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Integrating Design Thinking in Chemical Engineering Coursework for Enhanced Student Learning

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Jake Stengel is a graduate research student at Rowan University. He holds a BS from Rowan University in chemical engineering and is in his first year of the chemical engineering master's program at Rowan University. His research focuses on using engineering fundamentals to improve process efficiency, affordability, and sustainability. His versatile work includes computer simulation, optimization, data analytics, mathematical modeling, machine learning, and software development. He currently is working with Dr. Kirti M. Yenkie to explore different teaching methodologies to strengthen the understanding of theoretical concepts for undergraduate students.

Miss Swapana Subbarao Jerpoth, Rowan University

Swapana S. Jerpoth received her B.Tech degree in Chemical Engineering from Priyadarshini Institute of Engineering and Technology, India in 2017, and her M.Tech degree in Petrochemical Engineering from Laxminarayan Institute of Technology, India in 2019. She joined as a Ph.D. student in the Chemical Engineering Department, Rowan University in 2019 and is currently working under the supervision of Dr. Kirti M. Yenkie. Swapana's current research interests include sustainable process design and sustainability assessment of renewable and non-renewable energy resources with emphasis on analysis and optimization of transportation processes in multiproduct pipeline systems. She also serves as a teaching assistant at Rowan University Chemical Engineering Department courses in Thermodynamics, Separation Processes, and Process Dynamics and Controls. She is the graduate student mentor of the junior/senior engineering clinic for the industrial project funded by the EPA (Environmental Protection Agency) and the ExxonMobil Lubricant Oil Blending Facility Paulsboro NJ. Swapna is an active member of the American Institute of Chemical Engineers (AIChE) as well as a member of the American Chemical Society (ACS). At present, she has one peer-reviewed publication and has presented her work at three international conferences. Her computational skills include Ansys Fluent, GAMS, MATLAB, and Polymath. Her hobbies and interests are singing, cooking, and painting.

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Dr. Kirti M. Yenkie is an Assistant Professor of Chemical Engineering at Rowan University with 10+ years of experience working in the Process Systems Engineering (PSE) area with applications focusing on Sustainability and Environmental Resource Management. She is leading the Sustainable Design and Systems Medicine Lab (https://yenkiekm.com/), which has capabilities to work with major programming and simulation tools. She holds a Ph.D. in Bioengineering from the University of Illinois-Chicago (UIC), MTech from IIT Bombay, and BTech from LIT Nagpur in Chemical Engineering. She has prior postdoctoral research experience from the University of Wisconsin-Madison and the University of Delaware. Her ongoing research on Green engineering and Water asset management is funded by the US EPA, Atlantic County Utilities Authority, and ExxonMobil. Her expertise includes mathematical modeling, optimization, programming, uncertainty analysis, and sustainability evaluation.

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Introduction

We are living in a continually evolving world. Globalization and advances in technology demand the recent chemical engineering graduates be employed in fields that did not exist 10-20 years ago, such as biotechnology, nanotechnology, product development, and sustainable practices [1]. In response to the above challenges, besides gaining technological knowledge, the students also need to be emphatic and critical thinkers to become leaders in solving multidisciplinary problems [2]. Therefore, the traditional teaching techniques need to be improved and upgraded to bridge the gap between the existing chemical engineering curriculum and what the chemical engineering graduates need to learn to succeed in their careers [3], [4]. To this end, the graduate and undergraduate courses in Chemical Engineering at Rowan University have integrated Design Thinking pedagogy in their teaching/learning process to enhance the student's understanding of theoretical concepts via extensive use of Process Systems Engineering (PSE) computational tools. Design Thinking has attracted widespread attention in the educational community over the recent decades [5], [6]. In practice, Design Thinking is a process of identifying challenges and generating potential solutions that are human-centered [7]. It deals with a structured framework in finding solutions to wicked problems by applying creative strategies. Real-world problems do not have one definite formulation and can be solved in many ways. In this context, the implementation of Design Thinking focuses on stakeholder- and community-based thinking to develop holistic solutions [8], [9].

The Engineering Clinic program is one of the Hallmarks of the Henry M. Rowan College of Engineering (HMRCoE) that makes our curriculum unique. It is through this endeavor that the ideas and skills of Rowan students, faculty, and partner industries converge, and students experience a hands-on approach to learning and problem-solving. The faculty members offer these clinic projects based upon their research expertise, and the projects are funded by Federal agencies such as the US EPA (United States Environmental Protection Agency), NSF (National Science Foundation), and DOE (Department of Energy) and by our industrial partners such as ACUA (Atlantic County Utilities Authority), and ExxonMobil. Figure 1 illustrates our undergraduate curriculum and highlights the clinic programs in purple borders. The first year and sophomore year engineering clinics focus on fundamental engineering skills and include diverse topics such as creative and scientific writing, technical presentation, convergent thinking, problem-solving, product development, ethics, engineering design, and statistics. For the Junior/Senior year the students choose their discipline-specific clinics depending on their curiosity and area of interest Building on the foundation of PSE and Design Thinking, the Process Dynamics & Control course and the two elective courses: Process Optimization and Experimental Methods in Chemical Engineering (highlighted with star markers in Figure 1) integrate project-based learning and encourage students to develop deeper levels of contextual understanding.

FIRST YEAR			
FALL	CR	SPRING	CR
Rowan Core Elective	3	Composition I ENGL01.111	3
Calculus I MATH01.130	4	Calculus II MATH01.131	4
Chemistry I CHEM06.100	4	Chemistry II CHEM06.101	4
Fresh. Engineering Clinic I ENGR01.101	2	Fresh. Engineering Clinic II ENG01.102	2
Introductory Mechanics PHYS 00.220	4	*Rowan Core Elective*	3
Total	17	TOTAL	16
SECOND YEAR			
FALL	CR	SPRING	CR
Principles Chemical Processes I CHE06.201	2	Principles Chemical ProcessesII CHE6.202	2
Calculus III MATH01.230	4	Math for Engg Analysis MATH01.235	4
Organic Chemistry I CHEM07.200	4	ChE Fluid Mechanics CHE06.241	2
Soph. Engineering Clinic I ENGR01.201	4	Approved Advanced Chemistry Elective	3
		Soph. Engineering Clinic II ENGR01.202	4
TOTAL	14	TOTAL	15
THIRD YEAR			
FALL	CR	SPRING	CR
ChE Thermodynamics I CHE06.310	3	ChE Thermodynamics II CHE06.315	3
Separation Processes I CHE06.312	2	Separation Processes II CHE06.314	3
Process Fluid Transport CHE06.309	2	Chem Reaction Engineering CHE06.316	4
Jr Engineering Clinic I ENGR01.301	2	Jr Engineering Clinic II ENGR01.302	2
Heat Transfer Processes CHE06.311	3	*ChE Materials CHE06.381*	2
Chemical Engg Modeling CHE06.385	2		
TOTAL	14	TOTAL	14
FOURTH YEAR			
FALL	CR	SPRING	CR
ChE Process Component Design CHE06.401	3	Chemical Plant Design CHE06.406	3
Chemical Process Safety CHE06.407	2	Unit Operations Lab CHE06.403	3
Process Dynamics & Control CHE06.405	3	Approved ChE Elective II CHE06.___	3
Approved ChE Elective I CHE06.	3	Approved ChE Elective III CHE06.___	3
Sr Engineering Clinic I ENGR01.403	2	Sr Engineering Clinic II ENGR01.403	2
Rowan Core Elective	3		
TOTAL	16	TOTAL	14
TOTAL CREDITS 120			

Figure 1. Chemical engineering undergraduate curriculum highlighting the courses where Design Thinking is implemented

For each course topic, a supporting computer lab session is designed to provide students a hands-on approach to mathematical modeling and computational skills. These courses introduce students to a variety of computational tools which includes GAMS®, MATLAB®, COMSOL®, Python®, ASPEN®, and ImageJ®. Additionally, the Process Optimization course incorporates project-based learning with an aim to enhance student's real-world skills such as teamwork, persistence, determination, leadership, and an entrepreneurial mindset that plays a critical role in their professional success.

Design Thinking offers sound and innovative solutions to emerging complex problems. With this approach, solutions can be developed both to sustain existing and enhance the existing curriculum to combat the new challenges presented by the pandemic [10]. The world changed forever with the global pandemic of COVID-19. In the year 2020, the United States experienced a rapid increase of people working from home, from 20% in March going to 50% in April [11]. In the world of education, this meant a large increase of instructors and students operating from home using remote technologies and the internet. In a more technologically advanced country like the United States, the transfer to online learning happened more smoothly than in other countries, yet there are still some inefficiencies in this new system [12]. Many institutions around the world have resorted to roughly adapting their in-person courses into some online format via video conferencing tools like Zoom, Microsoft Teams, or WebEx [13]–[15]. The rough adaptation led to a new high stressed virtual environment for instructors which they were not used to and many struggled with teaching as well as capturing student attention [16], [17]. This has forced many instructors to re-evaluate their teaching methods and develop better methodologies to face the new era of hybrid learning.

In this article, we discuss how the novel Design Thinking pedagogy embedded in our engineering curriculum introduced students to the capabilities of computer-assisted methods in decision making for real-world problem solutions and applications. Furthermore, it can support the remote teaching/learning process in response to new needs that have arisen during the public health crisis.

Teaching methodology

This work proposes an advanced methodology of conducting team project assignments that would be suitable in the post-COVID-19 era, this involves the five stages of Design Thinking: (1) Empathize, (2) Define, (3) Ideate, (4) Prototype, (5) Test[18], [19]. Without COVID-19 classroom restrictions, these five stages consist of face-to-face meetings and interactions within the classroom, interviews, and team interactions. The students start in stage 1 (Empathize) where they do relevant research and data collection for the team projects. The students have access to many resources such as peer-reviewed journals and case studies which help the teams form a problem statement. Once the problem is identified the students move into stage 2 (Define), where the student team identifies a problem based on the relevant research that is done as part of the first stage. The first iterations of the solution are done in stage 3 (Ideate). Stage 3 is where students start to implement their ideas via computational programming tools such as General Algebraic Modeling System (GAMS), MATLAB, Simulink®, and P-graph® [20]–[22]. If possible, the students start to compare their solutions with the analytical models they obtained from the first two stages, and if their models seem accurate, they move onto stage 4. Stage 4 (Prototype) and stage 5 (Test) revolve around established simulation tools such as ASPENPlus®, SuperPro Designer ®, and GAMS. These simulation tools allow for the students to make complete virtual representations of the models which were found in the earlier stages.

This novel 5-stage approach allows students to develop many solutions to the same problem and assess the solutions from different perspectives. The students are encouraged to consider different viewpoints such as economical, commercial, environmental, social, and political when developing their problem statements and subsequent solutions [18]. COVID-19 has led to a decrease in in-person interactions which hinders the process of the five stages of Design Thinking, however, with some modifications, our proposed approach can be implemented smoothly into the current online curriculum for chemical engineering students.

To incorporate changes, it was important to understand the challenges and potential opportunities, so our team, comprising the course instructor and teaching assistants, explored the existing literature and supporting information prior to developing the modified Design Thinking approach. Current instructors are seeing a massive difference in the atmosphere between online and in-person modes of instruction. Many students find the online class settings daunting due to a lack of social interactions and difficulties concentrating [23]. They face additional challenges as many instructors are not properly trained to adapt their curriculum to an online setting [16].

To combat inefficient classroom settings many researchers have studied the best practices to use in an online classroom. The first step is to choose a delivery method of the content in the courses. From research, it is seen that a majority of students are able to adapt to learning from online video lectures when synchronous with the recordings posted for future review [24]. At Rowan University, Zoom™ and Canvas LMS™ (Learning Management System) is chosen to be the online platform to conform with the online teaching standards and the ease of use of these programs [25]. Now that the online platforms have been chosen, research is done on how to effectively teach in an online setting. To have a successful online learning environment the instructor must have an increased time commitment and virtual presence, include more time into planning and online course organization [26]. In addition, instructors participating in extra activities like discussion boards and breakout rooms are shown to provide a good outlet for socialization between students which is normally missing in an online atmosphere [27]. By using these good online teaching practices within the online platforms, the team of course instructors is able to reconstruct the delivery of Design Thinking to students which is suitable in an online learning environment.

As defined by the Kern Entrepreneurial Engineering Network (KEEN), an entrepreneurial mindset consists of Curiosity, Connections, and Creating value [28]. In a world of accelerating changes, it is important that the students are curious and empowered to investigate a rapidly evolving world. Just reading and learning about new discoveries are not enough because they will yield insights only when connected with the existing information and needs of the present world. Moreover, students must be champions at value creation and contribute towards global needs. To this end, the five stages of Design Thinking are modified to seamlessly embed them into the online curriculum of the highlighted courses. Through these modifications, the 5-stages are mapped to the three C's of an Entrepreneurial mindset [29]. This provides an effective mechanism to encourage an entrepreneurial mindset about the Chemical Engineering students via drawing connections between the theoretical principles and real-world applications. Table 1 shows how the five stages are mapped to the three C's of KEEN.

Table 1: Mapping of Design Thinking to 3 C's of an Entrepreneurial Mindset

Three C's of Entrepreneurial Mindset	**Stages of Design Thinking mapped to 3 C's**
Curiosity	Stage 1 & Stage 2 (Empathize & Define)
Connections	Stage 3 (Ideate)
Creating Value	Stage 4 & Stage 5 (Prototype & Test)

With all the three C's mapped to the specific Design Thinking stages, we proceeded to find a method of successfully incorporating each into the online courses. The first step is to introduce all the students to the ideas of the three C's [30]. **Curiosity** is developed through the numerous discussion boards where students are prompted to answer questions referring to course content. These questions are phrased to make the students think outside the box about how to incorporate what they are learning into scenarios outside the classroom. **Connections** are developed by showing how the whole course ties together to other courses learned in the Chemical Engineering curriculum. By showing students how concepts earlier in the semester can tie in with concepts they are learning in the present, the student can start to form links between all the course concepts. By doing this, the students see how everything they have learned can be beneficial and can help them solve problems. **Creating Value** is developed by having students solve real-world problems through classwork and lab work. By motivating the students to solve problems that they observe in everyday life, the students will continue to relate the experience beyond the course timeframe. The second step is to allow the students to experience the 3 C's on their own with moderate support from the instructor [30]. This is done through a term project which helps the students experience the 3 C's directly and get the full effect of integrated Design Thinking. The project rubric is developed from the 3 C's to give students moderate guidance, but ultimately this project can take different directions and can involve multiple aspects. The third step is to allow the students to solve real-world industrial or societal problems using Design Thinking. This step is structured in a way that resembles a workplace. The students are given tasks to do and timelines to follow to find solutions to problems that are relevant to the industry, society, etc. By following these three steps the students enhance their Design Thinking process allowing them to develop skills that are essential for excelling in the future workplace.

Creative and conceptual thinking through project-based learning

Project-based learning has become a widely used technique in engineering programs [31]. The Process Optimization course at Rowan University incorporates the term project pedagogy to mimic the real-world engineering atmosphere and provide students with opportunities to solve complex problems. Students are provided with the topic selection guidelines and evaluation rubrics (illustrated in Figure 2) at the initial phase of the semester-long project. They are encouraged to work in groups of three to four members and decide on a topic by conducting an extensive literature review and discussions with the instructor. The selected topic has to be based upon the 3 C's emphasizing the skills in an entrepreneurial mindset.

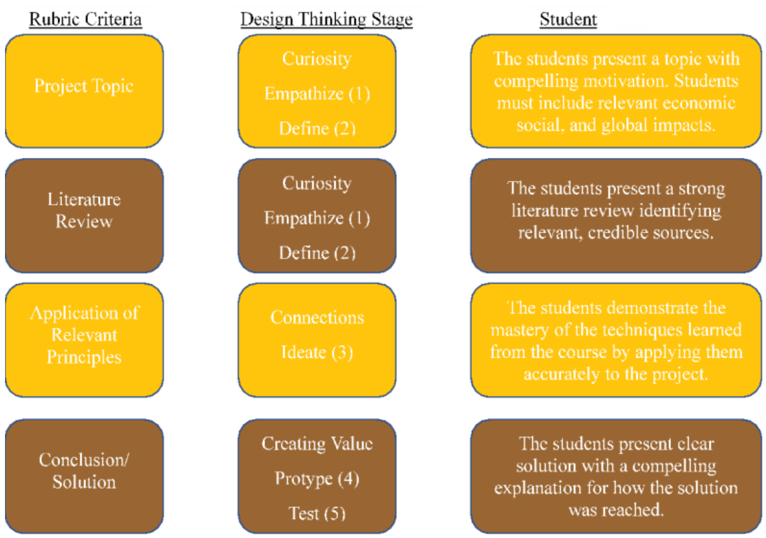

Figure 2. Evaluation Rubric for Optimization Term Project

During the course instruction, the well-designed computer lab training provides the students an understanding of selecting computational tools best suited for their projects. Beyond applying the theoretical concepts for solving realistic and complex problems, students also enhance their leadership, critical thinking, creative thinking, and communication skills by working in teams. The projects undertaken by students covered a variety of topics from traditional chemical engineering problems such as 'Optimization of the Production of Bioethanol' to practical need-based life examples such as 'Minimization Of Ventilator Distribution Centers for the treatment of COVID-19 Pandemic', and 'Economics and Sustainability of Wastewater Treatment'. The following sections provide a detailed discussion of the problem development and their solution strategies.

Term project examples

Minimization of ventilator distribution centers for the treatment of COVID-19 pandemic: In the spring semester of 2020, a team of four students worked on developing a distribution plan for ventilators to minimize their cost of delivery to hospitals treating COVID-19. The team arrived at the idea to combat the current COVID-19 pandemic by trying to minimize inefficiencies in the delivery of medical equipment. The primary objective was to minimize the cost of distributing ventilators with a secondary objective of minimizing delivery timelines of ventilators to all hospitals in New Jersey.

The students formulated the problem as a multi-objective mixed-integer non-linear programming (MINLP) model in GAMS. At the start of the project, the team's objective was to solve the problem by minimizing the distribution costs to all hospitals in New Jersey; yet, due to equation limitations of the free version of GAMS the students had to simplify the problem to the limited number of equations. Thus, the students researched ways to simplify the problem and decided to minimize the distribution costs to the 21 counties in New Jersey (see Figure 3) rather than the 100 plus hospitals. The objective then became to minimize the travel distances and economics by placing ventilator distribution centers in key counties around New Jersey. The students accomplished this objective by first making a distance matrix between all the counties. Then the students used the information they gathered from literature and online sources to make the equations they would code in GAMS. These equations included distribution center capacity, transportation cost, and ventilator requirement constraints. The objective function was the summation of the cost to build a distribution center and the estimated transportation costs of those distribution centers seen in equation (1)

$$Objective = \sum_{i=1}^{i=n} Q(i) + Transportation\ Cost\ (i) \qquad (1)$$

Q(i) depicts the distribution center cost at a certain county and n depicts the maximum number of distribution centers. When all the relevant information was put in GAMS, the team found that the optimal solution was to place five distribution centers in New Jersey. The students identified that their code still needed to be refined. However, given the limited resources, this was an important and timely accomplishment by the team.

Economics and sustainability in wastewater treatment: A group of four students worked on the problem of economics and sustainability of wastewater treatment. Focusing on the Design Thinking approach, the students were able to emphasize that the global demand for fresh water is continuously increasing. It is predicted that the global demand for fresh water will increase availability by 30% by 2030. Therefore, there is a need to resort to wastewater treatment and reuse to meet the increasing demands. Through an extensive literature review, the students determined that wastewater is treated in a stage-wise process: the primary, secondary, and tertiary stages. Various technologies can be used in each of these three stages [22]. However, the challenge arises when answering the question of which technology to select in each stage of the treatment so that the purity standards are satisfied and that the treatment cost is minimized. Moreover, the selected technologies must meet the sustainability goals. Therefore, the students proposed a methodology based on a superstructure approach (illustrated in Figure 3).

The problem is formulated as a multi-objective optimization problem and gives insights for selecting a sustainable network for the municipal wastewater treatment case study. In this work Sustainable Process Index (SPI) was used for evaluating the sustainability of the network. SPI method evaluates the sustainability of a process based on the total arable land required. A Pareto chart was developed for the multi-objective optimization approach, and the weighting method was used for the analysis. Mixed-integer non-linear programming (MINLP) optimization problem was developed and solved using BARON (Branch-and-Reduce-Optimization-Navigator) in GAMS. Students developed cost-effective wastewater treatment networks by considering the trade-offs between total cost and sustainability of the process. The students identified that the highest cost for the purification process is 13.9 million$ utilizing an area of 8.69E+9 m^2, while the lowest cost is 1.4 million$, corresponding to an area of 6.22 E+7m^2.

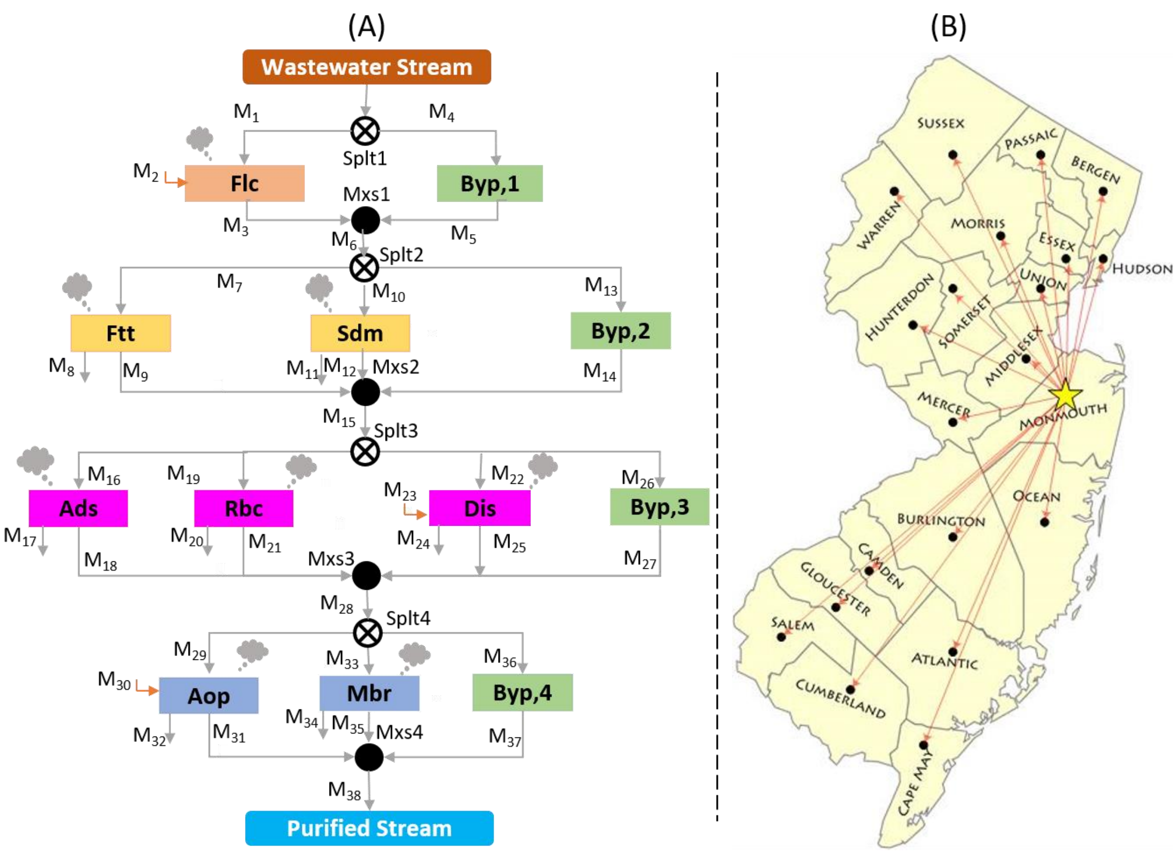

Figure 3: (a) The stagewise superstructure for municipal wastewater treatment showing all technologies in all stages, (b) The optimization of COVID-19 ventilators across the counties of New Jersey

Industry or government-sponsored engineering clinic projects

One of the key highlights of the HMRCoE at Rowan University is the Engineering Clinic program. This is a requirement for each undergraduate student for all four years of their degree program. In the junior and senior years, the student is required to join a project related to research offered by the Engineering Professors based on their area of research expertise as well as federal and industry sponsorship. These projects span from designing phone and computer applications to testing machinery for use in industry. There is a wide span of projects between all the different engineering disciplines offered by Rowan University. Within the chemical engineering department, many projects focus on individual faculty lab research or targeted research for companies or federal agencies. Most of our projects focus on the use of integrated Design Thinking to solve real-world large-scale design problems using computational methods. In addition to offering design projects, we focus on bolstering the teamwork between the undergraduates by requiring a minimum of four members to be part of each team. In addition, graduate students partake in the project to simulate a professional working environment with adequate support by acting as project managers to the undergraduate students. The following sections show how our team integrates Design Thinking into the clinic programs to strengthen the undergraduate perception and understanding of complex problems.

<u>Optimization of pipeline flushing operations in lube oil facilities</u>: The project 'Optimization of Pipeline Flushing Operations in lube oil Facilities' is supported by the US. EPA and focuses on understanding the flushing techniques that are currently being used in lubricant manufacturing and processing facilities. This project aims to improve the overall greenness of the process and contribute to the broad goals of pollution prevention by minimizing hazardous waste generation by implementing novel process optimization techniques. The Department of Chemical Engineering at Rowan University has had the opportunity to partner with one of the leading lubricant manufacturing facilities in North America and investigate their lubricant formulation and blending operations. A typical lube oil blending and packaging facility uses a complex network of the pipeline system for processing over thousand different products annually. This requires the manifold system to be reused for multiple operations and must be flushed/cleaned every time a new product is processed. The current flushing process utilizes a high-value finish product and leads to the downgrading of the product. Moreover, it also adds to a significant environmental burden. Therefore, the goal of this project is to minimize the downgrade of lube oil products, by exploring both engineering design solutions and the chemistry of the flushing process. The project activities involve the development of novel experimental plans, record keeping, data analysis, characterization, computer codes, programs, simulations, and the use of sophisticated computational tools. Building on the concept of Designing Thinking the goal will be achieved by mimicking the actual plant setup at Rowan lab in the form of a scaled-down experimental rig. Moreover, the students are involved in regular plant visits as well as weekly follow-ups through web meetings and group discussions with the academic and industry partners. Our estimations show that if our novel approach is implemented throughout the EPA's Region 2, the measures could save companies around $10 million and reduce waste by as much as three million pounds. Hence, we believe that the outcomes of this project will help in developing a systematic approach to understanding and optimizing the flushing processes in the petroleum and chemical industries.

<u>Roadmap for solvent recovery in industrial manufacturing</u>: The roadmap for solvent recovery is a US EPA-sponsored project aimed at reducing solvent waste being put into the environment by providing industries with a software tool to show possibilities of recycling the solvent back into the process. To build this tool, the students are tasked with using their knowledge from chemical engineering to develop technology models and make a network of interconnected technologies which can recycle solvent waste streams. This program has been offered to undergraduate students since the Fall semester of 2018 for every semester. Currently, the team consists of three graduate students and four undergraduate students working on developing the tool for use in the

industry. This project focuses on skill development in stages 3 (ideate), 4 (prototype), and 5 (test). This project utilizes many different software including GAMS, SuperPro Designer®, MATLAB®, and AspenPlus® allowing for creative freedom in the design of the project. With the weekly video calls, the graduate team can steer the undergraduates towards the correct path while showing the importance of each stage in Design Thinking. Through these weekly meetings, the team has successfully arrived at the final stage (test) within three years, while building the core skills.

Overall outcomes

Students' feedback has shown that they highly valued and benefitted from the Design Thinking pedagogy in the Chemical Engineering curriculum. The extensive knowledge acquired through project-based learning helped students in acquiring internships in eminent industries. The clinic programs helped students to gain valuable research experience at their undergraduate level. This helped students to develop their critical thinking, problem-solving, communication, and leadership skills and excel in their role as professional engineers.

Concluding remarks

Due to the adapted teaching methodology, students were able to experience the full benefits of integrated Design Thinking for problem-solving even in an online learning environment. By modifying the curriculum to effectively teach the five stages of Design Thinking, the students have developed a skill set that will be useful during the current and post COVID-19 pandemic. The students were first introduced to the idea of Design Thinking in the classroom setting and were encouraged to apply these concepts to broader term projects for courses and engineering clinic research projects. To this effect, Design Thinking allowed the students to accomplish large-scale optimization problems referring to industrial pipeline flushing and solvent recovery operations. From these efforts, many students have responded positively, and have noticed the development of new skillsets. Various feedback surveys have shown that the students now value this modified teaching methodology, as it helped them transition smoothly from a student to a valuable employee in the U.S. workforce.

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Works Cited

[1] C. H. T. Ng and S.-M. Cheah, “Chemical product engineering using CDIO enhanced with design thinking,” p. 9, 2012.

[2] M. Lynch, U. Kamovich, K. K. Longva, and M. Steinert, “Combining technology and entrepreneurial education through design thinking: Students’ reflections on the learning process,” *Technological Forecasting and Social Change*, vol. 164, p. 119689, Mar. 2021, doi: 10.1016/j.techfore.2019.06.015.

[3] T. F. Edgar, B. A. Ogunnaike, J. J. Downs, K. R. Muske, and B. W. Bequette, “Renovating the undergraduate process control course,” *Computers & Chemical Engineering*, vol. 30, no. 10, Art. no. 10, Sep. 2006, doi: 10.1016/j.compchemeng.2006.05.012.

[4] J. Perkins, “Education in process systems engineering: past, present and future,” *Computers & Chemical Engineering*, vol. 26, no. 2, Art. no. 2, Feb. 2002, doi: 10.1016/S0098-1354(01)00746-3.

[5] S. Panke, “Design Thinking in Education: Perspectives, Opportunities and Challenges,” *Open Education Studies*, vol. 1, no. 1, Art. no. 1, Dec. 2019, doi: 10.1515/edu-2019-0022.

[6] Y. Li *et al.*, “Design and Design Thinking in STEM Education,” *Journal for STEM Educ Res*, vol. 2, no. 2, pp. 93–104, Dec. 2019, doi: 10.1007/s41979-019-00020-z.

[7] K. D. Elsbach and I. Stigliani, “Design Thinking and Organizational Culture: A Review and Framework for Future Research,” *Journal of Management*, vol. 44, no. 6, Art. no. 6, Jul. 2018, doi: 10.1177/0149206317744252.

[8] D. Pusca and D. O. Northwood, “Design thinking and its application to problem solving,” p. 7.

[9] J. P. A. von Thienen, W. J. Clancey, G. E. Corazza, and C. Meinel, “Theoretical Foundations of Design Thinking,” in *Design Thinking Research: Making Distinctions: Collaboration versus Cooperation*, H. Plattner, C. Meinel, and L. Leifer, Eds. Cham: Springer International Publishing, 2018, pp. 13–40.

[10] A. Thakur, S. Soklaridis, A. Crawford, B. Mulsant, and S. Sockalingam, “Using Rapid Design Thinking to Overcome COVID-19 Challenges in Medical Education,” *Acad Med*, Sep. 2020, doi: 10.1097/ACM.0000000000003718.

[11] J. A. Weill, M. Stigler, O. Deschenes, and M. R. Springborn, “Social distancing responses to COVID-19 emergency declarations strongly differentiated by income,” *PNAS*, vol. 117, no. 33, pp. 19658–19660, Aug. 2020, doi: 10.1073/pnas.2009412117.

[12] M. Adnan and K. Anwar, *Online Learning amid the COVID-19 Pandemic: Students' Perspectives*, vol. 2, no. 1. 2020, pp. 45–51.

[13] Almarzooq Zaid I., Lopes Mathew, and Kochar Ajar, “Virtual Learning During the COVID-19 Pandemic,” *Journal of the American College of Cardiology*, vol. 75, no. 20, pp. 2635–2638, May 2020, doi: 10.1016/j.jacc.2020.04.015.

[14] J. Crawford *et al.*, “COVID-19: 20 countries’ higher education intra-period digital pedagogy responses,” *Journal of Applied Learning & Teaching*, vol. 3, no. 1, Art. no. 1, 2020, doi: 10.37074/jalt.2020.3.1.7.

[15] A. N. Giordano and C. R. Christopher, “Repurposing Best Teaching Practices for Remote Learning Environments: Chemistry in the News and Oral Examinations During COVID-19,” *J. Chem. Educ.*, vol. 97, no. 9, pp. 2815–2818, Sep. 2020, doi: 10.1021/acs.jchemed.0c00753.

[16] P. D. MacIntyre, T. Gregersen, and S. Mercer, “Language teachers’ coping strategies during the Covid-19 conversion to online teaching: Correlations with stress, wellbeing and negative emotions,” *System*, vol. 94, p. 102352, Nov. 2020, doi: 10.1016/j.system.2020.102352.

[17] A. Besser, S. Lotem, and V. Zeigler-Hill, “Psychological Stress and Vocal Symptoms Among University Professors in Israel: Implications of the Shift to Online Synchronous Teaching During the COVID-19 Pandemic,” *Journal of Voice*, Jun. 2020, doi: 10.1016/j.jvoice.2020.05.028.

[18] K. M. Yenkie, “Enhanced Undergraduate Learning through Integration of Theory and Computational Tools,” *Chemical Engineering Education*, vol. 54, no. 3, pp. 129–136, 2020.

[19] R. Wolniak, “The Design Thinking method and its stages,” *Systemy Wspomagania w Inżynierii Produkcji*, vol. Vol. 6, iss. 6, 2017, Accessed: Feb. 08, 2021. [Online]. Available:

http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-81d700a1-e4ea-4257-87cf-d0b790873bc8.

[20] I. Heckl, F. Friedler, and L. T. Fan, “Solution of separation-network synthesis problems by the P-graph methodology,” *Computers & Chemical Engineering*, vol. 34, no. 5, pp. 700–706, May 2010, doi: 10.1016/j.compchemeng.2010.01.019.

[21] F. Friedler, K. Tarján, Y. W. Huang, and L. T. Fan, “Graph-theoretic approach to process synthesis: axioms and theorems,” *Chemical Engineering Science*, vol. 47, no. 8, pp. 1973–1988, Jun. 1992, doi: 10.1016/0009-2509(92)80315-4.

[22] K. M. Yenkie, “Integrating the three E’s in wastewater treatment: efficient design, economic viability, and environmental sustainability,” *Current Opinion in Chemical Engineering*, vol. 26, pp. 131–138, Dec. 2019, doi: 10.1016/j.coche.2019.09.002.

[23] A. Patricia Aguilera-Hermida, “College students’ use and acceptance of emergency online learning due to COVID-19,” *International Journal of Educational Research Open*, vol. 1, p. 100011, Jan. 2020, doi: 10.1016/j.ijedro.2020.100011.

[24] N. I. Scagnoli, J. Choo, and J. Tian, “Students’ insights on the use of video lectures in online classes,” *British Journal of Educational Technology*, vol. 50, no. 1, pp. 399–414, 2019, doi: https://doi.org/10.1111/bjet.12572.

[25] M. M. Archibald, R. C. Ambagtsheer, M. G. Casey, and M. Lawless, “Using Zoom Videoconferencing for Qualitative Data Collection: Perceptions and Experiences of Researchers and Participants,” *International Journal of Qualitative Methods*, vol. 18, p. 1609406919874596, Jan. 2019, doi: 10.1177/1609406919874596.

[26] E. Baran and A.-P. Correia, “A professional development framework for online teaching,” *TechTrends: Linking Research & Practice to Improve Learning*, vol. 58, no. 5, pp. 95–101, Sep. 2014, doi: 10.1007/s11528-014-0791-0.

[27] J. Suler, “In Class and Online: Using Discussion Boards in Teaching,” *CyberPsychology & Behavior*, vol. 7, no. 4, pp. 395–401, Aug. 2004, doi: 10.1089/cpb.2004.7.395.

[28] J. Estell, D. Reeping, and H. Sapp, “Curiosity, Connection, Creating Value: Improving Service Learning by Applying the Entrepreneurial Mindset,” in *2016 ASEE Annual Conference & Exposition Proceedings*, New Orleans, Louisiana, Jun. 2016, p. 26621, doi: 10.18260/p.26621.

[29] N. Erdil, R. Harichandran, J. Nocito-Gobel, C. Li, and M.-I. Carnasciali, “Impact of Integrated E-Learning Modules in Developing an Entrepreneurial Mindset based on Deployment at 25 Institutions,” *Engineering and Applied Science Education Faculty Publications*, Jun. 2017, [Online]. Available: https://digitalcommons.newhaven.edu/sgiengineering-facpubs/16.

[30] E. Lindberg, H. Bohman, P. Hulten, and T. Wilson, “Enhancing students’ entrepreneurial mindset: a Swedish experience,” *Education & Training*, vol. 59, no. 7/8, pp. 768–779, 2017, doi: http://dx.doi.org.ezproxy.rowan.edu/10.1108/ET-09-2016-0140.

[31] A. Steiner, L. Hirshfield, C. Finelli, and D. Chachra, “Investigating Task Choice in First-Year Engineering Team Projects,” in *2016 ASEE Annual Conference & Exposition Proceedings*, New Orleans, Louisiana, Jun. 2016, p. 25481, doi: 10.18260/p.25481.