PROCESS SYSTEMS ENGINEERING EDUCATION: LEARNING BY RESEARCH

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Chemical Engineering (ChE) education is a challenging task and is quite demanding for both teacher and student. The teacher has to effectively convey subject matter while the student must continuously develop knowledge and skill. In today's world, universities are becoming more and more competitive grounds for the elite educators serving students who are demanding concise higher education.[1, 2] In this setting, the teacher must respond to this demand by providing a suitable and effective environment for learning. The broad question raised in this paper is "What constitutes such an environment?" In trying to answer this, we must recognize that the learning process is a complex interaction between the teacher, the student, the subject matter, and the learning environment. We further recognize that the teacher and the student carry with them inherent education attributes that also affect the learning process regardless of the subject matter and the environment.[3, 4] In dealing with the question raised, we have come to realize the significance of the concepts of "facilitating" knowledge, project-based learning, and generic attributes, to which we will first direct some attention before we discuss the question at hand in the context of Process Systems Engineering (PSE) education.

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TO FACILITATE

Firstly, the notion of facilitator replacing teacher is welcomed as a key ideological change in the mind of the educator. Many academics recognize that learning is the responsibility of the students as much as it is the responsibility of the teacher, if not more.[5] In many institutions we are starting to see the term teacher or lecturer being slowly phased out and replaced by the term facilitator. This is simply because these institutions see the teacher's role as that of a facilitator and a mentor rather than as someone who solely teaches. This is one aspect required for the creation of an effective environment for learning. Being among those who advocate this shift, we will use the word facilitator throughout the rest of this article to refer to the academic teacher.

In the past, teaching could be represented by Figure 1(a), which is a passive mode of instruction as practiced in the traditional lecture room. Bombarding students with knowledge during a lecture period does not achieve much learning nor does it contribute adequately to graduate attribute development. Enhancing the learning experience calls for active participation by the students in the subject matter. This is illustrated in Figure 1(b) by the active-learning model, where teacher-student interaction is promoted. A more advanced learning model is illustrated in Figure 1(c)—the interactive model, in which student-teacher contact is extended to allow for student-to-student interaction on the subject matter. Many educationalists advocate for this type of learning model, realizing that students tend to learn more from their peers and less from the teacher.

PROJECT-BASED LEARNING

Secondly, effective learning is inevitably related to the subject matter and to the degree the student enjoys the subject content. Making the learning of the content a matter of interest to the student becomes vital. One way of doing this is to provide students with real-life examples.[6] The learning activity is always made more interesting and appealing when one can relate what is being taught to something from previous knowledge or experience, or to a problem relevant to real life. Problems and projects become important tools to the facilitator who is able to focus the student's mind on the ideas and concepts of the subject matter. Problem- and project-based learning are great environments that allow the embodiment of learned matter and thus promote deep learning as opposed to surface learning.[7, 8] Thus, the context the subject matter is delivered in is what has impact on student learning. For instance, if one of the course's learning outcomes is to understand model predictive control (MPC), we could have students read about the control technique and then instruct them on how to tune the controller parameters. As an alternative, we could challenge them to implement MPC algorithm on a real-life dynamic process. Or we could extend the learning to explore other dimensions influenced by the control problem such as how the control solution to be offered by the students impacts process operation, efficiency, economics, or even the environment. It is argued here that we should facilitate learning as exemplified in the third case, where the subject matter (MPC control strategy) is better and more completely comprehended by the students. This is because the students' level of interest is elevated because they relate to the problem and consequently delve into it beyond its theoretical boundaries. The learning environment benefits greatly from students' perceptions of the subject matter. The context in which the problem is posed to students plays a key part in achieving learning outcomes.[9]

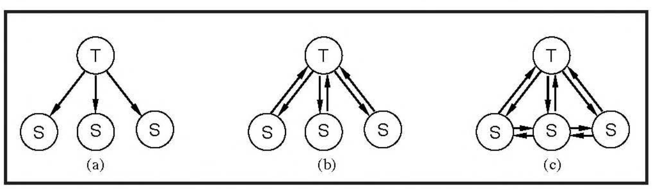


Figure 1. Learning models: (a) passive, (b) active, (c) interactive. (T) teacher, (S) student.

GENERIC ATTRIBUTES

Thirdly, the facilitator also has to consider students' non-technical development, viz. generic attributes. In this way, the facilitator is not only concerned with developing and extending students' engineering knowledge and technical know-how, but also with imparting a set of generic attributes necessary for post-graduation professional life. Three overarching attributes have been identified—a scholarly attitude to knowledge and understanding, global citizenship, and lifelong learning.[10] These are in turn represented by more specific attributes contextualized differently in different disciplinary domains.

Students in the ChE undergraduate program are being trained to become engineers with a certain set of skills and knowledge, and so the course being delivered has certain aims and learning outcomes.[11] Some of these outcomes directly relate to learning the subject matter, while others relate to student development. In this regard, the development of graduate generic attributes is now well recognized as an essential learning outcome and many progressive universities advocate developing them by imposing them in their academic policies. The generic attributes set by a higher education institution are a reflection of vision toward the development of graduates. Generic attributes are usually treated differently to subject matter and are typically found in university policy documents. They are less commonly found within the course outline document—which is usually stuffed with titles of content matter— and in the cases where they are found, they are referred to by simple statements that students rarely relate to. A key approach is to explicitly include the generic attributes within the course so as to recognize from both the facilitator's and students' ends that these attributes are part-and-parcel of the learning in the course. Students will appreciate that these attributes, when gained, will qualify them to progress forward in their profession. So, what generic attributes do you target and how do you manage their facilitation? We identify four attributes that students should develop through the PSE class:

1. *Research and inquiry: Students will be able to create new knowledge and understanding through the process of research and inquiry.*
2. *Critical thinking: Students should have certain thinking skills and exercise critical judgement. This involves rigorous and independent thinking that has logical and objective bases.*
3. *Communication: Students recognize and value communication as a tool for negotiating and creating new understanding, interacting with others, and furthering their own learning.*
4. *Professionalism: Students hold personal values and beliefs consistent with their role as responsible members of their engineering team.*

The facilitation of these attributes in the course can be achieved through use of key teaching tools. This is also very much related to, and should be aligned with, assessment.

Table 1 lists assessment items as well as what attributes these items target. Focusing on generic attributes stimulates student learning because students perceive this as personal development preparing them for the workforce. (This is our conjecture and is yet to be proven.) Beyond being a natural complement to learning, the development of generic attributes has direct positive influence on comprehending the subject matter. In the following sections, we discuss how we have integrated the three above-mentioned factors (*i.e.*, facilitation, project-based learning, and generic attributes) into the teaching and learning of the PSE course. We first describe the PSE course.

THE PSE COURSE

This course is offered to final-year students as an elective in the ChE degree program for the duration of one semester (13 weeks). The main objective is to make students familiar with strategies used by Process Systems Engineers in a team environment. The course involves students in many aspects of PSE and in a number of phases of process development, including process conceptualization, fundamentals of process development, process integration, process modelling, simulation, synthesis and design, optimization, control, and operation.[12]

TABLE 1
The Generic Attributes and Their Corresponding Teaching Tools

Attribute	Assessment Item
Research and inquiry	Literature search and review
Critical thinking	Problem analysis
Communication	Report writing, panel discussion and presentation
Professionalism	Peer evaluation and feedback

This course, like the final-year design project, may be considered to be a capstone course in ChE, although the PSE course integrates in a more concentrated way the various concepts and principles from the earlier PSE stream of courses (ChE computation, process modelling, process control, advanced process control). The course is designed as a project-based course and is dominated by activities aimed at achieving a practical solution outcome.

The students encounter problems typical of those faced by a practicing chemical engineer. These problems are carefully selected from postgraduate research projects and are presented to the students at the beginning of the semester in the format of a manager assigning a project to a group of engineers. In this format the problem is ill-defined in the sense that insufficient data and information are provided. Having the problem very much open-ended makes the scenario like that of a real work environment. Problems given do not have a solution to begin with while any solution is the result of students' efforts and output. Groups of three or four students are formed by instructors to distribute intellectual strengths evenly. Groups work together to achieve project milestones, which form the assessment items to be graded.

The first milestone, a preliminary report based on a thorough literature review, is due at three weeks, after which the students present a detailed problem definition and project solution plan. A progress report due at the end of week 8 is the second assessment task. It requires students to report back on their advancement toward their solution, and whether changes are needed in their initial plan. A final report submission at the end of the course (week 13) is immediately followed by a final presentation and discussion. Throughout the course there is continuous review and feedback. Students are asked to provide confidential feedback on their contributions as well as their peers' within each group via the report submissions and across groups via the presentation. This peer review is used as guidance in the process of grading the students.

The coordination and facilitation of the course is illustrated in Figure 2. Regular meetings with the project advisors (postgraduate students) are scheduled on a weekly basis and it is the responsibility of the students to arrange these. The course tutors who are postgraduate students hold meetings with the course coordinator as needed. In Figure 2, the typical management hierarchy found in an engineering company is put beside the PSE course organization chart to illustrate the similarity to a real-life workforce environment.

The course emphasizes the concepts and tools used in process engineering. Moreover, students are introduced to a number of new topics in the field of PSE, including

- *Introduction to process systems engineering*
- *Cost-benefits analysis*
- *Process modelling (steady state and dynamics)*
- *Process optimization (theory and applications)*
- *Advanced process control concepts*
- *Data management and process data reconciliation*
- *Process integration techniques*
- *Computer aided process engineering (CAPE)—students are introduced to typical commercial packages used by process engineers*

THE COURSE PROJECTS

In this section we report back on three projects previously given to students in the course and describe them in some detail.

<u>Project 1.</u> Model predictive control of a propylene glycol reactor

Model predictive control (MPC) was implemented on a dynamic HYSYS (Aspentech, USA) model of a propylene reactor. The controller was designed and built in Excel. The temperature of the reactor is controlled by manipulation of the heat input to the reactor. An MPC graphical interface shown in Figure 3 was developed in Excel and was connected to HYSYS allowing real-time data transfer. The control of temperature by the MPC is compared to that of a conventional PID controller to determine its control performance. The students comprehended the advantages of MPC over PID control.

<u>Project 2.</u> Data Reconciliation in a VCM Plant

This project involved the application of data reconciliation to a Vinyl Chloride Monomer (VCM) plant. In this study, mass flow rate data from a fully measured and a partially measured plant were reconciled. The VCM plant studied was modelled in HYSYS. In developing a solution to the data reconciliation problem, a number of software packages were used and a data reconciliation interface developed (Figure 4, next page). The linking of these packages and development of the interface were also resolved. A solution for the detection of gross error in sensor measurements was undertaken and a sample result is shown in Figure 5 (p. 63). In the conclusion of the submitted final report, this group of students stated:

> *"...the model is capable of detecting faulty sensors by the use of a global error test. More importantly, the partially measured case study has shown that a reduction in the number of sensors from 35 to 24 is possible without any loss in accuracy. This, of course, results in a significant drop in the cost of the sensors if this model is used in an actual VCM plant."*

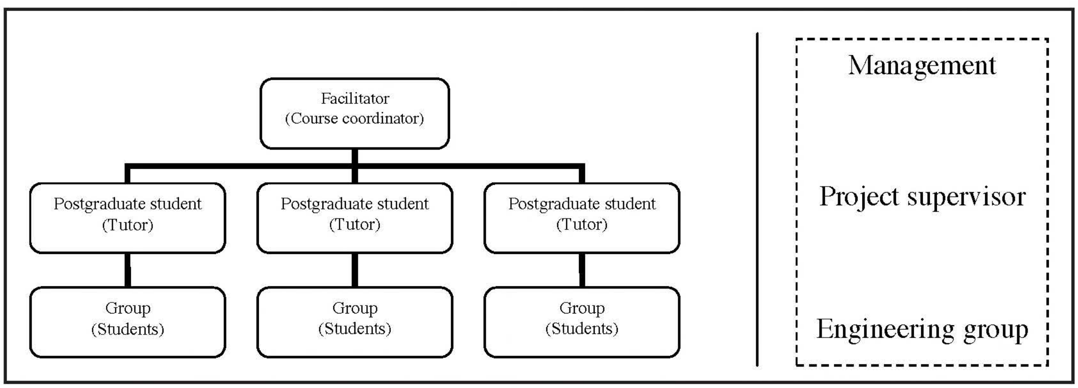
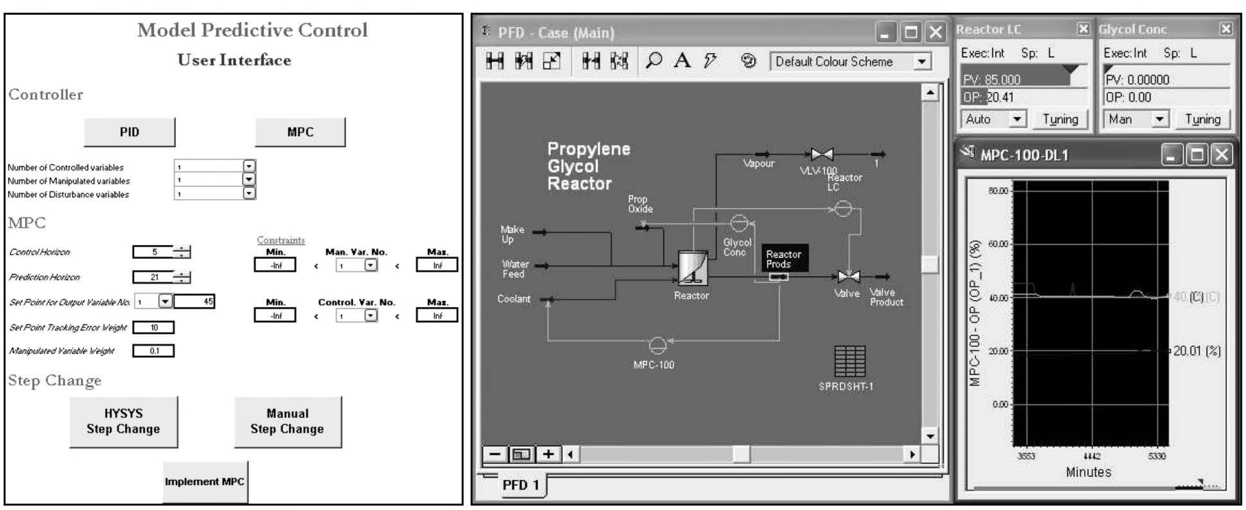


Figure 2 (left). *PSE Course organization chart.*

Figure 3 (below). *Model predictive control of a propylene glycol reactor. Left side: Main graphical interface. Right side: propylene glycol reactor HYSYS flow-sheet with control and monitoring facilities.*



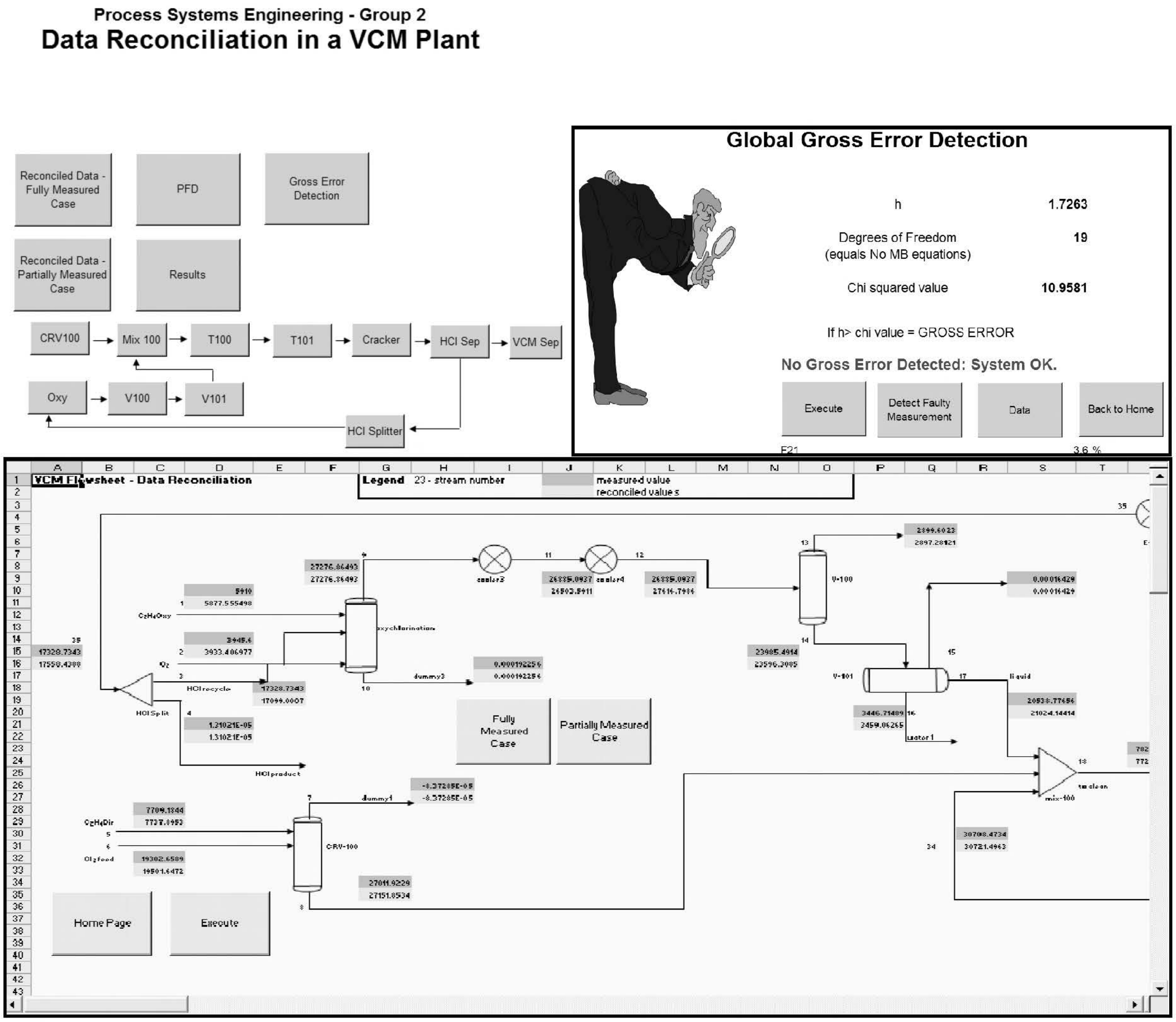


Figure 4. Data Reconciliation in a VCM Plant. Top left: Main graphical interface. Top right: Gross error detection interface. Bottom: VCM plant linked flowsheet.

Project 3. *Pinch Target Analyzer*

In this project, the students developed a good understanding of heat integration concepts and techniques and made use of this knowledge to develop an interactive Excel spreadsheet program that performs pinch analysis (Figure 6). The "Pinch Target Analyzer," as this group of students named it, is a heat integration software tool that integrates data extracted from a process with the available utilities for optimum energy utilization and minimum utilities usage. It uses thermodynamic pinch analysis as the basis for designing a heat exchanger network where it employs three main concepts: the problem table, the grand composite curve, and the pinch point. This program takes the required data (streams and utilities information) either manually (by the user) or automatically (directly from HYSYS flowsheet) to decide on the minimum amount of utilities usage. It plots the grand composite curve and the problem table, which shows the enthalpy of the process streams as a function of temperature.

LEARNING AND OTHER OUTCOMES

The projects presented in the previous section are there for illustrative purposes to provide the reader with a feel for the kind of activities undertaken by students in this course. From the result one could judge that in reaching the deliverables presented here by the students, they would have had to become competent in the necessary knowledge, know-how, and soft skills. It didn't take the students long to discover that what they had embarked on in this course is not what was previously experienced in the first years of their degree program. Their solution to their project problems was a unique one and was fashioned by their creativity. The main outcomes of this course can be summarized as follow:

1. *Positive interdependence and teamwork: Students grasp the idea of team success when their individual success depends on group's success. The groups are instructed to involve all members and determine the best way to use each member's talents. Students*

learned how to get along with others, how to manage their time, and how to integrate knowledge,[13] areas in which they enhance their leadership and interpersonal skills. Students are highly encouraged to be active in the groups and continuous feedback is given to each student.*

2. *Effective communication: Students worked together, talked and listened to each other, and respected each other. Good communication among group members was enforced and students used other communication tools such as e-mails and instant messaging. This improved their level of communicating ideas via report writing and oral presentation.[14]*

3. *Ownership of learning and research: Students took charge of their own learning, leading each other toward a common goal. The realization that the learning was their responsibility had a great impact on the students, who found themselves in a new homework scenario where they had to research to learn about and solve a given problem, rather than relying on the instructor to provide the relevant knowledge.[15] This also raised their level of interest as it drew upon their resourcefulness and creativity.*

4. *Individual accountability and personal responsibility: Group members shared the work of the project and individual accountability was evaluated based on the corresponding sections of the submitted reports and presentation. Students had enough flexibility to work alone as well as together in the team.*

5. *Engineers not students: Students are treated as professional engineers in an engineering consultancy environment where they are responsible for discovering solutions for open-ended problems. Students appreciated the complexities of real-life problems that lack necessary data for solution.*

6. *Research at undergraduate level: Teaching strategies such as peer teaching, collaborative learning, and individualized learning increase student involvement and comprehension—especially so in a research-based learning environment.[16] Moreover, students gain research skills as they are asked to update their knowledge and techniques using journals and other sources rather than being dependent on the textbooks.*

STUDENT FEEDBACK, DISCUSSION, AND FUTURE DIRECTIONS

Students in this course worked much harder than they expected, learning how to do literature review and how to complete a substantial writing project. Later, many students expressed gratitude toward the course tutors since their experience in the course made it much easier for them to do and write their final-year theses and complete the final-year design project—and in one instance, find a job. Feedback was collected at the end of the course during interview sessions with all groups present. Other than administrative issues raised by the students, positive feedback was prevalent. Students indicated that this method of learning was new to them but they found it useful in developing their skills. Students appreciated the research environment and the contact with the postgraduate researchers. Many suggested that this type of course administration should be delivered earlier in the degree program. Some students suggested that more assistance be given in the beginning of the course with learning certain tools such as the simulation and modelling packages.

Some benefits of conducting the PSE course in this way include learning by research. Research being conducted by the academic and/or the postgraduate student would be used as learning material at the undergraduate level. The undergraduate student in turn learns by researching the topic presented to him/her. The efforts of the undergraduate students are harnessed and their research project output supports the efforts of the postgraduate student in the first instance and the facilitating academic in the second. This win-win situation represents, in our opinion, a necessity in the teaching and

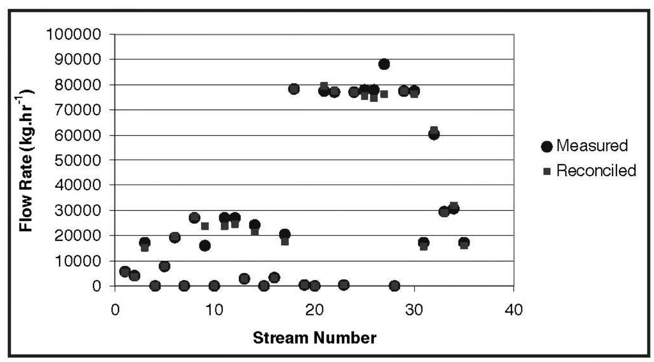
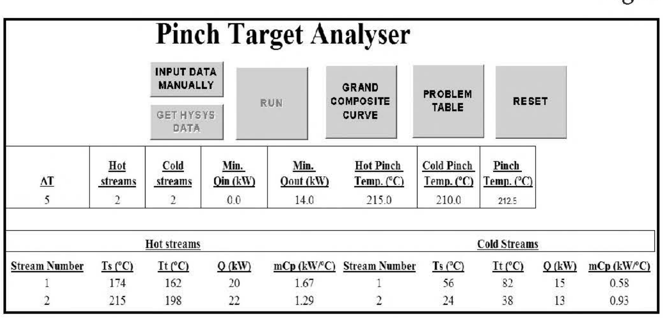


Figure 5. *Case with two gross errors at streams 9 and 27.*



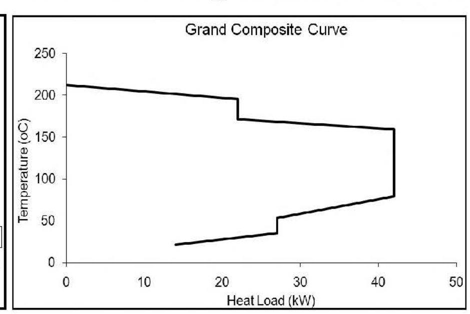


Figure 6. *Pinch technology and energy conservation. Left: Main graphical interface. Right: Grand composite curve.*

learning of higher education; all stakeholders in the teaching and learning process are rewarded for their efforts. The student benefits in gaining new knowledge and attributes, the postgraduate student's efforts in guiding the students provide him or her with help with the research, while the whole exercise is profitable for the facilitating academic and the research area. Effectively, in shifting toward this "learning by research" model of teaching, we are optimizing the time and resources available. Another benefit is the exposure of the students to the research environment, which may entice some to undertake postgraduate studies.

In this model of university teaching and learning, the ownership of learning is transferred directly to the student. To further enhance this, at the beginning of the course the students could be required to develop and sign a learning contract. The contract details the student's individual learning outcomes and methods for achieving them.[17] This kind of "ownership of learning" requires students to plan their learning and develop a path toward their desired outcomes, ultimately leading to responsible deep learning that is individualised.

Inter-group interaction could be enhanced to provide more stimulus and convey the interdisciplinary nature of real-life engineering problems. For instance, the data reconciliation project could have been integrated with the MPC project. The purpose of data reconciliation is to eliminate random errors from plant data so that accurate decisions and control of a process can be made. By linking the two projects, the importance of data reconciliation in an industrial control can be further elucidated. The reconciled data would also help the control group in the development and operation of their control system. Integrating projects in this way poses several challenges and should be considered after several iterations of conducting the PSE course. A key challenge is to achieve the desired learning outcomes when integrating projects. To do this, the facilitator should refine the projects so they are set at the appropriate skill level for the students, while ensuring the link between projects does not negatively affect the progress of individual groups. For instance, the facilitator should provide sample data to work with while one group is waiting for data from another group.

CONCLUSIONS

A project-based group learning approach in the PSE elective course was presented, with emphasis on both technical knowledge development and generic attributes. Students found this learning environment stimulating, especially because the assigned projects were derived from higher-level, real research problems and were challenging due to their open-ended nature. The course organization was presented, incorporating the academic supervisor and the postgraduate students, further enriching the learning environment for the PSE class. Three typical projects were described and corresponding student outputs were presented. These along with students' feedback demonstrate a deep level of learning and show the potential of this approach in PSE education.

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