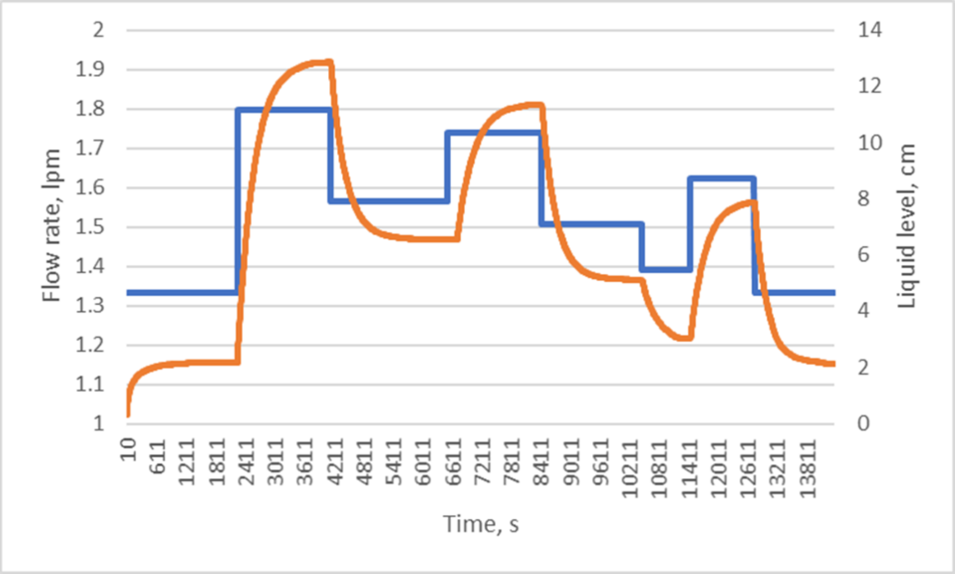


Figure 2. Small liquid tank, level control. The manipulated variable (flow rate, blue line) is managed to observe the transient response of the output variable (tank level, brown circles)

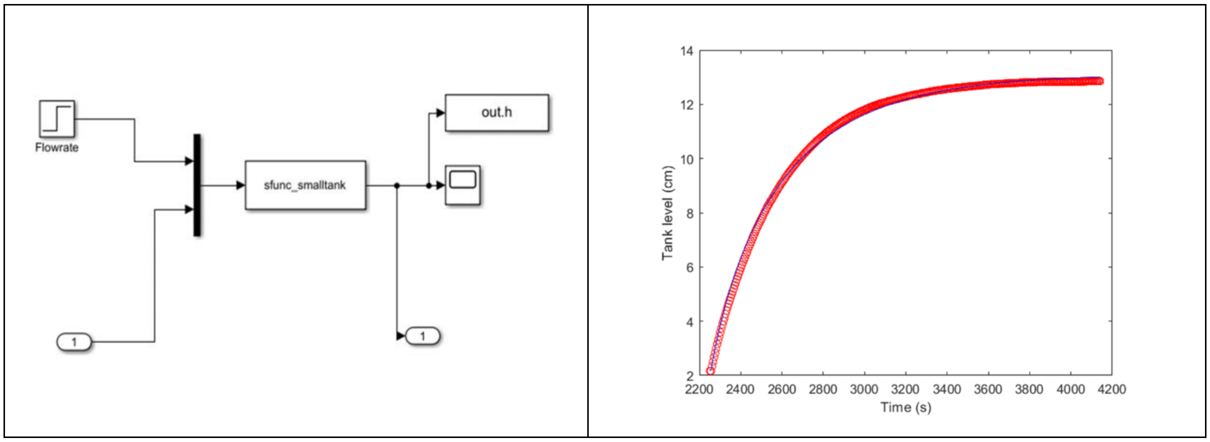


Figure 3. Example of Simulink/MATLAB simplified modeling structure (left) coupled with a parameter fitting subroutine to match experimental data (right, model on blue, data as red circles)

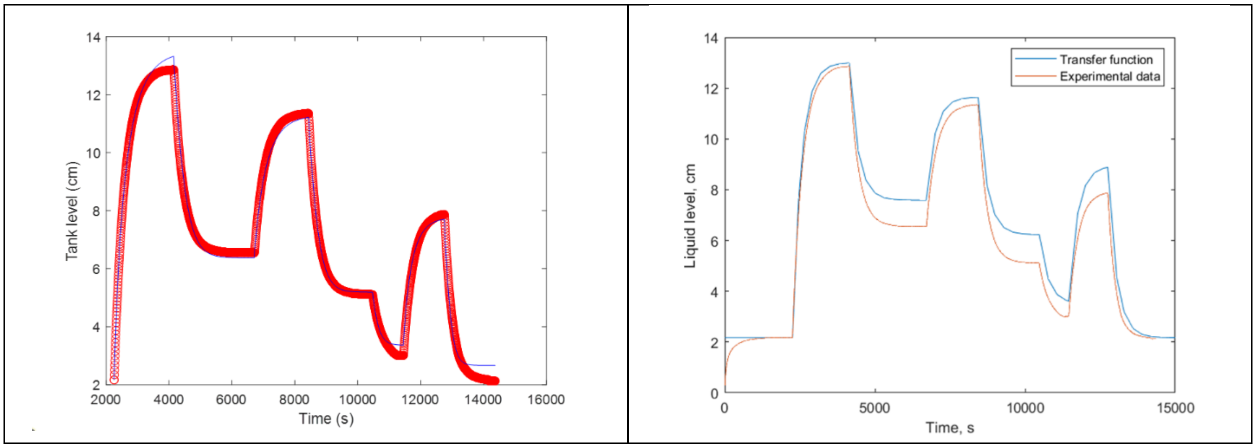


Figure 4. Example of model validation with ordinary differential equations (left) and transfer function by Laplace (right)

In the closed-loop experiments students manipulate the set point for the controlled variable and select values for the gain (direct and reverse action depending on the experiment), integral time, and derivative time in PID controllers. Students determine tuned parameters by sequence (first, gain, then integral time, and even derivative time) and re-tuning. They normally try “guess” values by on-line tuning, but they are also requested to derive parameters from the previously developed model (adapted from the previous group) once incorporated in the closed loop, including the Simulink modules for the final element (control valve, variable speed pump) and the controller (Figure 5)

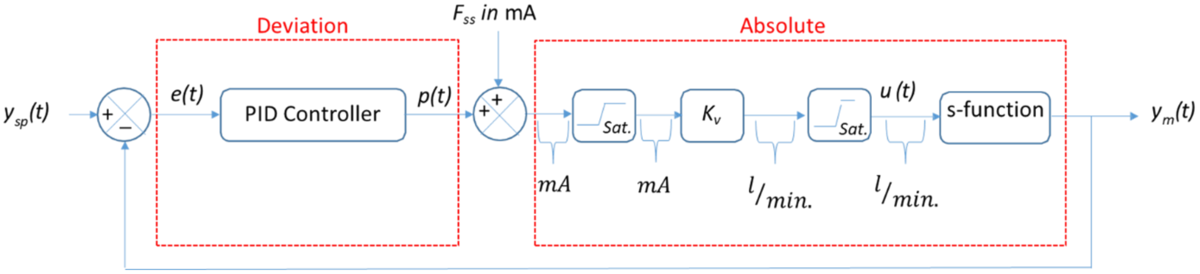


Figure 5. The open-loop model residing in the s-function module is integrated in Simulink with the final element module (including saturation blocks for physical limits) and the PID controller module for the closed-loop.

Students are also invited to use the previously developed transfer function model to synthetize controllers using various model-based tuning methods (IMC, AMIGO, ITAE, Z-N, and Relay auto-tuning) [3]. Students analyze performance curves (Figure 6) and select the best tuning parameters. In addition, they elaborate on the matching of model and experimental performance.

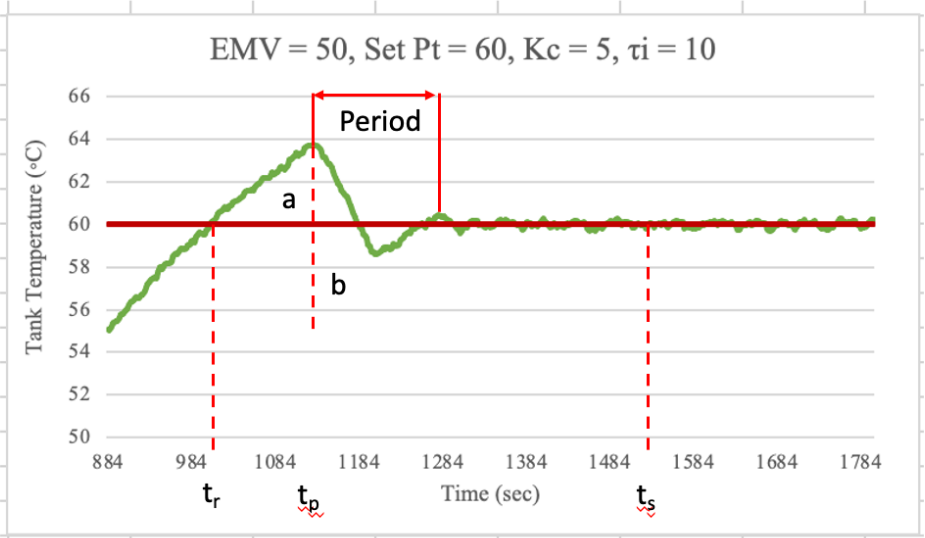


Figure 6. Example of controller synthesis by on-line adjustment in the large tank temperature control experiment, with disturbance in place (EMV=50% openness of a secondary drain), a target set-point of 60 °C from an initial condition of 55 °C, a gain value of K_c=5, and an integral time (τ_i) of 10 seconds for a PI controller. Plot displays the rising time (t_r) the time for the first peak (t_p), values for the calculation for the overshoot (a, b), period and settling time (t_s) [13]

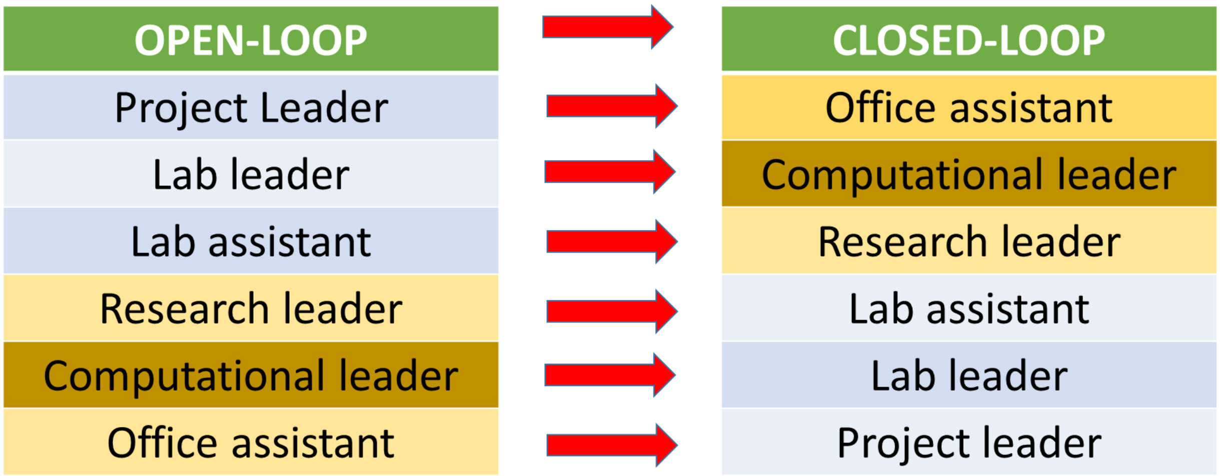
The lab course is structured by this in-depth and extensive experiential learning where students plan their experiments and develop their strategy to reach the goals of process modeling and process control that are communicated in a final report and a final presentation, both graded by a panel of experts. In addition, they are requested to include research on the characteristics of the sensors and final elements for the industrial process emulated in the lab and refer reported industrial applications including topics like control strategy, performance, economy, and safety. The structure of the reports (sections) and format are predetermined with clear instructions about content and style. Reports are graded in detail by the instructor (80%) and more generally by a panel (other instructors, TA, experts) (20%). Similarly, the 15-min presentations are also prescribed in the number and content of the slides, and the balanced participation of all members of the team. A panel grades the presentation by evaluating both the team and individual performance.

Team and communication skills development

The lab course also provides a comprehensive experience on team development, including training, coaching and performance evaluation (self, peer and external). There is a suggested cap number of 36 students in the lab, resulting in a maximum of six students per team to cover the six available experiments. Though 4-5-member teams have also been operative in the past, the current recommendation is for 6-member teams, as the same teams simultaneously run other projects in the companion course with a significant workload. Members are self-selected, favored by the fact that being seniors, they have had opportunities to interact previously in the career, align their interests and schedules, and they have already been exposed to work in non-self-selected teams.

The first session of the lab takes place in the classroom and provides basic information on the lab, scope, and syllabus for the course. In addition, students participate in a selection of team building games to reinforce team skills and strategies [14]. The first assignment consists of a 2-page assessment of that experience, where students report major takeaways to guide the participation in the team during the semester [14]. In addition, the teams must produce a signed "team contract" which includes a selected name, branding, mission statement, vision statement, main roles, responsibilities, leaderships, commitments and teamwork and conflict resolution strategies. This 2–3-page document follows closely the structure they were presented with in their first year. Students are invited to review this document as the course progresses and introduce modifications as needed.

The suggested strategy for teams is to subdivide them into an "office" and a "lab" sub team. The "office" sub-team oversees research for industrial applications, control strategies, characteristics sensors and controllers, process modeling (Matlab/Simulink), and developing the report and presentation. The "lab" sub-team oversees experimental plans, description of lab equipment, collecting and analyzing experimental data. The "office" sub-team includes the "research leader", leading the literature search and report narrative, the "computational leader", leading the development of models, and the "office assistant", taking assignments in both areas (research/report and modeling). The "lab" sub-team includes the "project leader", overseeing the entire project and mainly responsible for communications and conflict resolutions, the "lab leader", leading the proposal for experimental plans, execution of experimental procedures, and data collection and analysis, and the "lab assistant", taking assignments in both areas (project management and experiments). These two sub-teams exchange their functions and leaderships for the second project (Figure 7). Tables are provided in the lab for the members of the "office" sub-team to work comfortably, while "lab" sub-team members work at the benches for the experimental set ups. Exchange of information and mobility are encouraged, particularly for the project leader, and consultation with instructors and TA as needed. A MS TEAMS space provides a virtual office where intermediate results and report sections are progressively uploaded, with instructors providing advice as requested, reminders, and motivational messages (coaching), in addition to availability for office hours.



OPEN-LOOP	→	CLOSED-LOOP
Project Leader	→	Office assistant
Lab leader	→	Computational leader
Lab assistant	→	Research leader
Research leader	→	Lab assistant
Computational leader	→	Lab leader
Office assistant	→	Project leader

Figure 7. Structure and rotations for the sub-teams and members

The instructor grades the teamwork and individual performance according to the rubric presented in Appendix 1. It considers the grades for the report and presentation, the self-grade by the specific member, the peer grade by teammates, and the observed behaviors and reported contributions. Peer grade assessments are collected three times during the course using the rubric provided in Appendix 2. These are anonymous non-graded assessments where letters (A-F) identify teammates and are used to "sense" the team environment, but by the end of each project, students grade the teammates and provide feedback on behaviors and contributions, using the anonymous discussion feature in TOP HAT. The self-grade assessment at the end of each project reports on dedication, contributions, and reflections. It is intended to replicate an annual performance evaluation in job environments.

Table 1 reports the average grades for the two projects in one section of 35 students. The results show significant improvements in the grades for the second project grades over the first project, which is attributed to better training and expertise in the lab and assignments as a result of increasing experience. Presentations resulted in the lowest grades as the panel of four members identified weaknesses in procedures, results, and performance at presenting, followed closely by report grades. The averages compounded by the instructor are lower than the self-evaluation where some students honestly reflected some deficiencies. Peer grades are at the very top with very positive feedback on the performance of teammates, with very few instances of criticism, in what appears to be dominated by a sense of solidarity and the intention of not damaging the grades of their fellow students.

Table 1. Average grades for deliverables in the lab course with a section of 36 students

Type	Open-loop project	Closed-loop project
Presentation (by panel)	78.41	84.81
Report (by instructor, 80%, and panel, 20%)	80.89	84.99
Team/individual performance (by instructor)	87.56	94.52
Self-grades	93.58	96.32
Peer grades	98.69	99.09

The analysis of the self-grade assessment reveals interesting patterns of behavior. For example, only 12 out of 35 students reported to have dedicated the time assigned for the lab to work on the open-loop project, while the remaining students took some of that time for some other issues (upcoming exams or presentations) and a few absences (excused by sickness), with only one unexcused absence (Figure 8). The average for focused lab work was 10.79 instead of the expected 14 hours for the 7-week period. This has been a cause of concern in the past. Even when we have no quantitative data, it was observed by the instructor in previous courses that many students were using the lab time for other purposes, as only two students could perform the experimental set-up and data collection. The average time investment for the project (inside and outside the lab) was 24.27 hours. A striking observation from Figure 8 is the large variation in the time used outside the lab, ranging from only 3 hours up to 39 hours for the open loop project. About half of the students (17 out of 35 students) reported more than 21 hours involved in the project (a standard reference for 1 credit lab course with 2 hours of lab plus 1 hour of independent work per week)

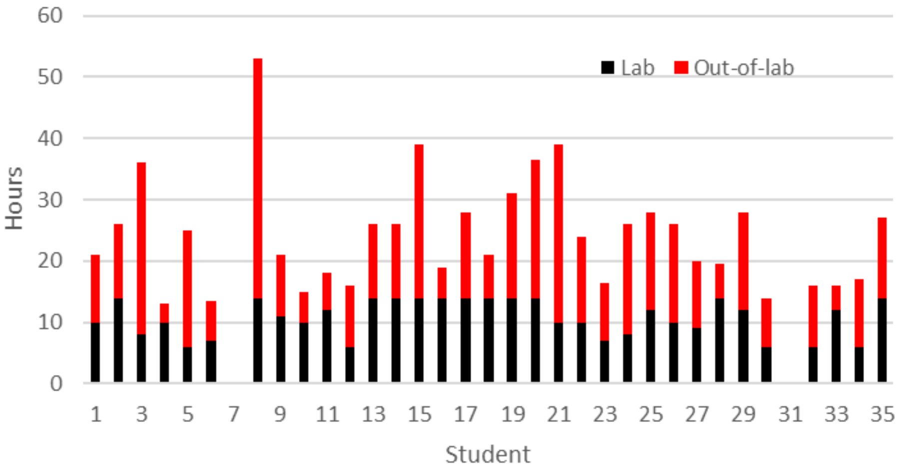


Figure 8. Time reports for students in the open-loop project

These variations were further analyzed by segregating them by group and leadership. Figure 9 displays this arrangement showing significant variations between groups and leaderships. Table 2 shows results comparing group and role performance in terms of time dedication for the open-loop project. The group average was in the order of 22-24 hours if considering that the highest 29.20 value for group 3 is related to the fact of being the only 5-member team. The high value of 26.33 for group 1 is heavily influenced by the extraordinary maximum of 53, and the lowest value of 20.60 for group 2 is lacking the data for the computational leader, generally the highest in the group. Groups 5 and 2 showed the least dispersion, with a general factor of 1.9-2.4 for the ratio maximum/minimum, except for group 1 that reached the value of 4 due to the reported extraordinary maximum of 53. For the leaderships comparison that factor ranges from 1.4 to 2.8.

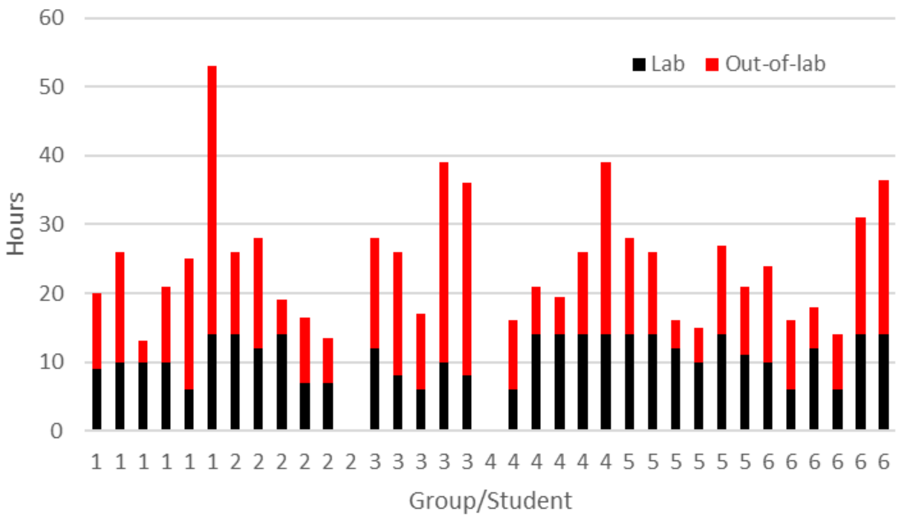


Figure 9. Time reports for students in the open-loop project arranged by groups and leaderships (with the sequence PL/LL/LA/RL/OA/CL). Group 3 is a 5-member team where one student took both the RL and OA leaderships.

Table 2. Summary of reported value by students for groups and leaderships time investment in the open-loop project. PL=Project leader, LL=Lab leader, LA=Lab assistant, RL=Research leader, OA=Office assistant, CL=Computational leader (as described above)

Type	Group						Leadership					
Hours	1	2	3	4	5	6	PL	LL	LA	RL	OA	CL
Ave.	26.33	20.60	29.20	24.30	22.17	23.25	25.20	23.00	17.33	20.83	24.50	37.10
StDev.	13.85	6.20	8.70	8.97	5.71	8.97	3.35	5.35	2.73	9.29	6.56	11.37
Min.	13	13.5	17	16	15	14	20	16	13	14	13.5	21
Max.	53	28	39	39	28	36.5	28	28	21	39	31	53

Project leadership, lab leadership and office assistantship took about 23-25 hours of time investment. The research leadership resulted in lower dedication (about 21 hours) but with large variations, while the lab assistantship ranked as the lowest (average of about 17 hours), but still the maximum reported time for this category was over the minimum of the other categories, meaning that there was no absolute divide between leadership time involvements. Lab assistantship was perceived in some students as a “minor” role (also reported for the office assistantship). Computational leadership clearly exceeded all others in dedication (except for one group). Computational leadership was claimed to be difficult to share. There is much room for improvement in balancing workload inside the groups. However, all students reported to be satisfied with teammates’ performance and the readiness for help. Table 3 displays the assessment average by group and member. Two groups gave everybody a perfect score of 10, three groups were in the 9.5-9.7 range, and one group showed significant variations, with an average of 8.74, though they reported no conflicts on the narrative for the assessment. The major takeaway reported was the self-criticism on limiting communications, procrastination, and the need to help each other.

Table 3. Teamwork performance assessment by week 6, at the end of the open-loop project

Member	1	2	3	4	5	6	Average
Group 1	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Group 2	9.50	9.48	9.29	9.31	9.81	9.81	9.53
Group 3	9.74	9.68	9.70	9.68	9.70	-	9.70
Group 4	9.59	9.67	8.41	7.94	8.11	-	8.74
Group 5	9.64	9.74	9.63	9.72	9.78	9.78	9.72
Group 6	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Moving into the close-loop project, only 9 out of 35 students reported to have used the total lab time for the project, with an average of 10.68 hours instead of the assigned 14 hours for the 7-week period, and 17 students out of 35 reported to have invested more than the reference 21 hours. The average for total time investment was 26.94 hours, an increase of 2.7 hours over the open-loop project, which would be expected due to the higher complexity of the project. The variations in time investment are again very significant (Figure 10).

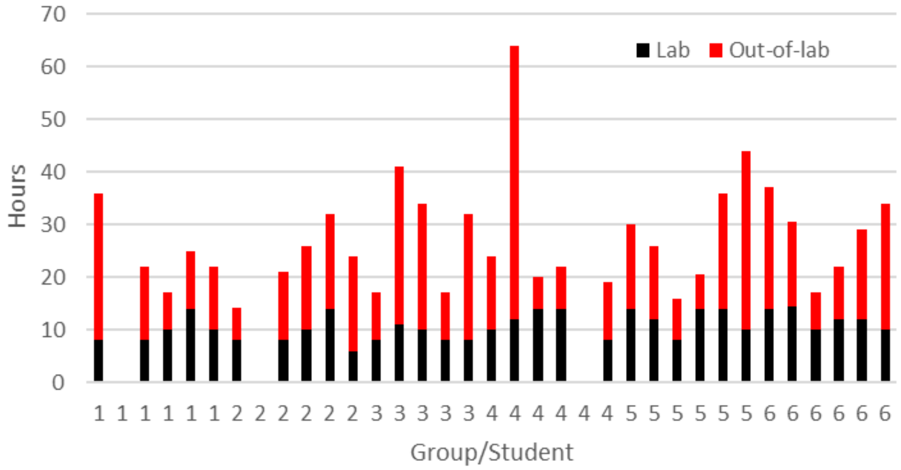


Figure 10. Time reports for students in the closed-loop project arranged by groups and leaderships (with the sequence PL/LL/LA/RL/OA/CL). Group 3 is a 5-member team where one student took both the LL and LA leaderships.

The group time average was in the range 23-29, with max/min ratios in the range 2.2-2.8 (if excluding the extraordinary maximum of 64 in group 4) (Table 4). Computational leadership time investment was now closer to project leadership and office assistantship, while the lab leadership was prominently the highest in time investment, but highly influenced by an extraordinary maximum of 64, with a runner up of 44 hours. The increased familiarity with the software on one side, and the increased complexity of the operations under the controllers on the other, may justify those trends. Research leadership and lab assistantships ranked again in the lower end for time involvement. Some students mentioned some team conflicts in their assessments for this project, however, the final peer grades (Table 1) taken at the end of this closed-loop project reported an average grade of 99/100 evaluation.

Table 4. Summary of reported values by students for groups and leaderships time investment in the closed-loop project. PL=Project leader, LL=Lab leader, LA=Lab assistant, RL=Research leader, OA=Office assistant, CL=Computational leader (as described above)

Type	Group						Leadership					
Hours	1	2	3	4	5	6	PL	LL	LA	RL	OA	CL
Ave.	24.40	23.45	29.17	29.80	28.75	28.25	26.38	40.38	19.20	23.58	27.80	29.17
StDev.	8.18	4.46	10.76	19.21	10.25	7.49	9.58	16.96	2.59	5.87	7.26	9.30
Min	17	14.25	17	19	16	17	14.25	26	16	17	17	19
Max	36	32	41	64	44	37	37	64	22	34	36	44

Figure 11 shows the distribution of time investment for the total lab. There remain significant differences in time investment after rotating leaderships, switching projects, and evolving with the course. Up to 9 students were below 40 hours, and 6 above 60 hours. Table 5 provides quantitative data for the class and groups. The class average of 50.67 hours is significantly influenced by the extraordinary maximum of 103 hours in Group 4, and the 57.40 hours average for the 5-member Group 3. This last figure points to the convenience of setting up 6-member teams for the extension of the assignments for the course. It is noticeable that every group included at least one student with a low dedication (below 35 hours). There is a significant spread inside the groups with a factor of about 2 for the ratio between maximum and minimum time investment, with some significant internal variations as computed by the standard deviation for every group.

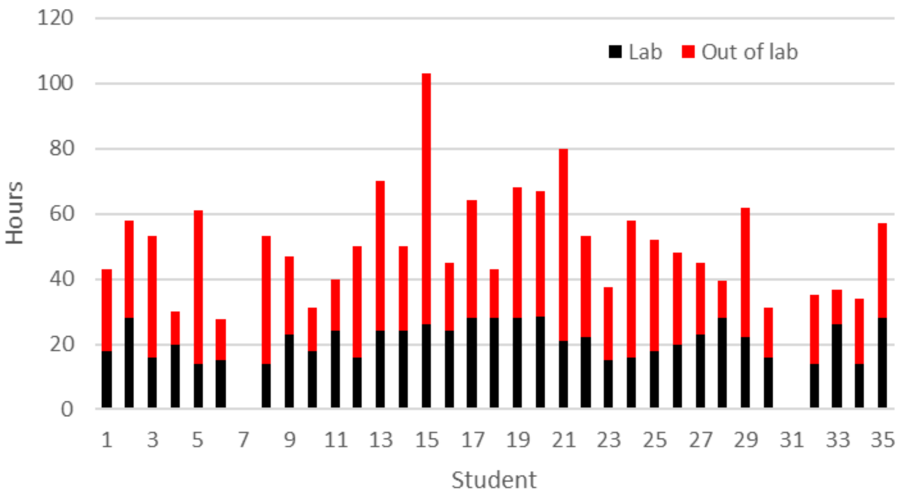


Figure 11. Time investment distribution for the whole lab

Table 5. Summary of reported values by students for time investment during the course

	Open-loop project			Closed loop project			Lab course			
Data	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	StDev
Class	14.25	64.00	27.23	113.00	53.00	24.27	27.75	103.00	50.67	16.49
Group 1	17.00	36.00	24.40	13.00	53.00	26.33	30.00	61.00	46.67	10.41
Group 2	14.25	32.00	23.45	13.50	28.00	20.60	27.75	58.00	44.05	15.11
Group 3	17.00	41.00	28.20	17.00	39.00	29.20	34.00	80.00	57.40	10.76
Group 4	19.00	64.00	29.80	16.00	39.00	24.30	35.00	103.00	54.10	19.21
Group 5	16.00	44.00	28.75	15.00	28.00	22.17	31.00	70.00	50.92	10.25
Group 6	17.00	37.00	28.25	14.00	36.50	23.25	31.00	68.00	51.50	7.49

Another interesting feature is the time investment distribution for the 7-week period of each project. Figure 12 displays the data for both projects. The open-loop project started with an introduction in the first week, a session on team building games to reinforce team skills, the assignment of the experiment (blind picking of experiment numbers), the availability of the manuals, and the description of the deliverables in the syllabus. Only 5 students reported some work out-of-lab that week, with a total average of 0.20 hours. The second week introduced a tutorial on Simulink and the statistical subroutines for parameters fitting. Only 12 students reported some follow-up work out of the lab, with a total average of 0.45 hours. Weeks 3-5 were lab sessions to collect data and to continue working on the research and report. The average time investments ranged from 1.02 hours to 1.64 hours for work out of the lab. Week 6 was reserved for teamwork on deliverables (available also to collect additional lab data if needed). Week 7 was for the presentation and submission of the report. Averages for these two weeks rose to 3.86 and 5.26 respectively for work out of the lab. The closed loop-project started with a lecture on instrumentation and the configuration of the lab controllers, the Simulink block configuration, and making available the reports from previous groups on the open-loop projects. The average out-of-lab time investment was 0.73 hours, with 17 students reporting no dedication. Weeks 2-5 were lab sessions, with out-of-lab time involvement increasing from 0.69 to 1.83 hours. Week 6 followed a recess period (Thanksgiving week) with lab time to advance deliverables (collection of lab data if needed, as only one group did), and week 7 was for presentations and reports submission. Averages reached 4.04 and 6.22 hours, respectively. It is clear the exponential trend in both projects, the large variations on the final two weeks of both projects, and the evidence of marked “outliers”. This confirms the procrastination criticism reported above and the trend for “last minute” efforts. The final week’s effort displays the largest variation on individual “behaviors”, accounted here by the time investment. This should warn teams of the potential for conflicts, though rarely reported here in the assessments and peer grading.

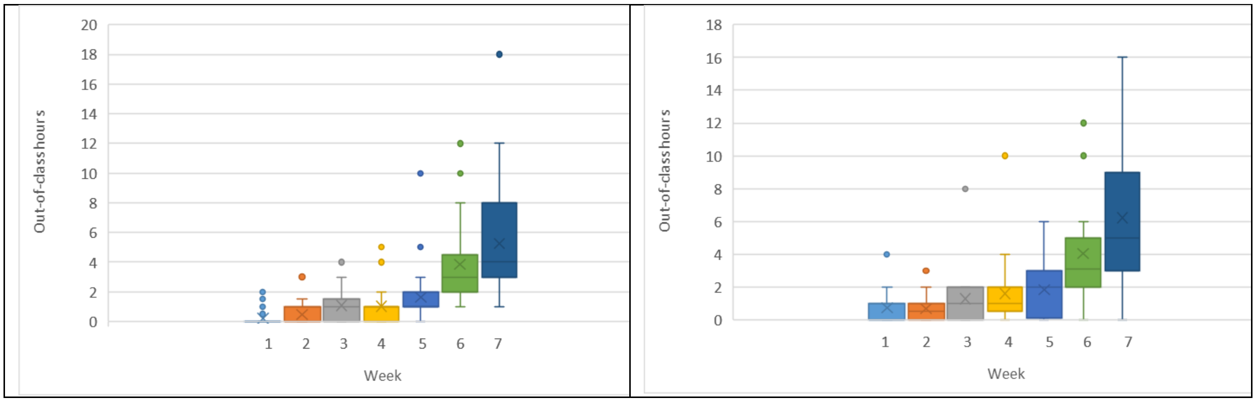


Figure 12. Time investment distribution for the open-loop (left) and closed-loop (right) projects.

The time investment metric used here to characterize team behavior is certainly not the only factor to relate to team results. In fact, Figure 13 suggests that increasing group average time investment was detrimental for grades on the reports and presentations. It can be noted that some teams performed better at presentation than in the report, and vice versa.

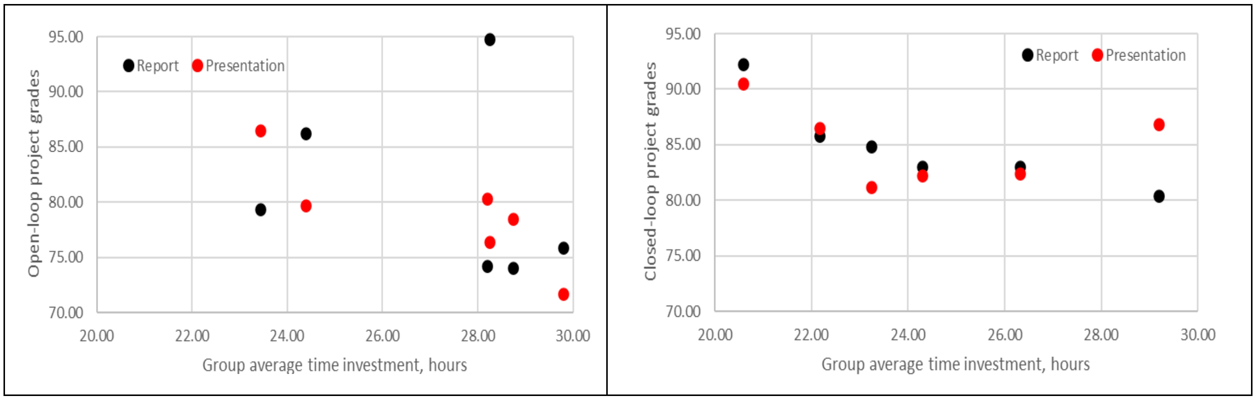


Figure 13. Report and presentation grades for the open-loop project (left) and closed-loop project (right) as a function of time investment (group average)

Students also addressed the quantitative assessment on the perceived contributions to the experimental work, research, report, and presentation, but variations introduced by the students in the format do not allow for normalization of results and cannot be analyzed at this time. The format for the assessment failed to present a normalized structure to collect the data.

Students also provided a narrative on their individual performance and highlighted main team behaviors. A sample of comments is provided in Appendix 3. A detailed analysis of that rich information goes beyond the scope of this paper. However, some clear trends showed that most students were very satisfied with the team experience and the learning value of the course (this was also addressed in a separate assessment taken at the companion core course). Some students showed resistance to the implementation of the office-lab team strategy. A frequent misunderstanding was to take the "leadership" assignment for a constrained "role" and to compartmentalize the associated activities, instead of exploring opportunities for collaboration by expanding communication to create synergies and more balanced workload. The computational work was considered more challenging and time demanding, also associated with some frustration on debugging the codes and perceived failures at lacking proper fitting of experimental data. However, all the groups produced sound reports and presentations.

These results show the convenience of more training and coaching on team performance, with emphasis on workload balance, communication, leadership, and synergies. Also, to avoid procrastination, "last minute" approach, and individual isolation. They also show opportunities to improve in clarifying open-ended assignments and specifying expectations. It seems that more scaffolding is required to assist on the computational assignments.

Global collaboration

It was documented above that many colleges face constraints in providing access to a process control lab for their students. However, it has been confirmed the interest and convenience of hands-on experience to deal with the abstract and difficult concepts involved in process control theory, mainly based on mathematical approaches. The authors want to offer collaboration in making the content and experiences of this course available to a broader community of chemical engineering students.

Another section of 36 students was also taking this course simultaneously, with the same approaches reported above. Analysis and comparison of results from both sections will be presented in the future, with more detailed assessment of the integrative experience with the companion core course, as reported by students. The reference is made here to point out the availability of a second set of experimental data and models for the same experiments, with proven efficacy in content learning and team skills development. In addition, new sets of data are collected in every iteration of the course, with variations due to experimental conditions and students' experimental approaches.

Also, an initial trial for external collaboration was run simultaneously during this course. It came halfway through the semester when two foreign professors of a similar Process Control course, with no or limited access to a Process Control Lab, showed interest in start to explore opportunities. Our students were asked to volunteer for the collaboration. They were offered 2 bonus points on the final grade for an estimated 4-hour involvement. A very positive result was that 48 out of the 71 students volunteered to connect with foreign students at these two universities in South Korea and Chile (South America). Five groups from South Korea and two groups from Chile were teamed up with the same number of our groups of students. Instructors encouraged their students to get in contact and share the lab projects data, models, and analysis. It was an entirely student guided experience monitored by the instructors. Four pairs of groups established introductory relationships, exchanging lab manuals and project descriptions, only two moved on with actual discussions on the lab projects during virtual meetings, and only one advanced into detailed analysis of data and simulation. Despite the limited progress of this attempt, restricted by the lack of sufficient planning, coordination, and proper timing, in addition to time-zone and language barriers, it confirmed the potential for a successful program of collaboration.

The authors envision a Process Control Global Academic Partnership (PCGAP) program where several institutions can share this experience. There are several formats to be considered.

1. Sets of experimental data can be shared for students to develop dynamic models and process control structures for level and temperature control experiments. The broad range of six different experiments provides a wide opportunity to adapt to time constraints or complexity of scope. The data can be provided in the EXCEL spreadsheet format to accommodate different software for modeling and simulation. The data can be accompanied by short videos to show the actual functioning of the equipment. Data is generated every year with variations, including potentially mistaken approaches requiring elucidation of the source of abnormal results. All this can bring "reality" to the experience. Instructors can adapt the content of the lab to the objectives and time of the course, selecting a convenient number of experiments and choice of scope (i.e., model development with estimation of parameters, process control with tuning parameters, correlation with industrial applications, and teamwork performance and strategies).

2. Collaboration can be arranged among groups of students, pivoting on our groups at the lab, to conduct and analyze experimental results, leading to the development of models and synthesis of PID controllers. This can also be combined with team strategies for improved training and performance in a more global environment of increasing importance. A more complex but feasible version could be arranging for teams composed of students from different universities to work out the same project.

3. Opportunities could also be arranged for running new experimental conditions following plans designed by distant students. A further option could be to implement remote operation of the equipment based on web communication as our lab is fully automated, though this option has never been tested and it may require further considerations on cybersecurity and safety protocols.

Certainly there is a need for planning and coordination. Some obstacles and barriers will come across. However, the motivation for making accessible process control lab experiences to students in colleges with no facilities, and the potential to develop teamwork skills in global partnerships provide a strong support to explore the opportunities. In addition, it can be a source for educational research, with an inexpensive structure.

Conclusions

A Process Control Lab proved to be an enriching training experience for chemical engineering students and fostered a better reception of the core course on dynamics modeling and controller synthesis. The setup of six fully automated experiments for level control and temperature control provided a wide range of technical content and practical applications to cover the extension of an intensive course in Process Control. In addition, the team strategy to harmonize several leaderships (literature research, computational modeling, experimental planning, and testing), with rotation in two projects, provided a rich experience in teamwork skills development. Metrics and assessments for team behavior, in addition to technical reports and presentation, provided relevant data to analyze and track individual and team performance. Finally, the experience, content (process description, experimental data, simulation), teamwork assessment and support are now being offered for global collaboration with colleges lacking experimental setups or enthusiastic to expand their students' training in process control by teaming up with other students across the world.

There is a need for further work in bringing down student's time investment to better compliance with curricular standards, targeting a maximum of 42 hours for the 1 credit-unit lab. In addition, more work is needed to reduce the disparities in time investment, strongly influenced by the task of modeling with the use of MATLAB and SIMULINK software. Three proposals are being considered: adjusting the number and extension of deliverables, reinforcing teamwork skills and coaching, and more guided support for simulations.

The development of a Process Control Global Academic Partnership (PCGAP) program offers instructors and students the opportunity to engage in a global partnership experience, enriching teamwork and collaboration skills, while advancing their knowledge of process control in the chemical engineering curricula.

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Appendix 1. Instructor to rubric for grading teamwork and individual performance

Systems Engineering, I: Dynamics and Modeling Lab
TWP1: Open-Loop Project Instructor Grading
Assigned: Tuesday 09/27/22 | Due: Tuesday 10/18/22
XXXXX XXXXXXXX

No submission required. Instructor will grade the teamwork and individual performance according to the following rubric.

Outcome Five	1	4	7	10	1-10
Team	Deficient	Apprentice	Proficient	Exemplary	Points
An ability to function effectively on a team	Little or no distribution of work efforts and responsibilities. No effort to match skills to tasks. Little or no ability to work together in a professional and productive manner adversely affecting end result.	Minimal organization and planning with limited contributions of most team members. There is considerable misuse or overlap of skills. Significant deficiencies in leadership, cooperation and/or interaction. End result may suffer to some degree.	Adequate organization and planning with contributions from all members of the team, although some individual's skills not used to best advantage. Some leadership, planning and interaction is evident.	Great organization and planning with full participation and technical contributions from all members. Utilized technical strengths of each team member to full advantage leading to productive interaction.	7
Individual					
Self-grade	Reflected on a deficient work to contribute significantly to the team performance	Reflected on missing opportunities to contribute to the team performance with limited support to the team	Reflected a moderate appreciation of the contributions to the team	Reflected an honest conviction of having excelled in contributions to the team	9
Peer-grade	Teammates gave very low grades for attitude and contributions to the team	Teammates gave low grades for attitudes and contribution to the team	Teammates gave positive but moderate grades for attitude and contributions to the team	Teammates gave high grades for attitude and contributions to the team	10
Other teamwork support materials	Unsatisfactory completion of other support materials included in the course for teamwork improvement	Limited completion of other support materials included in the course for teamwork improvement	Moderate completion of other support materials included in the course for teamwork improvement	Effective completion of other support materials included in the course for teamwork improvement	8
Communication with instructor	Very limited communication on frequency and content	Reduced communication on frequency and content	Moderate communication on frequency and content	Very effective communication on frequency and content	6
Observed performance at the lab	No significant engagement or enthusiasm in the lab, missing some sessions, involved in external activities, coming late, or leaving early	Limited engagement and enthusiasm, missing some session, occasionally involved in non-lab activities	Moderate engagement and enthusiasm in the lab	Engaged and enthusiastic, fully involved with lab activities	5
Instructor grade. Average (1-10)					7.50

Notes and Comments

Team	Report	86.20	Presentation	77.91	Contribution	N/A

Excellent team performance at MS TEAMS with 10 folders and 26 files on Experimental Plans, Experimental Results, Model development (Matlab, Simulink) and validation, and report sections. Limited scope for the team Contract. Good assessment of team games. Limited approach on peer grading

One missing lab session (unexcused)

Appendix 2. Peer grading assessment rubric

Adapted from C.J. Coronell, ® 2001							
Team							
Scale 0-10							
Date							
Member. XXXX XXXXX	A	B	C	D	E	F	
Leadership	10	10	10	10	10	10	
10 Very strong leader, provided direction, inspired and encouraged others							
5 Willing follower, took directions easily							
0 Frustrated the group, blocked progress, criticized others							
Cooperation	10	10	10	10	10	10	
10 Worked readily with others, outstanding contributor, anticipated requests							
5 Cooperated with occasional prompting							
0 Rarely contributed or cooperated, worked alone, had to be coerced							
Initiative	10	10	10	10	10	10	
10 Produced good ideas which helped others, "went the extra mile"							
5 Accepted other's ideas and improved on them							
0 Criticized other's ideas, never contributed original ideas							
Attitude	10	10	10	10	10	10	
10 Positive, enthusiastic, encouraging others to work better							
5 Neutral, worked with the group without either enthusiasm or grumbling							
0 Negative, complained about the project, worked unwillingly							
Effort	10	10	10	10	10	10	
10 Worked hard on assigned tasks, independently and cooperatively							
5 Worked reasonably hard, also socialized a lot. Occasional prodding needed							
0 Didn't contribute much at all, tasks were unsatisfactory							
Writing reports	10	10	10	10	10	10	
10 Enthusiastic, contributed substantially to production							
5 Contributed everything that was asked. Work needed revision							
0 Didn't contribute							
Preparation and delivery of presentations, posters	10	10	10	10	10	10	
10 Enthusiastic, contributed substantially to production							
5 Contributed everything that was asked. Work needed revision							
0 Didn't contribute							
Preparation and conduct of LAB work	10	10	10	10	10	10	
10 Enthusiastic, came prepared to meetings and lab							
5 Came to all meetings, somewhat prepared. Often helpful							
0 Missed lab, was unprepared, we'd have accomplished more without him/her							
Recitations	10	10	10	10	10	10	
10 Helped others to understand and use computer tools							
5 Good, but not incredible, use of computers							
0 Uninterested or unable to use computer tools effectively							
Grade	16.67	16.67	16.67	16.67	16.67	16.65	100
You have a total of 100 points. Distribute them among members in an equitable manner,							
where each score reflects effort and contribution (which aren't always the same).							
Assessment of the group. Please, do not override the calculation in the yellow boxes	10						
10 Best group I've ever worked with, the project was fun as a result							
5 Group sometimes worked well together, with occasional problems							
0 Worst group I've ever worked with (or not); this was a miserable experience							

Appendix 3. Selected comments on individual and team behaviors reported in students' assessments.

On the project leader

"I realized that I could have served as a better liaison and communicated between the groups more efficiently"

"Given the fact we are all seniors and have a lot of experience with similar projects, I did not feel the need to over-manage the group members' individual tasks given that they did not seem to need help. However, I did manage the timeline of getting deliverables completed."

On the lab leader

"My major takeaways from this report were how to structure and plan a successful experiment and how to present the data and succinct way"

On the lab assistant

"It was a little weird being separated into two separate groups, as it really hurt our team dynamic. As a whole, both research and modeling teams, we work very well together and are able to communicate and split up work well. However, we were never able to overcome the established roles and separation of lab and modeling. I think as an integrated team, we were very separated into lab and modeling to a point where it hurt our communication."

On the research leader

"I also found it difficult to not engage in the laboratory efforts as I was strictly "research" and wished I was able to participate more in the actual data, calculations, and modeling."

"I wish that I had improved my communication with the team when it came to understanding what was going on for the 'lab' section of the team, in addition to helping [the computational leader] with the codes and simulations"

On the office assistant

"I was not able to do as much as a like because my group members had larger roles than myself"

"My goals for the project were to contribute in meaningful ways and to assist the Computational Leader and Research Leader when they needed help. Most of the time they did not."

"I had a limited role during the open loop project as the office assistant, but I feel that I fulfilled my responsible well. My goal was to assist both the model and research leaders which I feel was done well. However; I believe that I could have done a better job organizing the final report and communicating with the lab team. So, for the next project having a greater leadership role I plan on having open communication between the lab and office team."

On the computational leader

“The one major flaw in how we went about our lab was that the computational leader had fallen in line with a lot of the tedious coding. To compensate for this I think our teamwork environment should embrace diffusing the computational work in the next series of sessions.”

“I did feel that the work load was heavily skewed in my direction.”

“I continually made myself available to help [computational leader], but he found it easier to work alone. […] No matter how much I offered, I couldn’t find anything to help him with. This is fine, but there are some concerns that I believe started to appear in the past week that we don’t have enough visibility into [his/her] progress. There were a lot of blanks on the modelling side for the presentation and report up until a couple of days ago, and in our meeting, it was difficult for us to get any idea on where [he/she] was at.” … “Difficult to work together on coding just because of the nature of it. […] my team members reached out to me to ask what they could help me with or if there was anything they could work on as far as the model went, and I really appreciated that.”

“Being the computational leader, it was my responsibility to make sure that the model and all coding was done properly. Because this was very clearly defined, I think it led to me doing more work and having harder work than others. In hindsight, I could have asked for more help on the section to divide the workload, but it is very hard to code as a team and break up working on code.”

On team performance

“One thing that was exceptionally appreciated was that there was zero tension in the group ever. It is very easy to perform your best in that comfortable of a setting.”

“Our teamwork environment was very efficient and collaborative. We had sufficient communication and helped whenever needed.”

“Our group agreed that working on the paper in the lab setting was tough which is why we spent a good amount of time outside the lab working on this paper, but I am proud of how it turned out.”

“The teamwork environment was very productive and overall, they was pretty open communication between the lab and office teams. […] Members also offered to take on extra work to help balance out the heavier roles in the group as well.”

“I think that the two sub-teams worked well together, and we were able to piece together a respectable set of deliverables by dividing the work according to our project focus areas. My other teammates also adhered to this concept well, and everyone was happy and willing to contribute on their respective responsibilities of the project.”

“The separation of experimental and computational teams left a disconnect that manifested in differing focal points (what temperatures to model, for instance). Furthermore, the sanctioning of roles led each of us to assume the burden of our responsibilities, often carrying those burdens alone.”

Overall

“One thing we could do better is to communicate more, as there were instances when we tackled some tasks on our own.”

“Ultimately, I feel that this project helped me to feel more confident in my abilities as an engineer within a laboratory setting and helped me to highlight gaps within my skillset to reinforce in the future.”

“The points I took away from this lab is that collaborative teamwork is key in generating a successful project. Also, controller systems can be finicky and complicated but with utilizing key concepts taught in class, guesses and assumptions can be made to simplify and solve problems with the process. Overall it was a useful lab that taught a lot about process control.”