TEACHING PROCESS DESIGN TO CHEMICAL ENGINEERING UNDERGRADUATES AT THE TECHNION – AN EVOLUTION

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INTRODUCTION

The capstone design sequence provides chemical engineering students with the opportunity to demonstrate mastery in process engineering acquired during their entire degree. It is therefore the ultimate "reality check" in outcome verification. The design sequence, taught in the last year of studies to chemical engineering undergraduates, is arguably the most challenging material both to teach and to master given that it addresses the three top tiers in Bloom's Taxonomy: analysis, synthesis, and evaluation.[1] A survey conducted by the AIChE Education Projects Committee in 2012[2], which received 69 usable responses from faculties in the U.S. and around the world, produced the following main conclusions:

a. Capstone design is taught in one (by 47% of responses) or two courses (by 44% of responses).
b. Most courses require students to complete at least one design project working in teams of four on average. Most of the projects are completed using a process flowsheet simulator, with the most commonly used being Aspen Plus®.
c. Course lectures usually cover process and plant design, simulation, economics, heuristics, heat integration, ethics, safety, and more. The list includes a mix of technical and non-technical subjects.
d. The design sequence is clearly seen in many faculties as a "catch all" course. Consequently, chemical engineering programs are likely to use the design sequence for outcomes assessment (e.g. ABET in the United States and the UK Engineering Council in Britain).
e. Most of the lecturers see the main instructional goals of the design sequence as teaching critical thinking and problem-solving skills, integrating concepts from throughout the curriculum, and developing fundamental competency. The biggest challenges mentioned by the instructors were dealing with large class sizes, developing quality project assignments, and coping with unprepared or unskilled students. All agreed that the design sequence is a challenge to teach.

A key principle that needs to be instilled in the student is that process design is best accomplished using a top-down approach, starting from fundamental principles (e.g. [3-6]). As more details are synthesized, the design process is made more efficient by using systematic, algorithmic approaches, such as distillation column sequencing using the Marginal Rate Method[7] and heat exchanger network (HEN) synthesis using the Pinch Method.[8] As expressed in the 2012 survey[2], most of the design sequences taught employ a process simulator as the main design enabler, leading to projects submitted as converged and optimized flowsheets, including their economic assessment. Relying on a process simulator can support good design practice, provided that students are taught first to assess simulation results critically, using their common sense and acquired experience in process fundamentals.[9]

EVOLUTION OF THE DESIGN SEQUENCE

Figure 1 shows the evolution of the curriculum for the design sequence at the Technion. In the 6th semester, which includes several topics that are fundamental in preparing for process design, students are taught multistage separation

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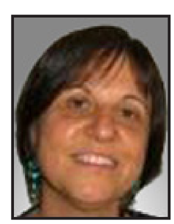

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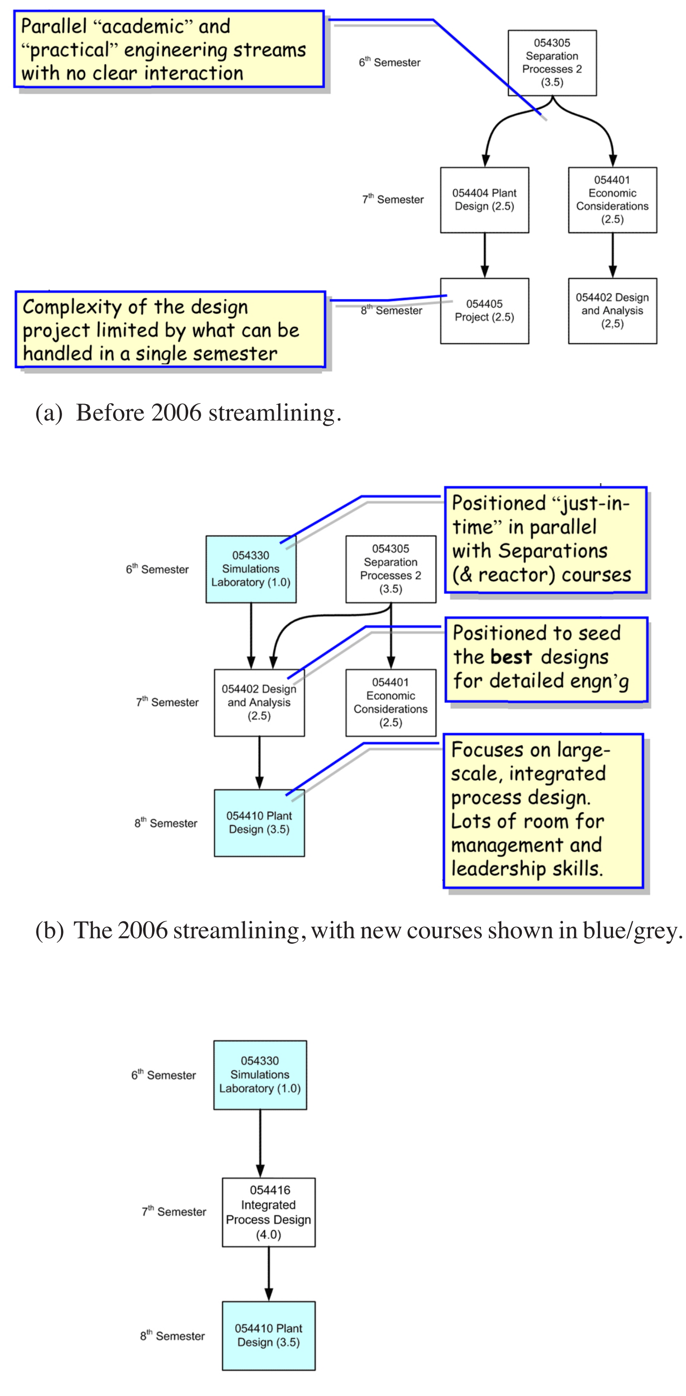
principles as well as advanced reactor design, giving time for a year of design-centred activity in the 7th and 8th semesters. The status of the design sequence before the thorough overhaul implemented in 2006 is shown in Figure 1(a), noting that the sequence was divided into two parallel tracks each involving two core courses: an "academic" track taught by faculty, shown on the right, and a "practical" sequence taught by adjuncts from industry, shown on the left, with all four courses taken by all students. The "academic" track consisted of a course on engineering economics, taught in the 7th semester, and a capstone design course, taught in the 8th semester that included a small project. In contrast, the industrial adjunct would cover "practical engineering" in a parallel track, reviewing topics taught previously in the curriculum, and also covering the theoretical background for mechanical design of processing units (flash vessels, heat exchangers, distillation columns, furnaces, pumps, compressors, pipe sizing and layout). In the last semester, the students completed small-scale plant design projects (usually limited to a single distillation column and its associated equipment items). The design sequence therefore involved four core courses in which there was no interaction between the "academic" and "practical" tracks, with much time being wasted repeating materials covered previously in the curriculum. Worse still, the very nature of this parallel structure reinforced the impression that "academic" engineering is not relevant in "practical" engineering.

In 2006, the design sequence was revised and streamlined to the form involving four courses, taught in three successive semesters, as shown in Figure 1(b):

a. *054330 Simulations Laboratory* – This new course was introduced in the 6th semester, where students become proficient in the usage of UniSim® for the design, analysis and evaluation of chemical process flowsheets involving two hours a week in a computer laboratory, using multimedia courseware for self-paced instruction[10]. This lab is taught in parallel with formal courses in multistage separation and advanced reactor design, and so students have the opportunity to integrate their acquired theoretical understanding with their computational capabilities. As such, this course provides students with suitable preparation, "just in time" for design work to be undertaken in their last year of study.

b. *054402 Design and Analysis* - The capstone design course was advanced from the 8th to the 7th semester, placing it together with the engineering economics course. The design course's project was expanded in scale to give groups of up to five students the opportunity to come to grips with



(a) Before 2006 streamlining.

(b) The 2006 streamlining, with new courses shown in blue/grey.

(c) 2015 streamlining and move to 054416 (flipped).

Figure 1. *Evolution of the design course sequence at the Technion. The numbers in the parentheses refer to course credit points: usually 1 point for each lecture hour and ½ point for each tutorial hour, and workshops counting for ¼ point. A typical course of two weekly lecture hours and 1 hour of tutorial is worth 2.5 credit points.*

integrated design of large-scale processes, in which the objective is to maximize the venture profit (VP, in US$/year):

$$VP = (1-t)(S-C) + r \cdot TCI, \quad (1)$$

where S is the annual revenue (in US$/year), C is the annual cost of sales (in US$/year), which includes raw materials, utilities, manpower, and others, t is the tax rate, r is the accepted interest rate, and TCI is the total capital investment, that is, the total cost of the installed plant (in US$). Thus, the VP is an approximate profitability measure based on a typical year of operation, which does not account for the time-value of money. A complete list of design projects tackled since 2006 is presented as Table 1, with details of one example project provided in the next section.

c. *054401 Economic Considerations* – Taught together with 054402, this course provided students with the ability to estimate process capital costs and in the assessment of profitability analysis, including the time value of money.

d. *054410 Plant Design* – This combines the essential content in the two courses previously taught by external adjuncts. In this new course, the best designs obtained in *054402 Design and Analysis* are used to seed work by groups of students who prepare complete chemical packages, involving process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), and layout for the complete process, as well as detailed mechanical design for each of the equipment items in the plant. In this way students work on a design project over an entire year. Lecture materials are limited to mechanical design of equipment items, which are taught in an accelerated mode in the first half of the semester, leaving time for design work in the second half. In this course, students work in larger groups (at least five, but sometimes as many as fifteen) on selected solutions to the year's design project initiated in *054402 Design and Analysis*. Chemical packages are prepared for complete, integrated plants, with all engineering work accomplished by the students themselves.

A second, important change in the curriculum was implemented in 2015. The two courses, *054402 Design and Analysis* and *054401 Economic Considerations*, were combined to form *054416 Integrated Process Design*. Two weeks of the new course are invested in teaching students to estimate plant capital investment, most accurately using Guthrie's method, and to perform approximate profitability analysis (e.g. venture profit), as well as by more rigorous methods accounting for the time-value of money (e.g. investor's rate of return and net present value). In addition to process economics, the course teaches an introduction to engineering ethics, the fundamentals of synthesis of separation sequences and heat exchanger networks, plantwide control, and safety assessment (hazard and operability studies and hazard analysis). An important component of the course is a large-scale open-ended process design problem, including its approximate profitability analysis (VP), where the students' project grades are in proportion to the profitability that their designs achieve. To level the playing field, they all work on the same design problem.

TABLE 1
Production facilities addressed in the design sequence, by year

Year	Production Facility	Comments
2006	NLG Processing	First project set for the new format course
2007	Ammonia	Facility for Israeli market demand, when NH3 prices were low, designing both synthesis gas production and ammonia synthesis
2008	Phthalic Anhydride (PA)	
2009	Methanol	Designing both synthesis gas production and methanol synthesis
2010	Propylene Glycol	
2011	Ethylene	Production of ethylene from natural gas.
2012	Ammonia	The feasibility of a facility to satisfy the Israeli market demand, when NH3 prices were high, and natural gas fields were discovered in Israeli territorial waters.
2013	Methanol	Production from natural gas
2014*	Combined Methanol/Ammonia production	
2015	Ethylbenzene	
2016	Cumene	Irreversible reactions
2017	Dimethyl Ether (DME)	
2018	Cumene Plant	Reversible reactions
2019	Ethylbenzene	New conditions
2020	Methyl Chloride (MeCl)	Desired reaction to MeCl is accompanied by undesired side-reaction to DME.

* – Prof. Lewin was on sabbatical this year and not involved in the course.

There are important advantages in extending the capstone design project to span over two sequential semesters:

a. The scope of the project is better served by two semesters of activity. As seen in Table 1, topical projects have been suggested by historical national necessity. For example, note the projects studying the feasibility of producing ammonia for the Israeli market (about 450,000 ton/year). In 2007, when ammonia prices were low (US$270/ton), the studies indicated the project could only be profitable if production levels were increased (to 1 million ton/year), suggesting that a joint effort with Israel's neighbor, Jordan, would be commercially feasible. In contrast, the same project, rerun in 2012, by which time the global ammonia price had jumped to US$600/ton and Israel had discovered offshore reserves of natural gas in her territorial waters, a project satisfying only the Israeli market for ammonia was found to be commercially viable.

b. The project activity acts as "academic glue," requiring students to harness theoretical aspects of their studies in the period that the project is active, thus reinforcing their learning by practical application. Moreover, the project requires and rewards cooperation between the student group members.

In addition to the above-mentioned curriculum modifications, two additional changes were incorporated, involving updating the teaching pedagogy with a view of improving the degree to which the learning outcomes are achieved by the students, namely:

a. Transforming the recitations, in 2011, from lecture-based sessions, where the teaching assistant largely demonstrated solutions of example problems to students, to active tutorials in which most of the time is allocated for students to solve problems for themselves.

b. Since its inception, *054416 Integrated Process Design* has been taught in flipped format, the first Technion course to fully-implement flipping. In this transformation, the lectures have been moved to an on-line format, including built-in quiz questions, which have become the students' home assignments. The lecturer's meetings with students have been converted to active problem-solving sessions with students' participation. The active tutorial component implemented in 2011 has been retained and rounds off each week's activity. Drawing on this course's successful transformation to a flipped format, the course *054410 Plant Design* was fortuitously converted to flipped format in time for the 2020 offering, which was the year of the COVID-19 pandemic.

The two principal desired course outcomes that have not been changed over time are the degree of success of teams of students on a competitive design project, and of the demonstration of students' individual mastery of the materials taught as measured by their exam grades. While both team and individual capabilities are important, only personal examinations can test the crucial mastery of individuals.[11] As postulated by Bloom[12], the degree to which students achieve mastery depends on four conditions:

1. Clear definition of what constitutes mastery
2. Systematic, well-organized instruction, focused on student needs
3. Assistance for students when and where they experience difficulties
4. Provision of sufficient time for students to achieve mastery

Bloom reports the modes of learning that improve outcomes, with the most significant obtained by personal tutoring, which increases the degree of mastery as exhibited by exam grades up to two standard deviations higher than for students taught conventionally by a lecture-based approach. Amongst other factors indicated by Bloom[13] as having significant positive effects on achieving learning mastery are positive reinforcement and praise from the instructors, student classroom participation and time on task, and cooperative or group learning. In the same spirit, Keller[14] proposed a personalized system of instruction, based on the idea of reinforcement in teaching processes.

Using the exam grade distributions in the capstone design course as a basis, it is of interest to test two hypotheses concerning the teaching pedagogy employed:

H1: The transformation from lecture-based recitations to active tutorials improved the degree to which entire cohorts of students achieved the desired learning mastery.

H2: The transformation of the course from lecture-based to the "flipped classroom" improved the degree to which entire cohorts of students achieved the desired learning mastery.

These two hypotheses are tested by considering both final exam grade distributions and on the basis of student impressions, as brought by the results of polls carried out over time.

A TYPICAL DESIGN PROJECT, AND DESIRABLE GROUP OUTCOMES

The design project requires students to improve the profitability of a given poorly performing preliminary design. It is thus an important feature of the design sequence in which good engineering decisions are rewarded by higher project grades. As a typical example, consider the design project posed to the class of 2020: a process for the production of 90,000 tons/year of methyl chloride (MeCl) at a composition of 99.5 mol% (or 96 mol%, for lower revenue) from feedstocks of pure methanol and HCl. The students were presented with a 17-page tender (a copy of the tender that was transmitted to the class of 2020 can be obtained from the authors at dlewin@technion.ac.il), describing a preliminary feasible design capable of supplying the product as required, but for an annual VP of -US$7.5M/year (a loss of US$7.5M a year), whose process flowsheet is shown in Figure 2. The tender also summarizes the reaction kinetics, and details of the venture profit calculation, based on the taxed gross profit and the discounted total capital investment, with the latter estimated using Guthrie's method. Estimating methods for the purchase cost of the equipment items reproduce correlations presented in Chapter 16 of Seider et al.[15] The requirements of the project are to redesign the process to maximize the VP.

The students' first objective was to identify the reasons for poor economic performance of the preliminary design. Driven by the desire to maximize the VP (and thus, their project grade), most of the student teams identified the most important of these to be:

1. The MeCl is produced in the preliminary design at 96 mol% purity because the reaction conditions do not achieve sufficiently high selectivity of MeCl relative to the undesired by-product, dimethyl ether (DME). This lower grade product is allowed in the tender, but returns a lower revenue, compared to the more desirable product at 99.5% purity.
2. Despite the need to preheat the reactor feed, accomplished in the preliminary design in Figure 2 by an expensive furnace, and the need for multiple distillation columns requiring utility heating and cooling, the preliminary process does not include any heat integration, even though both the primary reaction to MeCl and the side reaction to DME are both exothermic.
3. The separation section needs to produce the MeCl product at the required purity, water by-product at high purity to avoid environmental impact, and recycle unreacted methanol and HCl to enhance profitability. The preliminary design in Figure 2 accomplishes these objectives but inefficiently, because all columns are oversized and the first column does not remove the corrosive HCl in the reactor effluent, requiring more than one column to be constructed from corrosion-resistant steel.

To illustrate the best design features identified by the student teams, consider the best solution submitted shown in Figure 3, in which the reactor was operated at 30 bar, and obtained a VP of US$8M/year. This should be compared with the performances and characteristics of all of the submitted designs, summarized in Figures 4 and 5. The key design decisions found by the students to have the most effect on the obtained VP are:

a. *Optimal reactor feed HCl/MeOH molar ratio:* The desired reaction to MeCl is accompanied by an undesired competing reaction to DME, with both reactions being reversible. Since the boiling points of DME and MeCl are almost the same, all of the DME produced leaves the process with the MeCl product. Thus, to attain more profitable 99.5 mol% MeCl product, the MeCl/DME molar ratio in the reactor effluent needs to be at least 200 to 1. This is attained by ensuring HCl is in excess of MeOH in the reactor feed to attenuate the competing side reaction to DME. Most student groups addressed the selectivity requirement by opting for high HCl/MeOH molar feed ratios, which is highly correlated with the attained VPs, as shown in Figure 4.

b. *Optimal reactor operating conditions:* As the purchase cost of the adiabatic plug flow reactor accounts for a large percentage of the total capital investment, the reactor's operating pressure and feed temperature need to be selected to minimize the reactor volume while ensuring optimal conversion. Note that as the two competing reactions are reversible, the key to a successful design is to address selectivity, with conversion per pass being far less important. This would explain why most of the submitted designs used only one reactor bed, rather than more expensive multibed reactor configurations.

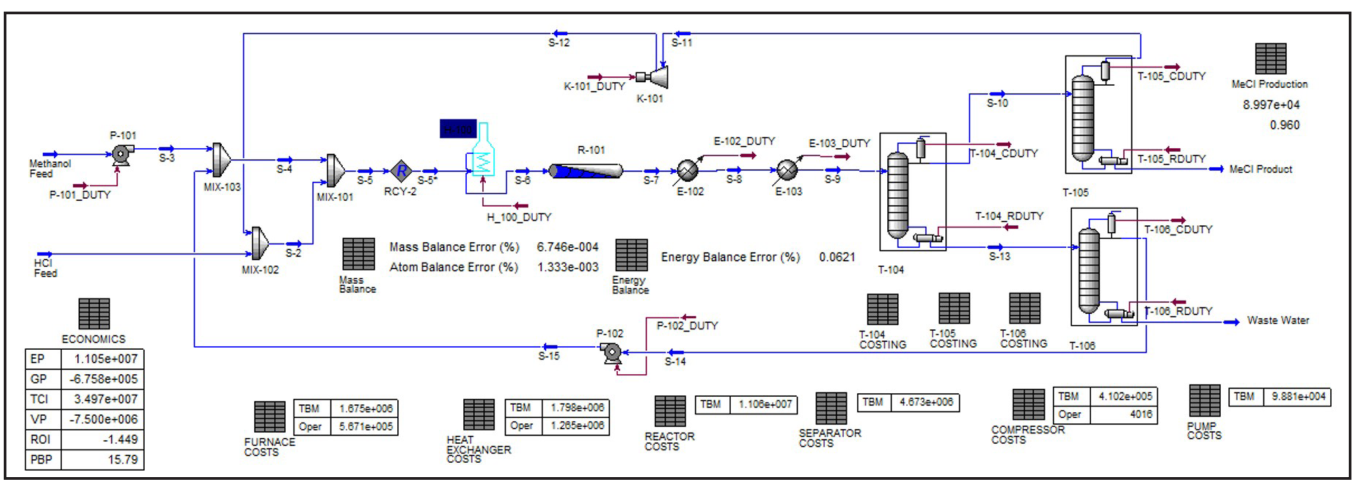


Figure 2. *Feasible initial design for the MeCl plant, with VP = -US$7.5M/year.*

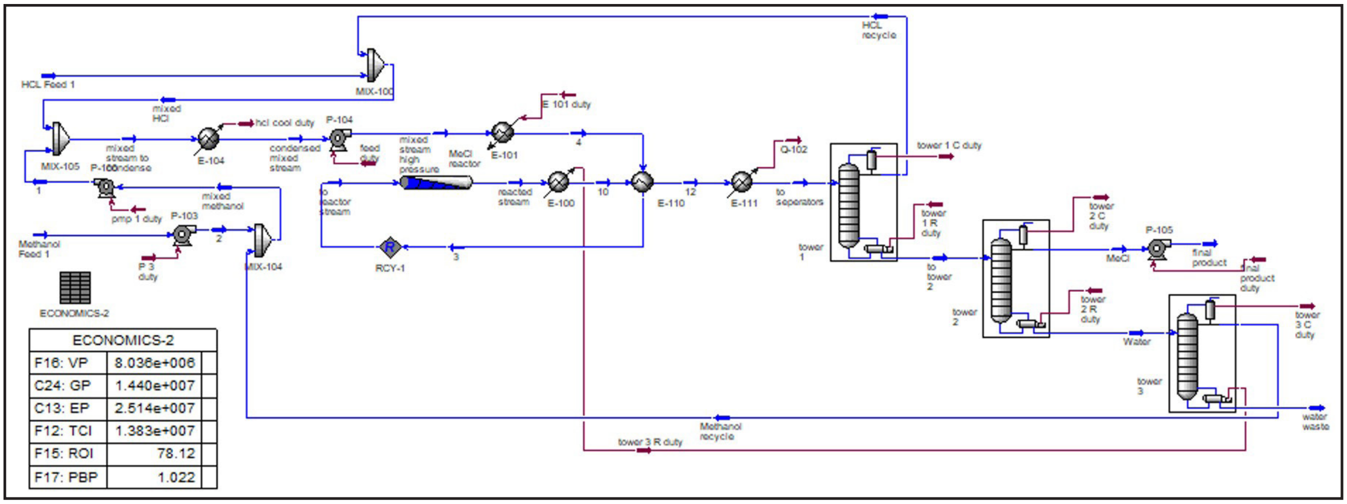


Figure 3. *Best design submitted by students for the MeCl plant, with VP = US$8M/year.*

Reduction of reactor costs are possible by high pressure operation, and sufficiently high feed temperature to promote reasonable reaction rates, as shown in Figure 5 – it is apparent that smaller reactors can be obtained with increasing operating pressures, and that for a given operating pressure, increasing the feed temperature will also reduce costs. Horizontal reactor vessels are cheaper than vertical ones.

c. If the reactor is operated at high pressure and with excess HCl in the reactor feed, this will require a large recycle of HCl. To minimize operating costs, the HCl recycle should be a liquid stream, driven by pumping rather than more expensive compression.

d. The HCl should be removed first from the reactor effluent to minimize the cost of the separation system.

As can be seen in Figure 3, all of the above key decisions were adopted by the leading design, as well as most of the better ones. These findings indicate how linkage of the awarded project grade with the obtained VP drives students to apply good engineering practice to improve the economic performance of their designs.

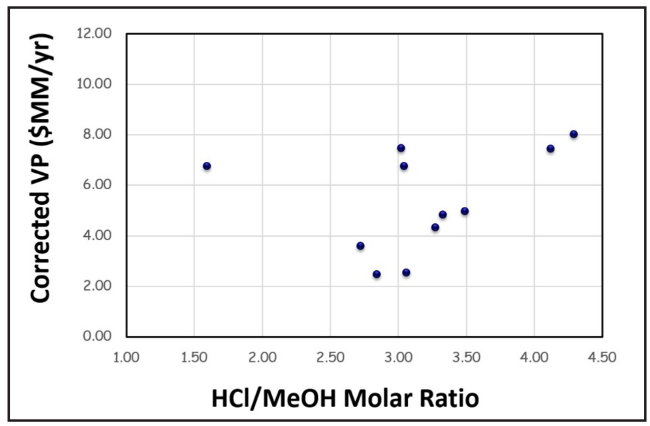


Figure 4. *Correlation between HCl/MeOH molar ratios in reactor feed and corrected VP for submitted solutions (The plotted VPs are the values obtained for each solution after correcting for errors in the submitted designs).*

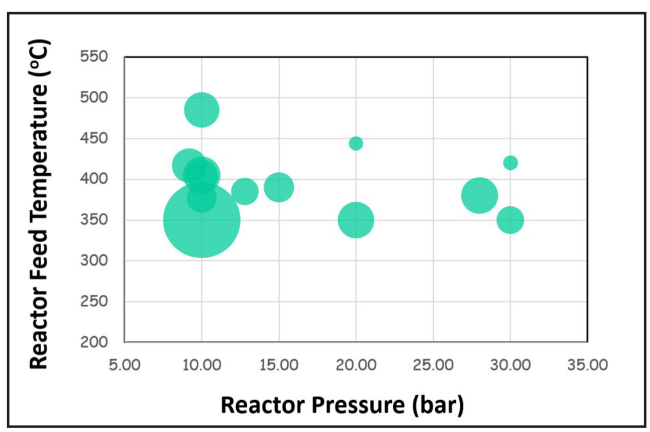


Figure 5. *Bubble plot indicating the effect of reactor feed pressure and temperature on the reactor purchase cost for all submitted solutions (area of bubbles proportional to reactor purchase cost).*

EXAM CONSIDERATIONS FOR THE COURSE 054402/054416

The capstone design course is examined in a three-hour final exam, consisting of three to four questions (usually three) that test mastery of the core subjects taught in the course. We first review the subjects typically examined, and then proceed to review the procedures used to prepare, manage, and grade the examination. To demonstrate that the exam level has been uniform over the lifetime of the course, four sample exams and their solutions, spanning the years 2005-2020, have been made available as a separate resource to this paper, which can be obtained from the authors at dlewin@technion.ac.il.

Subjects Examined

The students are not told explicitly what would come up in their exam – anything taught is possible. A so-called "Exam Catalogue," listing all previous examinations and their solutions are available for review on the course website, noting that since students can elect to take the exam twice, the final exam has two sittings, Exam A and Exam B, with the grade achieved in the last exam taken counting. The subjects almost always include:

a. Separation sequence synthesis (the questions posed usually involve azeotropes).
b. Heat exchanger network synthesis (usually computing maximum energy recovery (MER) and designing a HEN to satisfy it, but sometimes also requiring the usage of the grand composite curve).
c. Plantwide control system synthesis (using the approach of Luyben et al.[16]).
d. Linear programming (LP). In 054402, LP was also included in the curriculum. Its inclusion was discontinued in 054416 because of time limitations. This subject is better taught in the framework of a numerical methods course or a course on optimization.

Occasionally additional subjects may come up, for example:

a. Economic analysis (usually involving the time value of money).
b. Hazard Analysis (HAZAN) reliability calculation.
c. Finding errors in a P&ID.

Exam Preparation, Management and Grading Procedure

The following procedure was in use for the entire period that the course has been given:

Exam Preparation

a. The exam questions are prepared by the instructor. Enough questions are generated for at least two complete exams.
b. All of the exam questions are solved by two teaching assistants, who verify that each question has a solution. The level of difficulty of each question is assessed by the TAs, and the time they take to solve each question is noted. Exam questions that are considered either too easy or too difficult are either modified to make them suitable or discarded.
c. Exams are assembled so that the overall difficulty of each of the two exams to be used are at the same level, and consistent with the usual level of difficulty for the course exams. The mean time taken by the TAs for an assembled exam needs to be up to 50% of the time allowed for students, i.e., TAs need to be able to solve each exam in 90 minutes or less. If any of these conditions are not satisfied, then the exam is modified so that they are.
d. This preparation step needs to be completed well in advance of the date when the first of the two exams are given to the students.

Exam Management

a. In this course, exams are open book.
b. The instructor is available during the exam to answer students' questions. Helpful responses are provided only on issues relating to the understanding of the exam questions, with no help provided during the exam on the understanding or application of the course materials.
c. In principle, no extra time is ever given in exams. This is not necessary since sufficient time has been allocated in the exam preparation step.
d. After the exam is over, a complete solution to the exam is posted on the Exam Catalogue page in the course website.

Exam Grading Procedure

a. The exam books returned by students are reviewed before beginning grading to gauge how the students have handled the questions.
b. Noting the types of errors on each question made by those students who did not answer perfectly makes it possible to adjust grading so that a mean class grade of between 60 and 70% will be achieved. Partial credit is given for concept understanding, and demonstration of concept application, with difficult-to-spot arithmetical errors receiving minor penalties. However, arithmetical errors resulting in illogical, infeasible, or impossible results receive more substantial penalty. In any case, it should be stressed that the minimum grade on a question is zero, for a case where the student has not made a meaningful attempt to address the question.
c. Technion regulations require grading to be completed and grades transmitted to students within a week of the exam.
d. A week is allowed for grade appeals, with appeals being in writing by email only. All appeals are responded to in detail, and in writing, referring to the submitted exam book. From the first author's point of view, appeals are yet another opportunity to educate his students.

EMERGENCE OF THE FLIPPED CLASSROOM

The last step in the evolution of the sequence involved its streamlining to just three consecutive courses, but also the transformation of the capstone design course, renamed *054416 Integrated Process Design*, to flipped format. The main justification to move to flipped format was the desire to increase the proportion of the student-staff contact time in which students are actively learning, rather than just listening to lectures.[17-18] This format makes better use of shared time between teacher and students, which has a huge impact on students' engagement, as does aiming to maximize the degree to which students are participating actively with the teacher and with each other, rather than passively listening to lectures. There are many studies that provide quantitative evidence that active learning improves course outcomes.[12,19-21] This was the first fully flipped course to be run at the Technion, and it motivated other teachers on campus to flip. The first author has since flipped two additional courses – the core control course, flipped in 2016, as well as the last course in the design sequence, *054410 Plant Design*, flipped in 2020.

Figure 6 illustrates a representative week of course activity using conventional, lecture-based teaching. First, students typically attend a 2-3-hour lecture in which the materials are transmitted at the lecturer's pace, which is too fast for many of the students to follow. In this mode, there is modest interaction between the lecturer and the few students who actively participate, making it difficult for the lecturer to assess to what degree his students have learned. Most of the students who attend the lecture are passive listeners. Next, students attend a 1-2-hour exercise/recitation, where they hear another "lecture," this time by the teaching assistant, who shows students how to solve typical exercises. (This is about as useful as going to the gym and watching how one's *gym instructor* lifts weights.) As in the lecture, most of the students who attend the exercise are passive listeners. Finally, students are then asked to do homework exercises and now, for the first time, they are expected to be active, but on their own, with no help. If they are required to submit homework for credit, most of the students will do so, but not all work submitted will be original (enough said), making it impossible to reliably assess the competency attained by the class as a whole. Even if the work is graded and returned to the students, it will be too late to provide timely feedback.

In contrast, the format of the flipped course adopted by us follows the weekly schedule illustrated in Figure 7. In advance of the week's activities, students watch an on-line lesson, taking up to three hours to cover at home in their own time, which counts as their homework. An on-line lesson consists of a sequence of segments, each comprised of a short video clip (up to 15 minutes per clip, with most being a lot shorter) and an associated quiz question – each lesson consists of between 5 and 12 such segments. The students can watch these lessons at their own pace, repeating segments until they have mastered the materials, and the quiz questions maintain them active in this self-learning process. Since the videos in the on-line lessons are accessible from a video-server, it is possible to log students viewing times, which also logs how many clips are viewed. For a typical example of such a log, see the data (Figure 8) for viewing times and clip views for the third lesson of the course 054416, which is composed of 10 clips, which together run for 84 minutes, noting that many students watch videos at twice the speed. Hence, it can be stated that, in general, the majority of the students repeat segments to improve their mastery.

Next, they attend a two-hour class-meeting in which portions of that week's on-line lessons that were found to have been difficult for most of the students are explained in more detail, but mostly allowing for in-class activities (i.e. clicker questions and collaborative open-ended problem solving). Again, most of the class is active and participate, especially if quizzes are used. Finally, they attend a three-hour active tutorial session (with the class divided into two separate classrooms), in which groups of students solve classwork (previously called homework). The flipped approach therefore maintains the average student active throughout the learning process and, as such, it has a greater potential to succeed in attaining learning mastery, in comparison to the conventional lecture-based approach.[13]

The flipped classroom approach offers several opportunities for continuously assessing the degree to which the course goals are accomplished during the entire semester both from the point of view of the student and of the lecturer. The students participate actively in their learning, receiving immediate feedback on the on-line quiz questions, thus reinforcing their learning. They come to the class meeting where additional quiz questions are posed to them with clickers

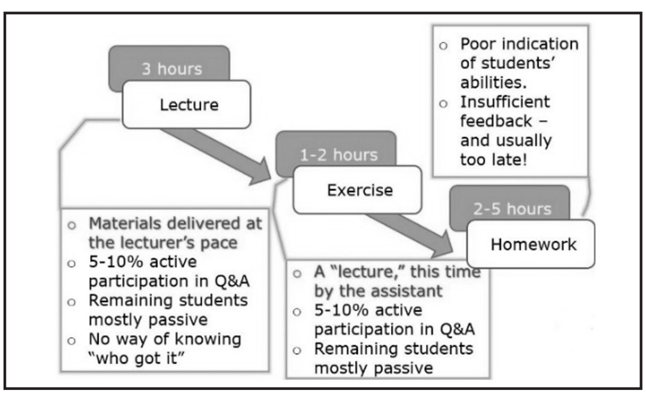


Figure 6. *A weekly cycle of a typical conventional classroom.*

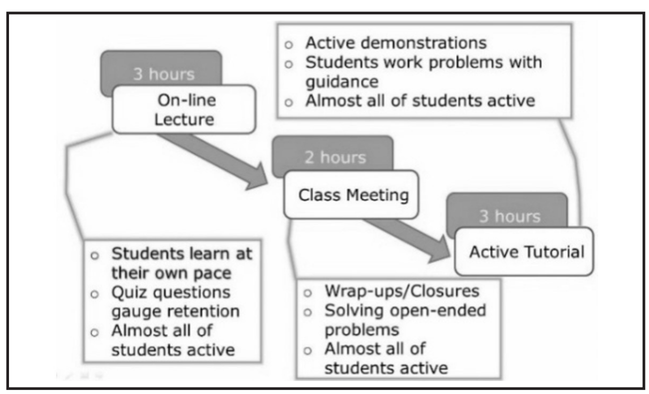


Figure 7. *A weekly cycle of a flipped classroom.*

used to collect the responses of the entire class and used to further drive discussion. Open-ended problem-solving further prepares them for the next step – the active tutorials, where they tackle classwork problems in cooperative efforts.

Since the weekly contact time is largely occupied by student-centered activities rather than lecturing, there are several features of this approach that can also provide the lecturer with on-going formative assessment of the degree to which course objectives are attained, as well as opportunities to continuously improve and modify delivery. First of all, by observing the class performance on the on-line quizzes ahead of the class meeting, the lecturer can tailor the materials delivered in the class meeting to focus the discussion to items/issues that most of the class found the most difficult. Furthermore, as illustrated in Figure 8, the lecturer can monitor lesson viewing activity, to ensure that the entire class is preparing for class in advance and follow up on those students who are not. In the class meeting, clicker questions provide opportunities for both additional testing of student capabilities, as well as nurturing discussion of the results, providing for deeper understanding. Finally, the active tutorials are the ultimate test of the capabilities of the students to handle problems on their own, and the presence of the staff enable them to truly assess the students' capabilities well ahead of the final exam.

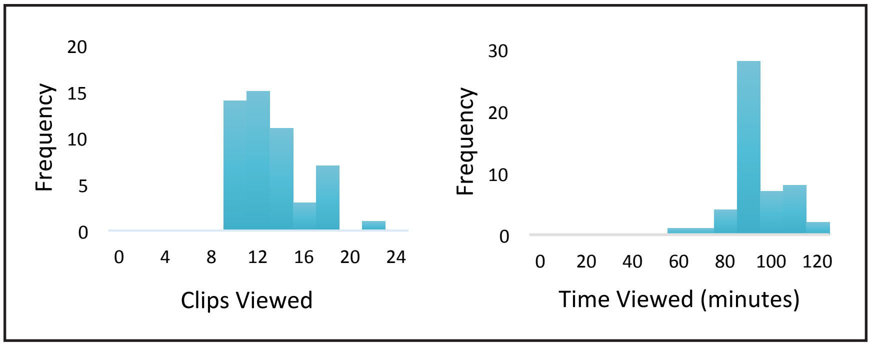


Figure 8. *A typical viewing record from November 2020 for Lesson 3 of 054416, showing distributions of clips viewed (10 clips in total for this lesson) and viewing times (total lesson viewing time is 84 min at regular speed), for a class of 53 students.*

The implementation of the flipped classroom, integrating self-paced on-line lessons, interactive class meetings, and active tutorials represents an updated instance of Keller's personal tutoring[14], where the conventional lecture is replaced by students self-studying the lecture materials, thus expanding the time available for all of the features indicated by Bloom[13] as contributing to learning mastery.

As shown in Table 2, the course is divided into three sections. The first section introduces the course and covers economics (Weeks 1-4). A second section covers systematic design methods: Weeks 5-6 on separation sequence design and Weeks 7-9 on heat exchanger network synthesis. Finally, a third section covers process control and safety (Weeks 10-13). In the flipped version of the course, each of the 13 weeks of course materials are presented to students as Moodle Lessons. Each of the Moodle Lessons is organized as a series of segments, each comprised of one or more quiz questions accompanied by an embedded video clip, prepared using Camtasia®. Depending on the subject matter covered, the lessons consist of between five and twelve segments, each covering an aspect of the subject matter. For example, Lesson 7, covering the introduction to HEN synthesis, has 10 segments and contains eight multiple choice questions, one matching question, and two problem-solving assignments to test the students' comprehension of the lecture materials, organized as in Table 3.

Figure 9 presents an example of a lesson segment, noting that the student can conveniently view the embedded video clip on the same page as the related quiz question, or can open the video in a separate window. The example is a typical advanced-level multiple choice question, requiring higher-level thinking to be able to reason out the correct solution. A typical lesson in the course involves mostly lower-and intermediate-level, retention-type multiple choice questions, with a few higher-level questions to make things more interesting for the more accomplished students. Note that each possible answer receives a response, whether correct or not. In the case of an incorrect response, this will at least provide a hint to the student that will explain why it is incorrect. The course policy is to allow the student up to four attempts on each question, so in the case of multiple-choice questions, every student can eventually get the correct answer by perseverance. Assuming that students also read the provided explanations for errors along the way, this is the intended result.

IMPACT OF THE FLIPPED APPROACH ON THE DESIGN COURSE

Each week, the lecture materials are studied by students at home ahead of the week's activity. The weekly materials are then reviewed and reinforced by the lecturer and the students in the class meeting to prepare the students to tackle problems in the active tutorial on their own or in teams of peers. Note that the class meetings should not simply repeat the lecture materials but should provide "value-added" content that deepens the comprehension, capabilities, and skills of the students. This is made possible because the students will have already covered the basics on their own before coming to class. Consequently, the materials are generally covered at a greater depth than what would have been possible for a course taught in the standard format. Consider the three-week schedule of materials taught as a "mini-course" on heat inte-

TABLE 2 **Weekly schedule of the course *054416 Integrated Process Design***			
Week	**Homework (Online)**	**Class Meeting**	**Active Tutorial**
Section A: Introduction and Economic Considerations			
1	L01a: Introduction L01b: Design heuristics	Introduction	Introduction to project
2	L02: Engineering ethics	Engineering Ethics	Project brainstorming
3	L03: Capital cost estimation	Capital cost estimation	Capital cost estimation
4	L04: Profitability analysis	Profitability analysis	—
Section B: Systematic Design Methodologies			
5	L05: Separation sequences	Separation sequences	Separation sequences
6	L06: Azeotropic separations	Azeotropic separations	Azeotropic separations
7	L07: Introduction to HEN synthesis (See Table 3)	Introduction to HEN synthesis	Introduction to HEN synthesis
8	L08: Advanced HEN synthesis	Advanced HEN synthesis	Advanced HEN synthesis
9	L09: Heat and power integration	Heat and power integration	Heat and power integration
Section C: Process Control and Safety			
10	L10: Process control and P&IDs	Process control and P&IDs	Project work
11	L11: Plantwide control	Plantwide control	Plantwide control
12	L12: HAZOP	HAZOP	Project work
13	L13: HAZAN	HAZAN	HAZAN

gration, shown in Table 4, and note how the students' skill-set is expanded and made more comprehensive and complete, giving students the opportunity to truly master the subject at ever-increasing levels of sophistication. A sequence with similar content was in the course before the switch to flipped format but covered with less depth and with less time to develop student-mastery and consequently, as will be shown in the next section, with significantly lower success rates as measured in the final exam.

LEARNING OUTCOMES AND THE ATTAINMENT OF MASTERY

It would be reasonable to suppose that teachers will only consider making changes to their teaching protocol if such changes will improve the learning outcomes. In most cases, these outcomes are quantified according to the performance of the students in final exams, which are hopefully designed to be in alignment with the learning objectives. The analysis of exam grade distributions is complicated by the fact that because students may have heterogeneous capabilities, it is usually the case that grade distributions are not normally distributed. A bimodal distribution is the simplest model that can be fitted to exam grade distributions with the capability of capturing class heterogeneity, and thus providing an estimate of how a class is distributed into high- and low-performing groups of students. The bimodal probability density function, involving five parameters, is:

$$f(x) = \frac{p}{\sigma_1\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} + \frac{1-p}{\sigma_2\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu_2}{\sigma_2}\right)^2}. \quad (2)$$

In Eq.(2) it is assumed that the grade distribution can be approximated by the weighted sum of two normal distributions with averages, μ_1 and μ_2, and standard deviations, σ_1 and σ_2, where p is the mixing parameter ($0 < p < 1$). The indices 1 and 2 indicate the high- and low-performing subpopulations, respectively, with the latter consisting of the fraction $1 - p$ of the total population. Thus, for a unimodal normal distribution with average and standard deviation of μ_1 and σ_1, respectively, $p = 1$. The degree of bimodality in grade distributions can be quantified by fitting the five model parameters to the actual grade distribution, and then computing Ashman's D[22]:

$$D = \sqrt{2}\frac{|\mu_1 - \mu_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}}, \quad (3)$$

where distributions with $D > 2$ will exhibit two distinguishable peaks. Given that the proposed diagnostic tool enables the classification of an overall grade distribution by high- and low-performers, it can be used to address the two hypotheses stated previously and therefore to provide insights into the impact of changes in the teaching pedagogies on the capstone design course's exam outcomes. Table 5 presents the resulting fitted bimodal model parameters as well as Ashman's D, obtained after diagnosis of the exam grades for 054402/054416

TABLE 3
The segments of Moodle Lesson 7 (Introduction to HEN synthesis)

Segment	Embedded Video (note viewing times)	Quiz Questions/Assignments
L07.01	**Introduction:** Learning objectives and list of topics covered, definitions and fundamentals, and Q-T curves (17.5 min).	Multiple-choice question to test retention of materials relating to Q-T curves (basic level).
L07.02	**MER targeting using composite curves:** Demonstration of targeting using composite curves (15.5 min).	Multiple-choice question to test retention of materials relating to composite curves (basic level).
L07.03	**MER targeting using composite curves:** Another example (6 min).	Multiple-choice question to test retention of materials relating to composite curves (basic level).
L07.04	**MER targeting using the TI method:** Description of method and its demonstration (14 min).	Matching question to test retention of materials (basic level).
L07.05	**MER targeting using the TI method – now you try a problem:** The segments introduces a TI problem for the student to try (2 min).	The student is supposed to solve the assigned exercise on his/her own before watching the next segment.
L07.06	**MER targeting using the TI method – problem solution:** The correct answer to the previous exercise is presented, to be compared with the student's (4.5 min).	Multiple-choice question to test fundamental understanding of materials relating to the pinch (basic level).
L07.07	**The significance of the pinch:** Physical insights and preliminary implications of the pinch (14.5 min).	Multiple-choice question to test fundamental understanding of materials relating to the pinch (basic level).
L07.08	**HEN design for MER:** Presentation of a systematic pinch method for HEN design to achieve MER targets (18.5 min).	Multiple-choice question to test fundamental understanding of materials relating to the pinch (intermediate level).
L07.09	**HEN design for MER – now you try a problem:** The segments introduces a HEN problem for the student to try (4.5 min).	Multiple-choice question to test fundamental understanding of materials relating to the pinch – See Figure 9 (intermediate level).
L07.10	**HEN design for MER – problem solution:** The correct answer to the previous exercise is presented, to be compared with the student's (8.5 min).	Multiple-choice question to test fundamental understanding of materials relating to the pinch (intermediate level).

TABLE 4
Subjects and concepts taught in the 3-week sequence that covers HEN design

Week	Subject	Concepts	Typical Exercises
7	Introduction to HEN Design	Composite Q-T Curves MER (maximum energy recovery) targeting Basic HEN synthesis principles	TI (temperature interval) Method for MER targeting Basic HEN MER design problems (matching rules at the pinch)
8	Advanced HEN Design	Loops, and loop breaking Stream splitting Threshold problems	Complex HEN problems (e.g., 4H4C) requiring multiple stream-splitting
9	Heat and Power Integration	Data extraction from flowsheets Grand Composite Curves (GCC) Heat integration of reactors, columns, heat pumps and heat engines	Applying the technology to real process streams. HEN design with multiple cold and hot utilities aided by the GCC. Heat integration of distillation column trains

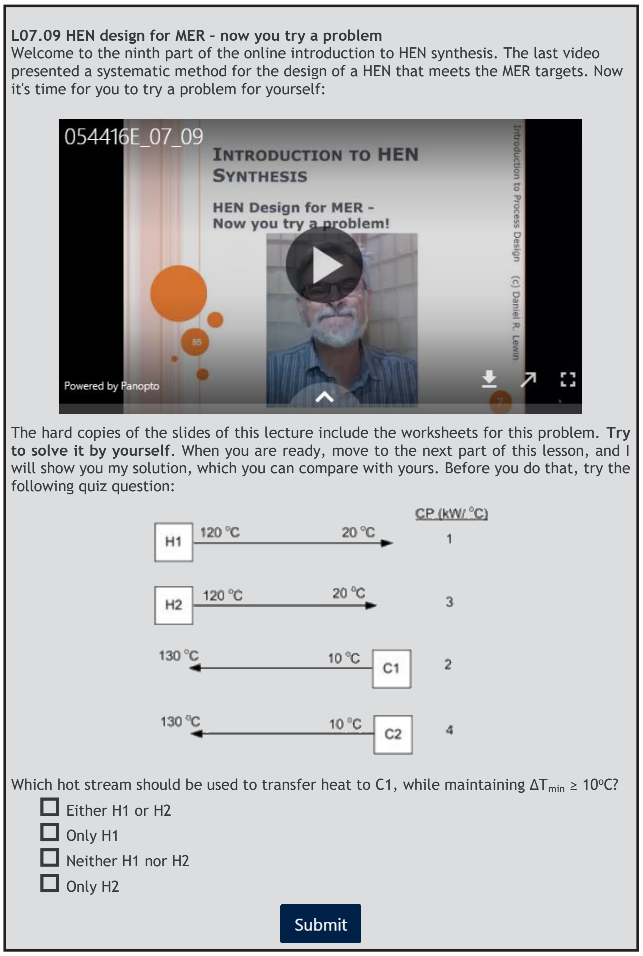
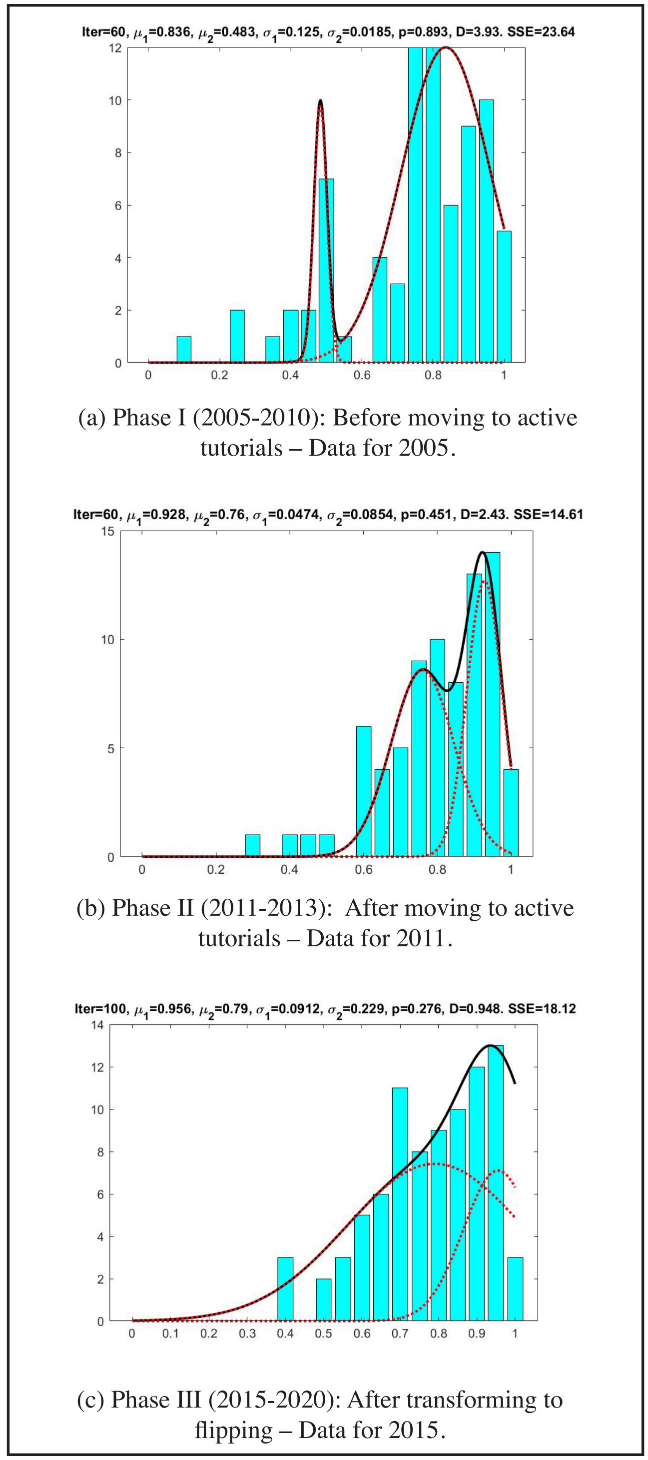


Figure 9. *Example Moodle Lesson segment, comprising embedded video and multiple-choice quiz question (L03.10).*

over the 15-year span from 2005-2020. Figure 10 shows three representative grade distributions, one for each phase of the pedagogic transformations effected on the course: Phase I (2005-2010), before moving to active tutorials; Phase II (2011-2013), after moving to active tutorials; Phase III (2015-2020), after transforming to flipping.

The results lead to the following observations:

1. There has been a gradual improvement in the average grades scored in the final exam of the design course, as well as a reduction in the failure rates. These changes have become most pronounced after the switch to active tutorials in 2011. This result supports *Hypothesis H1*, that switching to active tutorials has improved outcomes.
2. There is a degree of bimodality in all of the results shown in Figure 10 and Table 5, with the improvements reported gradually resulting from increased averages of both high- and low-performers. Again, the most significant improvements have occurred after active tutorials were introduced, again supporting *Hypothesis H1*.



(a) Phase I (2005-2010): Before moving to active tutorials – Data for 2005.

(b) Phase II (2011-2013): After moving to active tutorials – Data for 2011.

(c) Phase III (2015-2020): After transforming to flipping – Data for 2015.

Figure 10. *Representative diagnoses of final exam grade distributions for 054402/054416 for the three pedagogic phases. Each plot shows histograms of exam grade distributions, black lines indicating f(x) as predicted by Eq. (2), and red/grey dotted lines showing the high- and low-performing subpopulation contributions to f(x). The abscissa is the normalized exam grade while the ordinate is the number of students in each histogram bin, in steps of 5% of the total grade.*

3. There are large variations in possible class performance, as confirmed by the large swing in the estimated binomial distribution parameters. It is noted that the variations have been somewhat attenuated after the introduction of flipping.

To further facilitate elucidation of the results, the estimated values of μ_1, μ_2 and p are presented in the bubble plot shown in Figure 11, which shows bubbles of diameter proportional to the value of p plotted on the $\mu_1 - \mu_2$ plane. Note the bubbles are color-coded, with the period before the introduction of active tutorials (Phase I) shown in black, those for the period between the introduction of active tutorials but before flipping (Phase II) shown in grey, and the period after flipping (Phase III) shown in white. It was hoped that the bubble chart would show a clear separation between the three phases of the course's pedagogic evolution: before and after the introduction of active tutorials, and after the introduction of flipping. Instead, it demonstrates that annual grade results have significant variation, even when analyzing each period of the course's evolution, leading to overlap. This suggests that the inherent capabilities of each cohort have a significant impact on the results. Even so, some features are quite distinct:

1. The six exam results for the period before active tutorials were introduced, indicated by the black bubbles representing the years 2005-2010, are clustered on the lower-left, that is, with relatively low values of both μ_1 and μ_2. The instances in which relatively high values of μ_2 have been obtained have relatively low values of p. Table 5 indicates that the failure rates in this period are relatively high, averaging at 15%.
2. The results for the relatively short period between the introduction of active tutorials and before switching to flipping, indicated by the grey bubbles representing the years 2011-2013, have significant scatter. Even so, the average failure rate in this period was only 8%, indicating that, even though erratic and prone to bias depending on the nature of the class, there was a significant drop in the failure rate compared to the situation before active tutorials. It is apparent from these findings that the move to active tutorials have led to significantly better outcomes, thus strongly supporting *Hypothesis H1*. These conclusions are in line with the opinion of the students, who indicated that the active tutorial has had the most impact on their learning (discussed in the next section).
3. Most of the exam results for the period after flipping was introduced (five out of the six in all), indicated by the white bubbles representing the years 2015-2020, are clustered on the top right, that is, with relatively high values of both μ_1 and μ_2. In these circumstances, the value of p has less effect on the class performance. There is still some scatter, but it is less pronounced than for the exam results from active tutorials alone. The average performance of the six years with flipping is at the same level as that over the three years with active tutorials alone, noting that the failure rate in this period averages at 10%. However, flipping has achieved a more uniformly high performance, as indicated by the relatively tight clustering observed in the bubble plot of Figure 11, with a more consistent proportion of the class achieving higher performance, as indicated by the larger bubbles in the cluster on the right of the plot, compared with those of the other two phases. This indicates that the transformation from active tutorials to full flipping has advantages, thus supporting *Hypothesis H2*, that switching to the "flipped class" paradigm has improved outcomes.

TABLE 5
Analysis of capstone process design final exam grades, 2005-2020

Year	N	$N_{<55}$	μ	σ	μ_1	μ_2	σ_1	σ_2	p	D
2005	77	16 (21%)	0.73	0.21	0.84	0.48	0.12	0.02	0.89	3.93
2006	77	11 (15%)	0.69	0.15	0.81	0.67	0.04	0.19	0.16	0.91
2007	81	17 (21%)	0.68	0.18	0.75	0.67	0.04	0.12	0.12	0.37
2008	85	15 (18%)	0.68	0.17	0.77	0.63	0.30	0.04	0.91	0.69
2009	68	7 (10%)	0.75	0.24	0.86	0.34	0.16	0.01	0.96	4.53
2010	70	9 (13%)	0.74	0.18	0.90	0.76	0.02	0.29	0.15	0.67
2011	77	4 (5%)	0.78	0.15	0.93	0.76	0.05	0.09	0.45	2.43
2012	79	7 (9%)	0.77	0.18	0.94	0.77	0.03	0.14	0.33	1.78
2013	68	6 (9%)	0.74	0.14	0.80	0.70	0.20	0.05	0.91	0.66
2015	85	7 (8%)	0.76	0.15	0.96	0.79	0.09	0.23	0.28	0.95
2016	66	9 (14%)	0.71	0.20	0.83	0.33	0.20	0.02	0.90	3.59
2017	87	10 (11%)	0.72	0.16	0.90	0.59	0.10	0.16	0.55	2.22
2018	84	7 (8%)	0.75	0.16	0.88	0.72	0.08	0.16	0.35	1.26
2019	58	4 (7%)	0.79	0.15	0.92	0.56	0.17	0.16	0.86	2.20
2020	48	6 (13%)	0.73	0.17	0.92	0.74	0.26	0.04	0.85	0.98

Student Feedback

The previous discussion has indicated that moving courses to engage students more by active tutorials and flipping has led to quantifiable improvements in outcomes. What do the students think? Over the years, the students of the course *054416 Integrated Process Design* have been polled repeatedly to assess their attitude to active learning in general, and the implemented flipped approach in particular. The first time the course was given in flipped format,

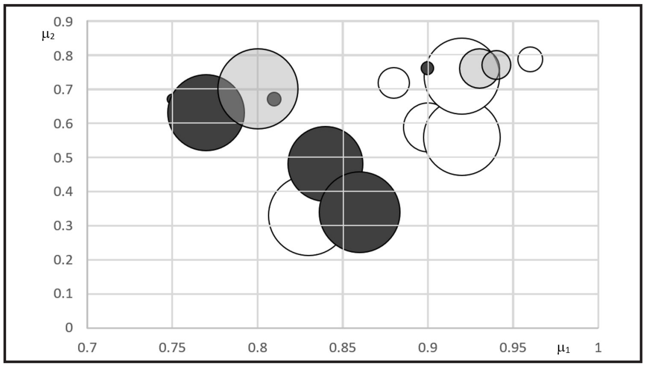
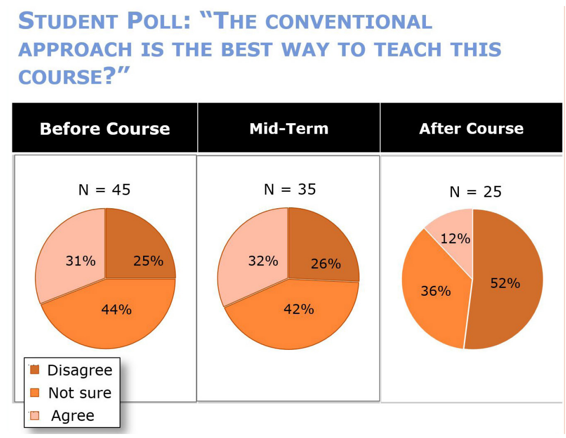


***Figure 11.** Bubble chart summarizing binomial distribution diagnosis. The statistics for each year is centred on the $\mu_1 - \mu_2$ plane, with the bubble diameter proportional to p. The bubbles are colour-coded according to period: black – Phase I: 2005-2010 (before active tutorials), grey – Phase II: 2011-2013 (before flipping), white – Phase III: 2015-2020 (after flipping).*

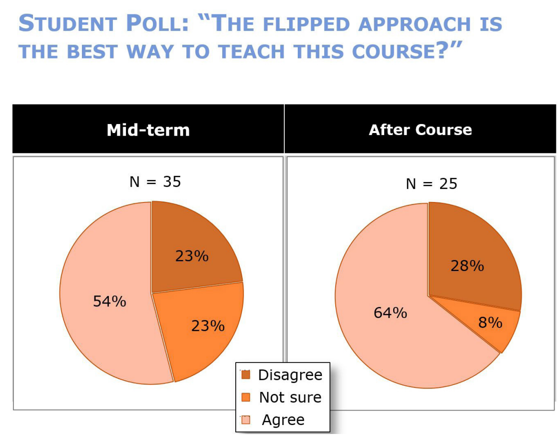
three polls were conducted – in the first week of the course, about half-way through the course, and at the end of the course. As shown in Figure 12(a), at the start of the course, students were ambivalent about the choice between flipped and conventional approaches. However, by the end of the course, only 12% still maintained that the conventional approach worked best for them, while 52% had been convinced that it did not. In contrast, as shown in Figure 12(b), by mid-way through the course, 54% of the students were already in favour of the flipped approach, increasing to 64% by the end of the course. In contrast, by mid-way through the course, 25% of the students did not take to the flipped classroom, and even by the end of the course, the same quarter of the class still did not take to the approach.

Tables 6 and 7 compare additional results obtained in the 2016 and 2019 academic years, noting that in Table 6 the responses are graded on a scale of 1 (for "strongly disagree/very poor") to 5 (for "strongly agree/very good"), noting that average scores and standard deviations are presented for the tabulated data, as well as Z-test results on the hypothesis that active tutorials improve students' confidence the most. Both of the polls are basically in agreement on the following general conclusions:

a. Most students prefer the flipped class to the traditional lecture-based paradigm. As indicated in Figure 12(b), the proportion of students who do not prefer this method may be significant. These students shared some of the reasons for their dissatisfaction with the flipped classroom in verbal comments, to be presented below.
b. As shown by the Z-test results presented at the bottom of Figure 6, it can be stated with statistical significance that of the three steps in the flipped approach, students rated the active tutorials as contributing most to their achievement capabilities. As indicated in Table 7, the main reasons for the effectiveness of the active tutorials were that they gave them rapid feedback from their peers and from the course staff. Very few students felt that the active tutorials were not useful to them.



(a) Distribution of agreement to the statement "the conventional approach is the best way to teach this course"



(b) Distribution of agreement to the statement "the flipped approach is the best way to teach this course"

***Figure 12.** Results of polls conducted on students of 054416 in 2015.*

The polls provided students with the opportunity to return specific comments to explain the reasons why they found flipping helpful or not. Here are some of the positive remarks:

P1.*"The active tutorial sessions were excellent. The TAs were around to help us solve the exercises, and also made us deal with questions and problems for ourselves."*

P2.*"This method should be applied to more courses."*

P3.*"The material is much clearer when you hear it a second time."*

P4.*"This method helped me learn at my own pace, making the most of my time."*

P5.*"The advantage of this method is the accessibility to lectures and the ability to repeat the material accurately."*

P6. *"I have never enjoyed an engineering course as much as I enjoyed this one."*

In contrast, here are some of the remarks indicating dissatisfaction with the method or suggesting improvements to it:

N1. *"I have no problems with flipping. It was the project that loaded this course."*

N2. *"The main thing is that it is very difficult to do half and half. Either it is all flipped or nothing. In my opinion, if the course material is delivered well, it can be delivered either way."*

N3. *"It's hard to watch the video and puts a higher load on the semester. I prefer regular lectures and homework."*

N4. *"Despite the many benefits of the method I personally find it easier to listen to regular lectures. It is difficult for me to sit continuously in front of the computer and listen to lectures."*

N5. *"The flipped method requires students to have free time and maximum concentration – It will be very hard for students to study many courses in this format."*

N6. *"Watching videos can be tiring."*

N7. *"The class meetings were a bit redundant. Most of them included repeats of the video lesson (which most of us watched). I recommend incorporating guided solutions to new examples, in addition to those that appeared in the video."*

N8. *"I think the format is great but still there are people who don't watch the videos properly, and then come to classes and hold them up by asking questions that are answered in the videos."*

The positive remarks by the students listed as P1-P6 are typical and constitute a majority opinion. Over the years, the critical comments raised by students have been addressed, wherever warranted. In the case of the above eight critical comments, N1 refers to the extended design project that constitutes an important part of the students' training, which the students need to be able to address, even if it is hard for some of them to accept. Comments N2-N6 refer to the preference of some students to retain face-to-face lecturing, and their dislike of video recordings. While this view may be understandable, they are the minority opinion, and replacing lecturing with the active participation of students in the class meetings and active tutorials are undoubtedly for the greater good, and as seen in the previous section, clearly improve learning outcomes. It is indeed impossible to please all of the people all of the time. Comment N7 is now out of date as most meetings involve materials not previously presented in the video recordings. Lastly, comment N8 has been addressed by linking the credit given for preparing the lessons in advance of class meetings to actually viewing the video recordings.

CONCLUSIONS

This paper has reviewed the last 15 years of teaching of the process design sequence at the Technion's Faculty of Chemical Engineering. The teaching methodology used has evolved from conventional lecture-based teaching and recitations, in which most of the students are passive during their contact time with staff, all the way to a fully-flipped format[23], in which the lectures are viewed interactively by students as homework, and all of the contact time between staff and students is released for active learning. All three courses in the sequence are essentially flipped: (a) 054330, the simulation laboratory, which involves self-guided multimedia modules that the students cover at their own pace during the semester, in tandem with gaining expertise in the usage of a commercial process simulator, UniSim®; (b) 054416, the capstone design course, taught since 2015 in flipped mode; and (c) 054410, the plant design course, taught since 2020 in flipped mode. Given that the entire sequence relies on asynchronous lessons, it can

TABLE 6
Comparing results of course questionnaires in 2016 and 2019. Average responses, where 5 = "strongly agree/very good," 4 = "agree/good," 3 = "undecided/fair," 2 = "disagree/poor," and 1 = "strongly disagree/very poor."

Question	2016, n = 36		2019, n = 28	
	μ	σ	μ	σ
I prefer the flipped class method to the traditional teaching method	4.06	0.98	4.07	0.94
The flipped classroom approach increases my motivation to learn	3.47	1.21	3.71	0.85
After completing the lessons, how do you rate your mastery?	3.21	0.88	3.25	0.65
After the Class Meeting (CM), how do you rate your mastery?	3.56	0.82	3.59	0.75
After the Active Tutorials (AT), how do you rate your mastery?	4.23	0.69	4.22	0.58
Z-test p-value results on hypothesis that $\mu_{CM} \neq \mu_{AT}$	$p = 0.0003$		$p = 0.0009$	

TABLE 7
Comparing results of course questionnaires in 2016 and 2019. "How were the active tutorials helpful to you?" Percentage of responders for each response.

Responses	2016	2019
I obtained immediate and constructive feedback from my peers	67%	59%
I obtained immediate and constructive feedback from the course staff	58%	78%
I did not find the active tutorials useful	17%	4%

also be taught totally on-line, with class meetings and active tutorials relying on Zoom meetings, using breakout rooms, as necessary. This has been tested by teaching both 054330 and 054410 online in the first COVID-19 lock-down semester of spring 2020, as well as 054416 in winter 2020. Quantitative evidence has been provided to show that the transition to active learning has led to better outcomes as corroborated by a consistently higher degree of mastery in final exams with lower failure rates, together with increased confidence and satisfaction exhibited by the students. The paper has highlighted the potential of active learning to improve the quality of mastery that can be achieved in design-based courses. This paper has presented a quantitative analysis of how the grade distributions changed over the period of transition of the teaching protocols adopted, as well as results of student polls, from which it can be concluded that:

a. The move from passive tutorials to active tutorials made the most impact on improving learning outcomes.
b. The move to flipping increased the proportion of student-staff contact time in which the average student takes an active part in learning, leading to a more modest improvement in learning outcomes compared to the move to active tutorials.
c. Most, but not all, students favor the flipping approach.

Experience with the flipped-class approach indicates that overall, engagement with the materials throughout the semester improved the students' level of confidence in their mastery of the subjects. This is principally because they come to class and to the tutorials better prepared than with the conventional version of the course. These observations could explain the improved performance in the final exam, as demonstrated, since adopting active learning and flipping. Following the students' improved achievements after the first offering of the flipped *054416 Integrated Process Design*, the core control course, *054314 Introduction to Process Dynamics and Control*, was transformed to flipped format, so that since 2016, our students have been engaged simultaneously in two flipped, design-oriented courses in their 7th semester.[24] The grade distributions in the final exams of both courses together were as encouraging as those experienced previously for the single flipped capstone design course, demonstrating that this format can be taught to good effect in more than one course at a time. We hope that these findings will encourage others in the chemical engineering community to follow our example.

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