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Teaching Process Optimization Online: Lessons from the Pandemic

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The lockdowns implemented in most countries in response to the COVID-19 pandemic led to the need for improvisation in the delivery of higher education. These measures involved the widespread use of remote learning platforms coupled with reconfiguring content and pedagogy to suit an electronic environment. While many of these emergency innovations may be abandoned once the pandemic ends, some lessons can be drawn from the experience and adapted for use in the post-COVID-19 world. This work describes the delivery of the module entitled “Optimization in Chemical Engineering” to postgraduate (masters and doctorate) students at De La Salle University in the first half of 2021. We emphasized model building skills through a series of structured exercises using case studies from literature. Mathematical foundations and software proficiency were initially taught separately in a parallel track. The final term project and oral exam were designed to combine the skills learned and to further emphasize the role of practical engineering interpretation of model outputs. In addition, students were required to work in pairs to address both mental health and invigilation issues. We also discuss the prospects for the use of this approach in face-to-face and hybrid delivery for both postgraduate curriculum and continuing education for professional engineers.

1. Introduction

The sudden onset of the COVID-19 pandemic and ensuing lockdowns forced universities all over the world to make rapid emergency adjustments by shifting to online learning (Pintarič and Kravanja, 2020). Although online learning helped to ensure the continuity of education, one notable problem was the decline in the enthusiasm of students due to social isolation (Yasmin, 2022). During this period, reduced interactivity hampered the learning process, while poor internet connectivity in some locations created disparities in outcomes (Ghasem and Ghannam, 2021). Another important challenge was ensuring the integrity of academic assessments (Pintarič and Kravanja, 2020). Although the use of online learning has led to reductions in the environmental footprint of higher education (Lopes Silva et al., 2021), the balance between costs and benefits of the sudden transition remains unclear. The long-term implications for chemical engineering education have not yet been thoroughly studied.

Process Systems Engineering (PSE) is the computational branch of the chemical engineering discipline (Stephanopoulos and Reklaitis, 2011). It deals with key tasks of design and control, and makes extensive use of computing tools to manage these engineering challenges. Optimization for profit maximization or cost minimization is a vital tool in the design of commercially competitive process plants (Smith, 2016); it is also critical for ensuring that such plants can be built and operated within sustainability limits (Bakshi, 2019). Mathematical Programming (MP) is one of the major approaches to dealing with optimization problems in chemical engineering (Klemeš and Kravanja, 2013). Use of MP models in the field date back to the mid-20th Century when Fenech and Acrivos (1956) first proposed the use of Linear Programming (LP) models in the context of chemical engineering. Other notable developments include the formulation of a Non-Linear Programming (NLP) model (Sriram and Stevens, 1973) for optimizing the fictitious process of Williams and Otto (1960), and the development of generic Mixed-Integer LP (MILP) models for general process synthesis (Grossmann and Santibanez, 1980). Optimization with MP models has now been integrated into mainstream chemical engineering education. In addition to theoretical foundations, optimization is taught nowadays with the

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aid of dedicated optimization software (Garcia et al., 2012) or commercial spreadsheet applications (Briones and Escola, 2018).

This paper describes the experience in the online delivery of the postgraduate course “Optimization in Chemical Engineering” at De La Salle University during the pandemic. The course was delivered concurrently as part of the course requirements at both masters (CHE616M) and Ph.D. (CHE616D) levels in the second quarter of 2021. Due to the prevailing conditions in the Philippines at the time, educational innovations were improvised to ensure the delivery of quality instruction. The key strategy was to organize the curriculum around the key skills of model building, model coding, and solution interpretation. Learning activities were based on micro-lectures (Liu et al., 2021) and team-based exercises and assessments. The rest of the paper is organized as follows. Section 2 gives an overview of the curriculum of postgraduate chemical engineering degree programs at De La Salle University. Section 3 describes the syllabus of CHE616M and CHE616D as it was delivered in 2021. Section 4 gives an account of experiences and student outcomes, including a description of an example of a project and assessment. Section 5 gives the conclusions and discusses prospects for drawing some lessons for more effective PSE education in the post-pandemic era.

2. Curriculum Description

This section describes the overall structure of the postgraduate chemical engineering degree programs at De La Salle University. The key features of the programs are shown in Table 1.

Table 1: Postgraduate chemical engineering degree programs at De La Salle University

Degree name	Abbreviation	General requirements
Master of Science in Chemical Engineering	M.S. Ch.E.	Coursework (30 units) Master’s thesis (6 units)
Master of Engineering (Major in Chemical Engineering)	M.Eng. Ch.E.	Coursework (42 units) Industry project (6 units)
Bachelor of Science/Master of Science in Chemical Engineering (“Ladderized”)	B.S./M.S. Ch.E.	B.S. Coursework (196 units) M.S. Coursework (30 units) Thesis (8 Units)
Doctor of Philosophy in Chemical Engineering	Ph.D. Ch.E.	Coursework (18 units) Dissertation (12 units)

These programs target distinct groups of students. The M.S. Ch.E. program leads to a research-based master’s degree for students with academic careers, or those who intend to pursue further postgraduate studies. The master’s thesis in this program is a scaled-down version of a Ph.D. dissertation. On the other hand, the M.Eng. Ch.E. program requires a capstone industrial project instead of a thesis. Both programs can be completed in 2 y by full-time students. The B.S./M.S. Ch.E. program is designed for high-aptitude undergraduate students, and appends an accelerated version of the M.S. Ch.E. curriculum to the B.S. Ch.E. program to allow both degrees to be earned in 5 y. The Ph.D. program is a research-based program that requires students to make a novel contribution to the discipline’s general body of knowledge.

Each module in all of these programs is typically equivalent to 3 academic credit units, which corresponds to a total of 42 contact hours over a standard 14-week trimester. These contact hours include assessments such as written and oral exams. Most modules are common to both master’s and Ph.D. degree programs, with the official course code being designated with either M or D to signify the student level. However, student assessments are generally different for Ph.D. students

3. Teaching CHE616M/D

The CHE616M/D module was delivered online in the second trimester of the 2020–2021 academic year of De La Salle University using Canvas as the learning management system (LMS) and Zoom as the teleconferencing platform. This period coincided approximately with the second quarter of 2021. Three lecturers were assigned to teach the module for redundancy in case of adverse events such as illness. A total of 18 students enrolled in the module, with 2 at the Ph.D. level. They were assigned to teams of 2 persons each for all assessments.

To manage the potential cognitive bottleneck in remote teaching, the three key skills shown in Figure 1 were identified and taught separately the first half of the trimester. Lectures and other learning activities were organized based on these three main areas:

- Skill 1: Model-building, or the translation of an engineering problem into computable form as an MP.
- Skill 2: Model encoding, or the implementation of a given MP in an appropriate software environment.

- Skill 3: Interpretation, or the deduction of engineering insights from the MP solution.

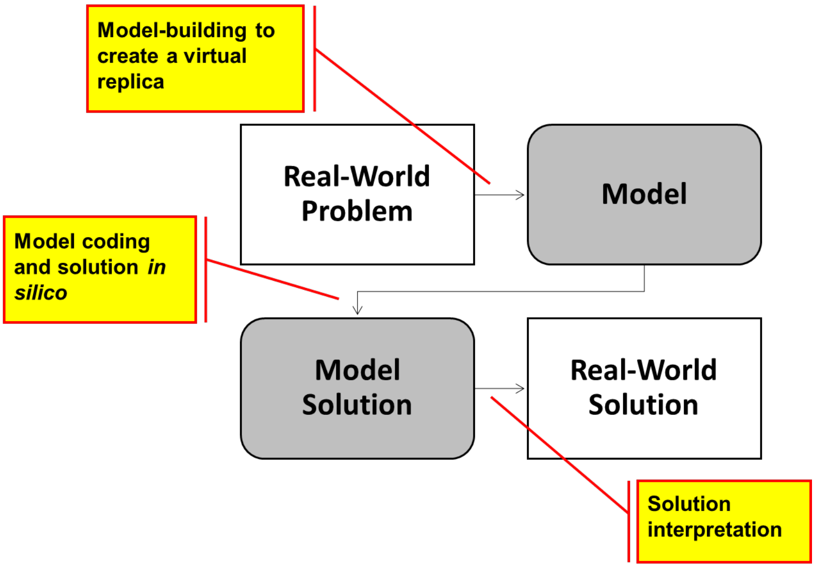

Figure 1: Key skills developed in CHE616M/D

Model-building was given the most emphasis since prior experience with CHE616M/D suggested that this skill took longest to develop. The ability to formulate an MP that gives a reasonable balance between fidelity to the real physical world, while being sufficiently simplified to ensure computability (i.e., capacity to identify global optima) is important for future academic or industry career needs. For example, this skill is critical for any student who intends to do a PSE-oriented thesis. This skill was developed progressively through three activities. First, the students were exposed to a number of small-scale MP models such as those compiled in Ryoo and Sahinidis (1995). By being shown both the original engineering problem and its corresponding MP, students were challenged to understand the "translation" process in both forward and reverse directions. Second, students were asked to select a small-scale model from the literature and to perform "reverse engineering" by deducing the original engineering problem from the MP formulation. This step was taken as the precursor to developing the skill of ultimately being able to perform model-building, or translation of a problem into an MP; it was also used as the midterm assessment. Although this topic was introduced in the very first lecture session of the trimester, ample time was given for the learning process by delaying the assessment until the 10th week (as Assessment 2). Acquisition of this skill was facilitated by exposure to a variety of template models, such as the generic MILP formulation for process synthesis that was first proposed by Grossmann and Santibanez (1980), or source-sink models commonly used in Process Integration (PI) applications (Foo, 2012). The important role of integer variables in MP models was also demonstrated using problems in reliability engineering (Luus, 1975) and pollution reduction portfolio optimization (Kantardgi et al., 2006). A modified form of the MILP model for generic process synthesis was taught in the context of optimal design of an integrated energy system (Sy et al., 2016).
Model encoding skill is more mechanical than model-building, but is still a critical component of the module. The main software used was LINGO (Lindo Systems, 2022), since its equation-based interface lends itself well to a virtual learning environment (Schrage, 1999). Figure 2 shows a screenshot of the LINGO interface. Microsoft Excel and its built-in Solver toolbox was also used as a secondary environment for implementing MP models. Students were encouraged to explore the features of both programming environments to highlight the capabilities and limitations of their solvers. For example, distinction between global and local optima was reinforced using the non-linear programming (NLP) and mixed-integer NLP (MINLP) compiled by Ryoo and Sahinidis (1995); the frequent failure of gradient-based solvers to determine the known global optima of these problems provided a clear lesson in the computational consequences of non-linearity. Supplementary videos were also used to highlight key mathematical topics, such as the Karush-Kuhn-Tucker optimality conditions and the simplex algorithm for solving LP models. These assigned videos ensured that students understood the inner workings of the optimization software they used. This skill was assessed via a practical examination (Assessment 1) in the 5th week, in which students were given an MP model to encode and solve in both LINGO and Excel. Student marks were based on the number of attempts they needed to find the correct solutions.

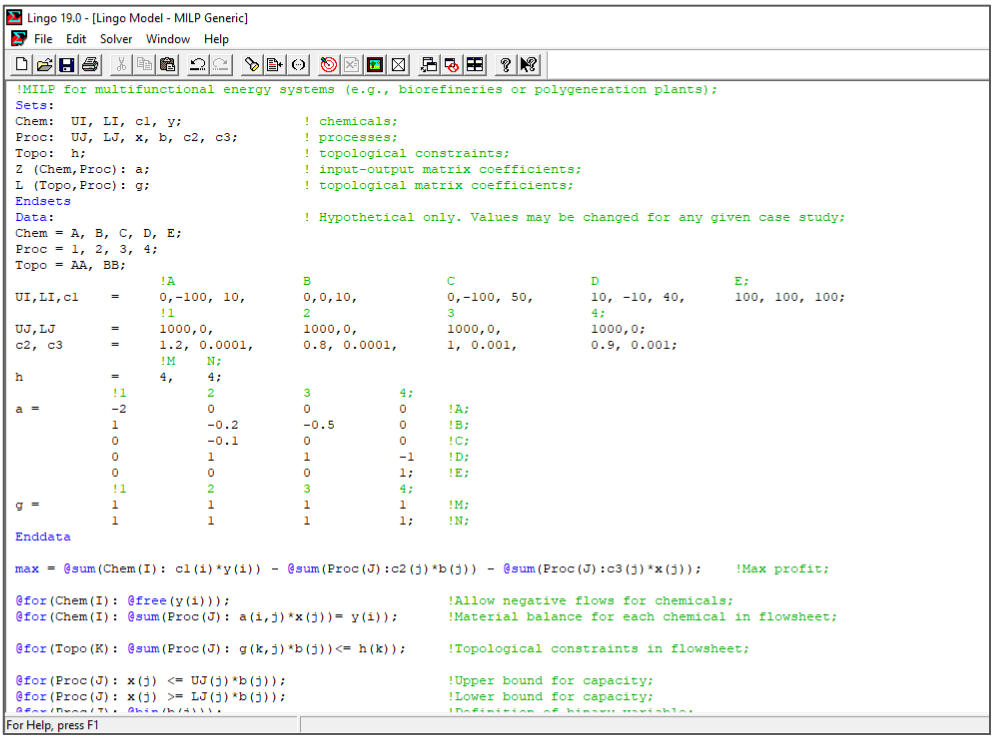

Figure 2: Screenshot of a LINGO model

In the second half of the trimester, additional effort was put into the convergence of the first two key skills discussed above. Assessment 2, which was primarily intended to test students' capability to reverse-engineer MP models, included a component of software proficiency aspect since the required output was an annotated model file in LINGO and/or Excel. Students were then asked to identify a suitable topic for their term project, consisting of a substantial modification of a previously encountered model from PSE literature. Consultation sessions were used to ensure reasonable uniformity in degree of difficulty; the two Ph.D. students were also given a more challenging topic than their peers. The final project was documented via a brief term paper of up to 3 pages in length, coupled with a 10-min video presentation discussing the engineering problem, the MP model formulation, and the practical interpretation of the model solution.
The last two lecture sessions were dedicated to miscellaneous topics, including multi-objective optimization (Clark and Westerberg, 1983), fuzzy optimization (Zimmermann, 1978), and process graphs (Friedler et al., 2022). Alternative software environments such as P-graph Studio (P-graph, 2022) and AIMMS (2022) were also introduced. The schedule of topics and activities throughout the trimester is summarized in Table 2.

Table 2: Schedule of topics and activities

Week	Topic	Main lecturer
1	General orientation	R.R. Tan
2	Basics of engineering optimization	R.R. Tan
3	Implementing MP models in LINGO and Excel	R.R. Tan
4	Advanced coding in LINGO	K.B. Aviso
5	Assessment 1: MP coding in LINGO and Excel (30% of total marks)	
6	LP and NLP models	J.F.D. Tapia
7	Integer LP (ILP) and integer NLP (INLP) models	K.B. Aviso
8	MILP and MINLP models	J.F.D. Tapia
9	Identification of topic for Assessments 2 and 3 (midterm and final reports)	
10	Assessment 2: Midterm report (30 % of total marks)	
11	Multi-objective and fuzzy optimization	R.R. Tan
12	Process graphs	K.B. Aviso
13	Alternative software environments (AIMMS)	J.F.D. Tapia
14	Assessment 3: Final report (40 % of total marks)	

4. Sample Student Output

A sample student output for the oral examination is shown in Figure 3. The project deals with a model for matching sources to utilization facilities in a CO_2 capture and utilization (CCU) system. The students were required to implement the model by Aviso (2014) in LINGO using the first case study as the example during their midterm report. The analogy of flow rate and concentration constraints allows them to develop a different model that can be applied for CO_2 capture and utilization. In Figure 3, the model shows the objective function that considers the discounting factor used to express the benefit of delaying the emissions through CO_2 utilization. The output of the students was sent as a pre-recorded presentation with the supplementary files (e.g., LINGO codes, Excel files).
From the project that the students presented, it is clear how the knowledge and skills in developing mathematical programming models and implementing it are transferred through online delivery. The model-encoding task was demonstrated by replicating the results of a previously published work. The model-building task is demonstrated through modification of a published work. The latter skill is a critical initial step towards deeper proficiency in the development and use of MP models (e.g., for Ph.D. research).

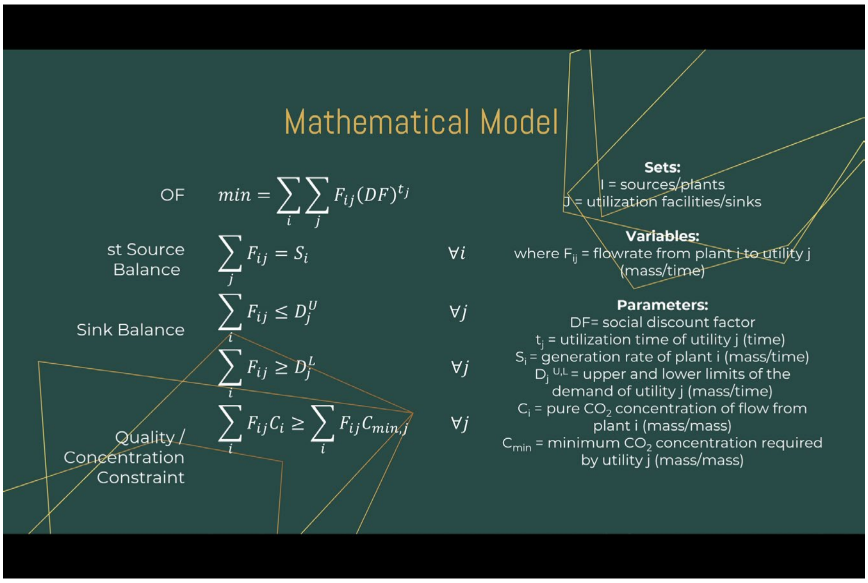

Figure 3: Screenshot of a final presentation showing a modified model

5. Conclusions

This paper describes the experience in the online delivery of the course Optimization in Chemical Engineering during the COVID-19 pandemic in the second quarter of 2021. This module was part of the coursework requirements for masters and Ph.D. degree programs in chemical engineering at De La Salle University. The main macro-strategy used was to create separate learning tracks for the key skills of model building, model coding, and solution interpretation. Learning activities used in the virtual classroom relied heavily on video micro-lectures coupled with hands-on team activities to develop soft skills and create an interactive social environment. Three lecturers were assigned for shared delivery of the course content to give redundancy in the event of internet connectivity issues or health problems.
Some of the strategies used may prove to be effective in the post-pandemic era. More rigorous assessment of the effectiveness of these approaches should be made under face-to-face, online, or hybrid modes. As of the time of writing, hybrid delivery is planned in the third quarter of 2022, which will allow further evaluation of the pedagogical approaches used. These techniques can also be tested on the delivery of content in other emerging computation-oriented topics in chemical engineering, such as artificial intelligence and machine learning applications in PSE.

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