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Teaching chemical product design

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ABSTRACT

The CACHE Design Task Force has conducted a comprehensive, year-long study on the teaching of chemical product design across global chemical engineering programs. This paper reviews existing literature and highlights distinctions between product and process design, emphasizing the predominance of process design education in universities. Drawing from co-author contributions and responses to a widely distributed questionnaire, we present recent teaching methodologies for chemical product design. The paper discusses trends in chemical engineering diversification and the gradual inclusion of diverse applications in curricula. It concludes with a call to action for chemical engineering educators to integrate well-established product design strategies into undergraduate programs and reflects on insights shared during the 2024 FOCAPD Conference.

1. Introduction and background

Beginning in November 2016, the CACHE Design Task Force, comprised of 10–15 design instructors, met at the Annual Meeting of the AIChE, and elsewhere, to carry out its mission to examine the teaching of both process design and product design. Gradually, additional members joined to assist, some volunteering to prepare case studies and teaching materials to be distributed by CACHE. With process design taught actively at nearly all schools, it became clear that more emphasis was needed to upgrade the instruction of product design. And, gradually the task force, as well as the entire CACHE Board, became aware of exemplary new approaches for teaching product design.

Then, in October 2023, the CACHE Design Task Force initiated a comprehensive review of how chemical product design is taught globally. Our objective was to understand and document current practices, identify gaps, and highlight opportunities for innovation in chemical engineering education. This paper aims to address the growing importance of chemical product design in an industry that increasingly values

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high-value specialty products over traditional commodity chemicals.

To achieve these objectives, the Task Force began by inviting nine of the instructors that teach these exemplary chemical product design courses to describe their courses and how they originated from their earlier courses that emphasized process design. Each responded with 5–7 page descriptions, which were placed in a report titled: CACHE Report on Teaching Chemical Product Design (which appears in the Supplemental Material for this manuscript). Other design instructors, and industrial persons involved in teaching product design at universities, were asked to provide comments and possibly suggest other approaches. Then, the CACHE Design Task Force prepared a Questionnaire, which with the 74-page report, was sent to over 200 design instructors worldwide. Several sources helped to identify these instructors based upon their descriptions of teaching design in books, lectures, design education manuscripts, and the like. With only 36 responses from these carefully selected design instructors, it was clear that most are not teaching, or advocating for teaching, product design.

The motivation for this study stems from the rapid evolution of the chemical engineering field, where graduates must be prepared to design innovative, market-driven products that align with societal needs and technological advancements. Our findings draw on insights from survey data, co-author contributions, and feedback from industry collaborators. By presenting a view of the challenges and best practices in teaching chemical product design, we aim to guide departments in refining capstone design courses to ensure students are equipped with the skills needed for future industry demands.

Despite the well-established emphasis on process design in most curricula, the integration of product design remains limited. This paper explores why process design continues to dominate, discusses recent advancements in product design education, and presents strategies for merging both disciplines to prepare students better.

1.1. Prior advances in teaching chemical product design

Also, readers should appreciate that, in recent years, the literature contains several suggested new approaches that predated our year-long study.

Dating back to 2006, at the University of Queensland, St. Lucia, Australia, a paper described the introduction of chemical product design into the chemical engineering curriculum as an introductory second year subject, followed by product-specific electives in the third year (biochemistry, food technology, materials and particle and polymer science, physical chemistry, and so on), and culminating in a capstone year-long project in the fourth and final year (Kavanagh and Lant, 2006). This experimental sequence, introduced in 2003, was described as the first group of seniors graduated in 2006. It was concluded that the work load was significantly higher than in normal curricula. Modifications were anticipated given lecturer and student feedback.

In 2013, at VIT University in Vellore, India, the changing need to design specialty products, such as formulated products, by fresh chemical engineering graduates was emphasized. Gurumoorthy and Smith, 2013 described how they launched an annual, third-year-elective, chemical product design course in 2005 – using the first edition of the Cussler and Moggridge (2001) textbook, the second edition of Seider et al. (2004), and the book by Wei (2007). They concluded that such courses are needed to accompany the shift of the chemical process industries towards high-value specialty chemicals from low-value commodity chemicals.

In 2016, Rodrigues and Cussler (2016), similarly reflected on the emerging need for change toward courses on both process and product design. But, they concluded that there was "no clear agreement on what the changes should be." Furthermore, they stated: "these new directions are very difficult to teach, at least in the current environment." They discussed different efforts and successes to incorporate product design into the chemical engineering curriculum.

To our knowledge, Fung and Ng, 2018 were the first to describe how to teach chemical product design using design projects. They indicated that "product design is considered hard to teach by most faculty members, partly because there exist only limited teaching materials, particularly those that can be used for independent student design projects." In their paper, they presented a multidisciplinary, hierarchical procedure that guides students to design a chemical product – while providing two case studies "to illustrate the learning process of, as well as the contents for, such student projects"

In a most unusual approach, Salcedo Galan et al. (2018) showed how product design has facilitated the understanding of the fundamental concepts in transport phenomena for students using active learning methodologies centered on the evaluation of market needs. They suggested that "students perceive the chemical engineering field as abstract and difficult to apply due to the fashion in which the problems are posed, the mathematics involved, and the three-dimensional view required to understand the phenomena." They saw chemical product design, on the other hand, as permitting the evolution of the engineer to a more market-oriented designer, becoming more aware of the impact of his/her design.

Yet, another unusual approach was proposed by Feijoo et al. (2018). They used games in the process of brainstorming. By presenting problems in a game format, they "elude" conventional lecturing and free the participants to think creatively to solve problems. At the Univ. of Santiago de Compostela, in Spain, the aim was to develop students' creativity and teamwork, with working groups proposing and assessing alternatives in the conceptual design of products and processes. Their paper presented two examples to apply their methodology, one involving the remodeling of a wood box for wine storage, given various consumer needs, and the other involving the design of a process to remove pollutants from a gaseous product stream with pre-specified process requirements.

Next, came a presentation that addressed the chemical industries desire to manufacture commodity chemicals as well as to convert them into higher-value chemical products (Zhang et al., 2020). Their focus is on the design of chemical processes as well as the selection of sustainable products, marketing, and waste disposal. Much attention is addressed to computer-aided methods for chemicals product development, with their advantage to quickly identify promising candidates, while recognizing that models and data are often not available for the design of chemical products using new technologies. This is often complicated by the need for multiscale and multidisciplinary chemical product designs. Therefore, it is recognized that, to find new and innovative chemicals-based products, systematic computer-aided methods and tools, capable of managing these complexities, are needed. Their paper addresses the challenges and opportunities for computer-aided design, including experiment-, knowledge-, rule- and model-based approaches.

To our knowledge, a first paper focusing on the selection of biologically active ingredients for formulated chemical products in pharmaceutical or agrochemical applications was provided by JB Ten Kate et al. (2022). It calls for improved applications of chemical engineering principles, using structured approaches, to select active ingredients; e.g., for drugs and pesticides, as well as for non-scientific developments. For the former, it recognizes that semi-empirical approaches, heavily based on personal experience and preference, are often used – and when reliable solid-state and surfactant performance predictions are not available, it calls for improved access to relevant, well-curated data in well-maintained databases, including measures for accuracy. For the latter, it calls for better education of industrial practitioners.

Most recently, Rivera Gil et al. (2022), published a review on chemical product design. The Abstract for this paper reads: "The product design project is a complex problem because objectives and constraints must be considered simultaneously, the sustainability context is highly relevant and specific, decision-making involves not only customer needs but also of other stakeholders, especially the organization in which the design project takes place. This work presents a systematic literature review of design methodologies for chemical products to identify how that problem has been addressed and which are the future challenges to be met. The review involved the analysis of 262 research papers and 336 patents, classified according to the chemical product type, the design phase studied, and whether they consider association with a business context. The study highlights the need for holistic product design methodologies applicable from the early design stages, covering the assessment of customer needs and the requirements of other stakeholders, as well as the business context where the design process is carried out." In short, many strategies for chemical product design are described, but the coverage does not offer perspectives regarding why process design is taught at nearly all universities, while product design is taught at very few.

1.2. Organization of this paper

Having introduced and provided background in this Section 1, including a brief review of recent advances in teaching chemical product design, this manuscript proceeds to consider the current world of product design in Section 2. Next, it briefly addresses the distinctions between teaching product and process design in Section 3, before Section 4 considers the worldwide teaching of process design. The heart of this paper addresses the teaching of product design in Section 5. In concluding, Section 6 summarizes some on the advances herein in teaching chemical product design, and Section 7 predicts the future of chemical engineering design education.

Combined with these recent approaches, the co-author contributions herein (detailed in the Supplementary Materials,) enables this manuscript to offer the collective views of approximately 40 persons that teach, have considered teaching, have helped teach, or have encouraged teaching, product design.

2. World of product design

Certainly, a growing number of companies are actively designing new chemical products and processes to manufacture them, including GE, Procter and Gamble, L'Oreal, Gore, Hershey, Bristol-Myers-Squibb, Merck, among many others. But, first, beginning in 1904 with abrasives (sandpaper), 3M Co. created and marketed a consumer-oriented product business, probably the first large-scale worldwide. To work on the third edition of *Product and Process Design Principles* (Seider et al., 2009), in 2007, Prof. W.D. Seider, spent his sabbatical leave at 3M, writing with his former student and new co-author, Soemantri Widagdo. In 2010, 3M sales were at $24.5 billion, with subsidiaries in more than 60 countries, sales in 200 countries, 8000 technical staff (mainly in St. Paul, MN), having created over 60,000 chemical products (in their Innovation Museum), and 45 established technology platforms – with products for 10 markets (mostly for consumers and offices; display and graphics; electro and communications; safety, security, and protective services; health care; industrial and transportation.

It is well-recognized that **INNOVATION** is the creation of new products by linking **NEW TECHNOLOGIES** from R&D to satisfy perceived consumer needs; the **VOICE OF THE CONSUMER**. Often these products are **TECHNOLOGY DRIVEN** or **MARKET DRIVEN.** At this point, three noteworthy high-tech products are worthy of mention, with brief descriptors of their new technologies:

mRNA Covid Vaccines – created using lipid nanoparticles to carry mRNA through blood without inflammation
Liquid Crystal Displays (LCDs) – created using Corning's Isopipe process and Gorilla glass
3D Printed Medical Products – created using software to drive moving jet printers

Of course, not all new chemical products are created using such advanced new technologies.

Before leaving this brief discussion on the World of Product Design, as mentioned in Section 1, Introduction and Background, readers are reminded of the comprehensive review of industrial strategies for carrying out chemical product design (Rivera Gil et al., 2022).

3. Distinctions between teaching product and process design

Before proceeding, it is important to recognize two well-known questions that distinguish product design from process design:

Product Design – What to make?

Process Design – How to make it?

Students need to learn to <u>innovate</u> in product design; i.e., to apply the latest new technologies to design products that satisfy consumer needs (the voice of the customer). For process design, students need to learn to insert process operations (e.g., chemical reactions, mixers, separations, heaters and coolers, compressors and expanders) when preparing a process flowsheet (e.g., carrying out process synthesis.)

In recent years, several noteworthy authors have drawn attention to the growing importance of product design, including Cussler and Moggridge, 2011, Wei (2007), Seider et al. (2017), and Ng et al. (2007)

4. Teaching process design

As confirmed by our Questionnaire, nearly all ChE departments worldwide teach process design with syllabi similar to that shown in Fig. 1.

Of note, however, in nearly all design projects, the processes are too big to build. Also, they usually don't involve device, functional, and formulated products. And, they are often limited in scope, involving just simple molecule products, having simple rheology and chemical kinetic models.

In spite of these drawbacks/limitations/constraints, responses to our Questionnaire indicated that:

1. While important to expose students to product design, highest priority should be given to process design – which distinguishes ChEs from other engineering disciplines (who usually emphasize product design). Also, process design addresses challenges in sustainability (plastics recycle, water reuse and recycle, etc.) – I. Grossmann, CMU
2. Many product designs (to select solvents, refrigerants, mass separating agents, etc.) require thorough knowledge of process design. So, with only one semester available, we choose process design for the capstone design experience – J. J. Siirola, Purdue
3. The shift toward product design is driven by lab researchers – does not benefit students employed in industry (that don't go to grad. school) – T. Meadowcroft, Rowan Univ.

And, to add to these sentiments, Christos Maravelias, Princeton

Process Synthesis
Process Simulation (e.g., ASPEN PLUS, HYSYS)
Separation Train Design
Heat Integration (ΔT_{min}, Pinch)
Heat Exchanger Design
Separation Tower Design
Capital Cost Estimation
Profitability Analysis

Fig. 1. Typical chemical process design subjects.

University, described the design course at Princeton. To summarize here (with a more complete statement in the CACHE report):

4. In the early 2000's, Princeton revised its undergraduate curriculum to have eight required ChE courses **plus** a research-based two-semester senior thesis. A Fall senior design course (Energy and Process Systems Design) has a lecture-based component as well as a group project (recently focusing on renewable energy systems). For some aspects, students use a process simulator and develop analyses of TEA and LCA.

5. Teaching product design

This section begins with a brief review of well-recognized resources to assist in teaching product design. Then, it presents a summary of recent approaches for teaching product design at nine chemical engineering departments. Note that these are described in more detail in the Supplemental Materials that accompany this manuscript (i.e., 74-page CACHE Report on Teaching Chemical Product Design). Next, the origin of the CACHE Questionnaire is presented, with coverage of its results and important recommendations by several design instructors.

5.1. Resources for teaching product design

At the outset, we briefly describe two well-recognized textbooks that assist in teaching product design.

Chemical Product Design (Cussler and Moggridge, 2011. The textbook, *Chemical Product Design* (Cussler and Moggridge, 2011, which appeared in a first edition in 2001, presented the first systematic 4-stage approach for designing and developing new chemically-related products and devices:

Stage 1 Begin with customer interviews
Stage 2 Identify needs, Seek ideas
Stage 3 Select the best ideas – using chemical and engineering criteria satisfying comfort, safety, …, criteria. Translate customer needs into engineering specifications
Stage 4 Consider manufacturing

The book covers specialty chemicals such as pharmaceuticals and coatings, but also considers micro-structured products (based upon complex fluids) and devices that perform chemical operations. This approach is applied for many product examples, involving molecular structure design (fluids for deicing airplanes, less-polluting laundry detergents, tranqualizer synthesis, amines for CO_2 removal from flue gases) and consumer devices (coffee cup design, home ventilators, dehydrators of farm milk. blood oxygenators, and improved thermopane windows).

Product and Process Design Principles (Seider et al., 2017). A significant departure from this approach is in the textbook, *Product and Process Design Principles* (Seider et al., 2017), which provides two parallel tracks. The first introduces the strategies for chemical product design in Chapter 1, questioning which new chemical products to design, and presents examples of designing new devices, functional, and formulated products in Chapters 4 and 5, followed by chapters that include business decision making and six-sigma product design. The second track introduces chemical process design in Chapter 2, questioning how to design new processes to manufacture the new chemical products. and introducing heuristic approaches for process synthesis. This is followed by chapters including the systematic usage of heuristics for process synthesis, the use of process simulators to assist in process design, the design of chemical reactor networks, separation trains, heat exchanger networks, equipment sizing and cost estimation, and profitability analysis.

Other resources include books of case studies referenced herein (Block and Miller, 2022; Brockel et al. 2007; Brockel et al. 2013; Cheng et al, 2009; Coe, 2000; Cooper, 2005; Gundling, 2000; Hill, 2008; Isaacson, 2014; Kavanagh and Lant, 2006; Pisano, 1997; Wibowo and Ng, 2001).

5.2. Recommended approaches for teaching product design at nine ChE departments

In many of these descriptions of current and recommended approaches, note the importance of preparing students to understand the new technologies associated with their product design projects. Also, please note the 5–7 page descriptions in the Supplemental Materials for this manuscript (that contain the 74-page CACHE Report on Teaching Chemical Product Design).

Furthermore, these 5–7 page reports describe how their courses evolved from process design courses over several years. Exemplary reports from Cornell Univ., Univ. of New South Wales, Univ. of Cal.-Santa Barbara, Univ. of Michigan, and others, described how their courses were improved over these years. In 5–7 pages, detailed numerical assessments cannot be provided – lengthy reports were not requested, as they could not be circulated to design instructors with the Questionnaire described next in this manuscript. Also, see Section 6 where several of these reports are shown to have advanced the teaching of product design.

1. Cornell – Tobias Hanrath and Kathy Vaeth, Qualitrol Corp.
   Since 2012, Cornell has focused on the design of chemical products, recognizing that at many companies design of the product is as important as the design of a process – such as pharmaceuticals, food, consumer products, medical devices, energy, and microelectronics. Industrial partner companies compose customer and business needs statements to design a product. Each group designs, builds, and tests a prototype. Students cycle from classroom theory, to lab-work, to customer feedback, and to design and redesign of their prototypes to meet customer and market requirements. Using theory, as in finite-element modeling, students check the performance of their products. It has been challenging to find the right balance between manager- and student-defined projects. Also, the coordination of teaching the principles of product design in time for student work to satisfy due dates of deliverables has been challenging.
2. UC Santa Barbara – Todd Squires.
   Many ChE students seek work in fields involving formulated chemical products – such as consumer products, pharmaceuticals, oil, gas and minerals, foods, household and construction materials, etc.). Often 10 + ingredients, spanning solvents, solutes, polymers, colloids, and surfactants) are combined to achieve the product's flow properties (rheology), stability, chemical functionality, and aesthetic or sensory qualities. Often, the basic sciences and advanced topics are spread across many courses in different departments, with challenges from the interactions between ingredients. To adequately prepare design groups, an elective course was created to facilitate design of such formulated soft-material products.
3. U. New South Wales – Patrick Spicer and Stuart Prescott.
   In 2017, Spicer and Prescott recognized the need for educating ChEs to develop polymer production processes, an industry nearly extinct in Australia. Spicer, after 15 years at Procter & Gamble, recognized that ChE fundamentals are needed, in addition to making such products, to design and quantify the performance of the products. Prescott had similar experience through industrial research partnerships. They created a ChE program to target food, consumer product, and pharmaceutical industries, employers of their students. Their product engineering program is designed to teach intermediate-process engineering courses, intermediate-chemistry courses and courses that focus on the design, innovation and finance cycles in chemical product engineering. The final year of the program has its own capstone design project, a two-semester

Chemical Product Design structured as an authentic design experience.

4. U. Michigan – Laura Hirshfield, Elaine Wisniewski, Xiaoxia "Nina" Lim.

   Students are required to complete 5-credits of senior design prior to graduation. They can select between a one-semester process design course or, since 2008, a two-semester product design course, in which they research, design, develop a chemical product, and build a prototype in the laboratory. Most students take process design (~130), with 30–45 annually taking product design, seeking careers in food and beverage, consumer products, personal care, or cosmetics. Teams of 4–5 students are created. In a 2-credit Fall semester course, students are guided through the design process of defining a problem or opportunity, ideating solutions, demonstrating need for a product, conducting and analyzing market research, and communicating their findings. In a 3-credit Winter semester course, students develop their product in the product design laboratory.

5. Colorado St. U. – Minnie Piffarario.

   Two courses are taught in the senior year. Groups of 4–6 students begin in the Fall to gain familiarity with design projects, selected as juniors in the Spring, occasionally involving students from other CSU engineering departments. As they learn soft skills, they begin to work as a team. Then, as they study background materials, they plan work on their projects, and begin to formulate product/process specifications. This leads into the study of process simulation and process synthesis – applied to provide a study-level mass and energy balance along with equipment sizes. In the Spring semester, they cover more on equipment sizing, with pricing and profitability analysis. Students construct product prototypes or virtual models of their designs. Much attention is devoted to understanding product specifications, defining quality parameters, and product design approaches – covering key topics from the Seider et al. (2017) textbook. In the CACHE supplementary report, lecture topics are listed along with recent design projects. They also refer to ~60 people that volunteer time to serve as advisors, guest speakers, and technical consultants – including faculty and industrial persons – throughout the year.

6. Texas A&M U. (TAMU) – Mahmoud El-Halwagi and Faruque Hasan.

   Two senior-level courses are dedicated to process design: CHEN 425 (Process Integration, Simulation, and Economics) and CHEN 426 (Chemical Engineering Plant Design). For CHEN 425, three extensive topic outlines (on Introduction to Process Design, Process Economics, and Process Integration) are provided in the CACHE report. The report also provides a listing of topics for the Simulation Lab and notes that the term project for the entire class is on process simulation, integration, and economic evaluation. For CHEN 426, materials are integrated from other courses and teams of 4–6 students work on "front-end loading (FEL)" for industrially sponsored design projects. TAMU has no course dedicated to product design, but many product design topics are taught in CHEN 322 (Thermodynamics), CHEN 425, and CHEN 426 – with specifics in the CACHE supplementary report.

7. Georgia Tech – Saad Bhamla.

   Two senior-level courses are dedicated to process design (Process Design and Economics; and Capstone Design Project), which integrate core ChE principles into a process design application. Usually, the same industry-sponsored design project is solved by all groups of 4–6 students. A popular elective Chemical Product Design course is taken by 35–45 % of students in the Fall semester, being offered every year since Fall 2003 when it launched in collaboration with P&G Foundation. Using the Cussler & Moggridge (2011), the course has objectives to provide industry exposure through guest lectures; understanding product differentiation and profitability; mastery of structure/property relationships; a focus on sustainability; contemporary product development methodologies. The students provide written and oral reports on various product design projects. Particularly starting in 2024, a significant focus is placed on projects that strongly align with United Nations Sustainable Development Goals (UN SDGs)

8. UPenn – Warren Seider.

   During the 2000's, emphasis on process design in a Fall lecture course was augmented with several topics on product design. This preceded a Spring design projects course, mostly having process design projects with a few product design projects. Note that, since the 1940s, a large fraction of our ChE faculty, advise senior design projects with the assistance of industrial persons. For product designs, projects are often proposed by faculty, closely related to their research efforts.

   Gradually, during the 2010's, product design topics were removed to lighten the load in the Fall, with very few product design projects remaining in the Spring. Beginning in 2020, we provided a Spring elective product-design course, taken mostly by master's students, with a few junior students (no seniors because it conflicts with the senior design projects course). For the product-design course, lecture topics, with homework, from the Seider et al. (2017) textbook included: stage-gate product design, voice of the customer, product devices, formulated products, functional products, molecular product design, six-sigma design, business decision making, and design optimization. Then, during the last six weeks of the semester, students worked on oral and written product-design term projects (of their choosing), with several products listed in the CACHE supplementary report.

9. Brigham Young Univ. – John Hedengren

   An unorthodox senior product design course, Ch En 461, focuses on making students proficient problem solvers. Students are encouraged to revisit the content from their core courses and explore new knowledge from available literature. Students are expected to spend at least nine hours per week on this class, including three in-class hours and six on outside work. The course activities center around a single product design project that spans the entire semester. These activities include group organization, initial investigation into the subject, proposal writing and presentation, interim status reports, draft report writing, and final presentation. By emphasizing experiential learning and teaching students to work on projects with incomplete or messy information, Ch En 461 bridges the gap between theoretical knowledge and practical application, preparing students for success in industry or graduate school.

   While specific project topics may vary, the course covers fundamental aspects of chemical product design, including problem formulation, research, proposal development, project execution, and final reporting. These topics provide a comprehensive overview of the product design process. The specific topics are dictated by the project and the sponsor requirements for the project. Projects are sponsored by senior-level engineers in industry, ensuring that students work on real engineering challenges. Faculty members, such as Dr. Andrew Fry, play a crucial role in guiding students throughout the project. Their expertise and mentorship enhance the learning experience.

5.3. CACHE teaching product design questionnaire

Given these nine recent approaches for teaching product design, the CACHE Design Task Force, setup a questionnaire to assess how product design is taught worldwide, which was sent to over 200 well-recognized design instructors – along with the CACHE Report on Teaching Chemical Product Design. It requested identification of topics covered in lectures, an indication of textbooks used (as well as course notes and course packs), titles of product designs carried out by student design groups, identification of the roles of design project formulators. In this subsection, we discuss the origin of the questions and critique the responses.

First, we formulated many questions designed to measure the extent to which and how product design is taught. Then, to use the Survey Monkey, especially its ability to tabulate results from many respondents, when possible, we sought to obtain yes or no responses, as well as brief few word responses. When paragraphs were anticipated; e.g., to describe design projects, space was allocated and responses were summarized as well as possible.

Consider an early question concerning how product design was taught. Table 1 shows the alternative responses possible and the number of schools responding. Of the 36 responses obtained, we learned that product design was covered in 23 required courses, with two departments providing elective courses and seven covering subjects in other courses. Of the 36 responding departments, four do not teach product design and, perhaps more importantly, on the order of 180 design instructors chose not to respond to the questionnaire. Clearly, few design instructors expressed views about teaching product design.

Regarding lecture topics, Table 2 lists topics emphasized in the textbook by Seider et al. (2017). Because, as shown in Table 3, 17 departments use the Seider et al. textbook, it may not be coincidental that the sum of departments covering topics in product design and other courses is on the order of 17 – with the remaining departments not covering the topics or not responding.

It is noteworthy that many of the product design projects identified by departments in response to the Questionnaire, and listed in Table 4, involve products similar to those discussed in the course resources.

It is also noteworthy, as shown in Table 5, that on the order of 10 departments have indicated that their product design projects were formulated by industrial persons or faculty, with 10 departments showing faculty having provided personnel to assist students on technical issues and having provided software. This implies that undergraduate seniors need this assistance to design projects involving advanced technologies. (As we have seen, UC Santa Barbara and U. New South Wales have created courses to provide this technical assistance.) The funding and company facilities tours are also consistent with these observations. While 10 ChE departments are few, these roles for project formulators are consistent with the large numbers of engineering departments (other than ChE) whose seniors solve product design projects.

Clearly, more data are needed, which should become available as more departments offer courses that teach product design. Regarding steps to stimulate the teaching of chemical product design, see Section 7 on Predict the Future of Chemical Engineering Design Education.

5.4. Additional statements on teaching product design

These quantitative results above are accompanied next by important statements from the Questionnaire responses, as well as statements, solicited and unsolicited, on important approaches needed/expected when teaching product design. These are included next in this subsection that completes Section 5 on Teaching Product Design.

CMU – Chrysanthos Gounaris

This Questionnaire response from Prof. Gounaris summarized how the CMU department is adding product design instruction. Process design, taught in the Fall, and product design, taught in the Spring, are required courses at CMU. Note that double majors in Biomedical Eng. take a course on biomedical product design instead. In the Spring course, emphasis is on product selection, usually with order-of-magnitude property estimates because accurate data are often unavailable. With challenges in obtaining data, it is especially difficult to satisfy technical standard requirements. Although, because students learn process design in the Fall, students seek to establish good cost estimates in "design-to-manufacturability" – as they consider the tradeoffs between functional requirements and profitability.

Next, summaries of approaches presented for teaching life-cycle analysis (LCA) and sustainability in product design courses are provided. These are presented in detail in the Supplementary Materials associated with this manuscript

Life cycle analysis (LCA) – Jennifer Dunn (Northwestern U.)

In addition to evaluating manufacturing costs, product selling prices, and the like, the importance of quantifying life-cycle effects of products is emphasized, topics not often covered in courses prior to product and process design. Next, factors often considered in an LCA of a product, such as energy, solvents, raw materials, and water are covered, leading into methods for developing an LCA in a design course. These involve concepts ranging from safety to the foundations of design. For design courses, Prof. Dunn suggests following the

Table 1
How is product design taught? – No. of responses from 36 departments.

Alternative to Process Design	4	12.5 %
Primary Design Course	5	15.6 %
Combined with Process Design	14	43.8 %
As an Elective	2	6.3 %
In Other Courses	7	21.9 %
Total	32	100 %
Not Taught	4	

Table 2
Product design topic covered in lectures – No. Responses from 36.

Topic	Product Design Course	Other Courses	Not Covered	No Response
Stage-Gate Product Design	11 (30.6 %)	5 (13.9 %)	13 (36.1 %)	7 (19.4 %)
Voice of the Customer	8 (22.2 %)	4 (11.1 %)	15 (41.7 %)	9 (25 %)
Product Devices	7 (19.4 %)	4 (11.1 %)	15 (41.7 %)	10 (27.8 %)
Formulated Products	10 (27.8 %)	8 (22.2 %)	10 (27.8 %)	8 (22.2 %)
Functional Products	9 (25 %)	5 (13.9 %)	13 (36.1 %)	9 (25 %)
Molecular Structure Design	9 (25 %)	7 (19.4 %)	14 (38.9 %	6 (16.7 %)
Six Sigma Design	4 (11.1 %)	7 (19.4 %)	15 (41.7 %)	10 (27.8 %)
Business Decision Making	4 (11.1 %)	13 (36.1 %)	10 (27.8 %)	9 (25 %)

Table 3
Reading materials – No. of departments using each resource.

Resource		
Seider et al. (2017) Product and Process Design Principles	17	47.2 %
Cussler & Moggridge (2011) Chemical Product Design	7	19.4 %
Course Notes and Course Packs	12	33.4 %

Table 4
Product Design Projects.

Waste to Products
Sustainable Bio-based Polymer
Insect-based Protein Product
Biodegradable Hot Cup
Sulfur Production in the Petrochemical Industry
Biosolids Combustion/Gasification/Pyrolysis
Teal Hydrogen
Aviation Fuel from CO_2 and Green Hydrogen
Sustainable DME Phenol/Acetone from Cumene plant
H_2 via Biomass

Table 5
Role of product design project formulators – No. Responses from 36.

Activity	Industrial Person	School Faculty	Student
Formulation of Project	3 (27.3 %)	7 (63.6 %)	1 (9.1 %)
Provide Funding	2 (28.6 %)	4 (57.1 %)	1 (14.3 %)
Company Facilities Tour	3 (37.5 %)	5 (62.5 %)	
Provide Personnel to Assist Technically	0 (0 %)	10 (100 %)	
Provide Software	1 (9.1 %)	10 (90.9 %)	

four phases of LCA embodied in the International Standards Organization (ISO) LCA standards. See the Supplementary Materials for an introduction to these phases. She includes a description of the use of the Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) open-source model, developed and maintained by the Argonne National Laboratory, to obtain emission factors and water and energy consumption factors. Examples are provided with discussion of how to deal with specialized chemicals, when they are not available in GREET, with recommendations concerning how to handle such data gaps in design courses. As Prof. Dunn concludes, she includes a suggestion to explore and interpret LCA results using sensitivity analyses as an example.

Sustainability – Warren Seider (UPenn)
This section recommends usage of the book, Sustainable Engineering, by Prof. B. R. Bakshi (2019), which begins with (1) an introduction to the concept of sustainability. Then, it focuses on (2) reasons for unsustainability, followed by (3) approaches for assessing the extent of sustainability, and concludes with (4) solutions for achieving sustainability. Methods for assessment include energy and material flow analysis, leading into measures for energy quality, such as exergy and emergy, often applied in life-cycle analyses. Then, solutions are discussed that include the <u>design</u> of sustainable processes and products, accompanied by ecosystem ecology, economic policies, and societal development. In a product-design course, using lectures or student term projects, it is recommended that items (1)-(4) be illustrated for design of typical products and the processes to manufacture them. Students need to learn step-by-step strategies for adjusting their designs to become more sustainable.
At the FOCAPD-2024 Conference, during the discussion following Plenary Lectures on Teaching Chemical Product and Process Design, Prof. Bakshi recommended and volunteered to assist in arranging for young colleagues to create case studies that illustrate items (1)-(4) for the design of a few typical chemical products.

Next, comments on AI were provided anonymously in a Questionnaire response, but are closely aligned with the statement prepared by Prof. Victor Zavala, Wisconsin, in the Supplementary report, entitled: Incorporating Artificial Intelligence and Machine Learning in Design: Linking Molecules, Products, and Manufacturing.

AI comments - Anonymous
As we embrace Industry 4.0 and transition to a circular economy, implementing AI in product design is paramount. By leveraging AI capabilities such as predictive design optimization and generative design, designers can effectively minimize material use, waste generation, and energy consumption, while ensuring optimal product performance. AI-driven material selection processes enable the identification of green and sustainable materials, while AI-integrated life-cycle assessment tools continually assess environmental impacts, facilitating design optimization in real time. Additionally, AI-powered supply-chain optimization reduces waste and energy consumption throughout the production process. Through AI-enabled localized and personalized manufacturing, products can be tailored to individual needs, reducing overproduction and transportation-related emissions. Establishing circular design feedback loops and AI-powered predictive maintenance systems ensures that products are designed with end-of-life considerations in mind, promoting product life extension and facilitating material flows closed circuit. Overall, AI plays a crucial role in driving sustainable innovation in product design, paving the way towards a circular and more environmentally conscious future.

Yet another important consideration, when teaching product design, is the role of collaborators from local industries, which has not been emphasized thus far in this paper. Fortunately, we received statements from three collaborators, which appear in our Supplementary Materials. Summaries of their statements are provided next.

Kathleent M. Vaeth, Qualitrol Corporation (with Tobias Hanrath collaboration)
Dr. Vaeth has played a key role in the Cornell product design courses in providing design teams a hands-on opportunity to design, build, and test prototype products using Taguchi's robust design methodologies. She began as an instructor at Cornell before transferring to her industrial position. At the outset, she emphasized the advantages of design projects posed by sponsor companies. In the CACHE report, she lists the various valuable interactions she provided, one of which indicates that once a project has been run a few times by the same instructors, it is often possible to re-use the project statement, or variations of it, without the company sponsor, as instructors have become sufficiently experienced to serve as mentors. Then, she discusses the importance of helping students learn the voice of the customer. This leads to concerns about having more than one team working on the same project statement – and the advantages of students learning how project teams at larger companies work to design related products for different markets. Other topics include helping students understand the importance of the technology readiness level (TRL) and the stage-gate product development process used in industry. She also discusses the need for safety instruction as students work on product prototype construction – and the relative ease of creating prototypes when little or no chemical conversions are involved. Related issues involve the sharing of lab space and the organization of the lab to convey safety rules. Yet another concern involves helping students learn strategies for process design; i.e., the design of processes to manufacture their products. Please see the CACHE supplementary report for more complete statements and other issues.

Cristina U. Thomas – Formerly 3M corporation
After many years at 3M Corporation, Dr. Thomas' statements in the CACHE supplementary report bring key perspectives that cannot be summarized easily. To prepare students well, she states the importance of chemical engineering departments to incorporate in their curriculum, core and elective classes covering product design. These classes provide the most value to students when they are experiential and practical, that is they are project-based. She continues that: The need for participation from industry is clear. Securing the engagement of non-academic partners is key. My experience indicates that this participation is maximized and hence sustainable for a long period of time when it is thought of as a partnership between industry and the corresponding chemical engineering department. We

should then strive to solidify that partnership so that the students receive maximum benefits from the project-based course. The industry partner and the professor must be mindful of openness regarding the exchange of information and the resources that are needed for project understanding, execution, and completion. Both sides benefit from direct and honest feedback as they structure the project and communicate and engage with students. Experience with setting up intellectual property agreements benefits both parties as professors, TAs, students may be asked to sign non-disclosure agreements, memoranda of understanding, materials transfer agreements, etc. Please see the CACHE supplementary report for other important issues.

Jean Tom – formerly Bristol Myers Squibb

Her statement recognizes the broad array of industries employing chemical engineers and emphasizes that chemical process design does not happen in a vacuum without understanding product design. In the pharmaceutical industry, chemical engineers are working on translating chemical transformations invented by a chemist. Here, the factors which impact the process design are tied to the product design. We have to consider such factors as intellectual property (is there an aspect of the chemistry which is patented), supply chain consideration of the raw materials (is this catalyst readily available), overall sustainability, safety profiles of the chemicals involved (is there a higher safety risk with this chemical), safety of the unit operations (does this chemistry require less desirable unit operations), the exposure to chemical operators, as well as the characteristics of the product (impurity profile, physical properties). In the pharmaceutical industry, the final product is not a single molecule, but a formulated product, which must take into consideration the patient population, the dosing regimen, the properties of the active ingredient (biologic vs small molecule). The traditional process design course seems very narrow. The programs which can partner with industrial partners to identify product design projects are likely most effective in teaching the topic.

Finally, at the FOCAPD-2024 Conference, in the Plenary Lecture focusing on Teaching Process Design by Prof. Daniel Lewin and the discussion that followed, there was much interest in active learning approaches.

Active Learning – Daniel R. Lewin – Technion (Israel Inst. of Technology)

Prof. Lewin promotes active learning as a means of increasing the proportion of students who achieve mastery in a course's learning objectives. He advocates the adoption of the "flipped class" (Lewin and Barzilai, 2022) in which short video segments of lecture materials, combined with quizzes, are studied by students as homework in advance of class activity, followed by open-ended problem-solving during scheduled class times and recitations (exercise sessions). This combination of preparation by students and active learning in the contact time between students and course staff mean that students are actively engaged in most of the time they invest. To be successful, this mode of learning requires a lower student/staff ratio; Prof. Lewin recommends at least one teaching assistant (TA) for every 20–25 students. Obviously, the TAs need to be suitably trained to provide effective mentoring to students. For very large classes, he also advocates Zoom Breakout Rooms be employed as a means to distribute students in such a way that class work be manageable.

In discussion at the FOCAPD-2024 Conference, enthusiasm for flipping in active learning was expressed with questions related to its role in courses requiring significant design activity. Prof. Lewin responded that it leads to better understanding in less time for most students, thus permitting them to contribute better to their design teams when solving design project problems.

6. Advances in teaching chemical product design

Returning to Section 1, Introduction and Background – specifically Prior Advances in Teaching Chemical Product Design, after having discussed the results of our worldwide study of teaching chemical product design in 2023–2024, this section is intended to describe some of the advances herein. First, we consider advances beyond those in the prior papers described in Section 1. Then, we add the findings obtained in our study and the Questionnaire that accompanied it.

Let's begin with one of the early attempts, at the University of Queensland, to teach chemical product design at the sophomore level (Kavanagh and Lant, 2006). Their introductory sophomore subject preceded their third-year product-specific electives in biochemistry, food technology, and the like, before their capstone year-long project in the fourth year. Herein, at UCal Santa Barbara and the Univ. of New South Wales, we describe similar electives to prepare students to carry-out formulated chemical product designs at the senior level. Also noteworthy is the emphasis on selecting biologically-active ingredients for formulated chemical products in pharmaceutical or agrochemical industries (ten Kate et al., 2022). In addition to improved application of chemical engineering principles, their paper calls for improved education to prepare industrial practitioners.

We also refer to the move by chemical industries to convert their commodity chemicals to higher-value chemical products (Zhang et al., 2020). Therein, much attention is devoted to computer-aided methods for chemicals product development, with their advantage of quickly identifying promising candidates, while recognizing that models are often not available for the design of chemical products using new technologies. They address the challenges and opportunities for computer-aided design, including experiment-, knowledge-, rule- and model-based approaches. In this regard, herein, we describe comments that seek to embrace Industry 4.0 and transition to a circular economy, implementing AI and machine-learning in product design. It is stated that: "By leveraging AI capabilities such as predictive design optimization and generative design, designers can effectively minimize material use, waste generation, and energy consumption, while ensuring optimal product performance. AI-driven material selection processes enable the identification of green and sustainable materials, while AI-integrated life-cycle assessment tools continually assess environmental impacts, facilitating design optimization in real time."

Also, of special note, is the paper by Fung and Ng (2018) who describe how to teach chemical product design using design projects. They indicated that "product design is considered hard to teach by most faculty members, partly because there exist only limited teaching materials, particularly those that can be used for independent student design projects." Herein, building on this concept, the Univ. of Michigan describes its product design laboratory for the purpose of creating product prototypes. Similarly, product prototypes are constructed at Colorado State Univ.

The use of games by design groups to assess alternatives in the conceptual design of products and processes was a novel approach by Feijoo et al. (2018). Herein, a comparable approach at Brigham Young Univ., involving experiential learning to design chemical products suggested by engineers in industry, is described.

Yet, another observation, as summarized in Section 1, is that the comprehensive review of chemical product design by Rivera Gil et al. (2022), which focuses on so many aspects of product design in industry, does not suggest new approaches for product-design education.

Consider next the many advances in chemical product design education resulting from our study and the Questionnaire that accompanied it. These include:

1. Many new approaches for teaching product design, sometimes as a replacement for teaching process design, at different universities, summarized in the paper, with details in the Supplementary Materials

2. Clear statements on the role of industrial practitioners in helping universities teach product design
3. Clear statements regarding the ease of teaching process design – the low regard many faculties have for teaching process design – and lack of enthusiasm for teaching product design to undergraduate students.
4. The preference of students to prepare for employment in companies that emphasize product design using new technologies.
5. The need to use AI/ML approaches to identify improved products that satisfy customer needs – especially where new technologies are difficult to invent.
6. The need to carry out product design with limited data available (Gounaris at CMU)
7. An approach to involve young faculty in creating case studies illustrating how to achieve sustainability when designing a few typical chemical products.
8. The use of active learning (e.g., flipped courses) to achieve better understanding in less time, permitting students to contribute better to solving product design projects.

7. Predict the future of chemical engineering design education

The current status is clear. There is a growing need to teach chemical product design – in line with the increasing emphasis on developing new technologies to be incorporated in new chemical products. But, among the engineering disciplines, chemical engineering is unique in designing new processes (process designs) to manufacture new chemical products (product designs). This paper, and the CACHE report on Teaching Chemical Product Design in its Supplemental Material, provides many approaches to teaching product design and the motivation to do so.

Clearly, the ChE profession is diversifying, with slow, gradual emphasis on new subjects, such as food, pharmaceuticals, vaccines, soft materials, self-organizing colloids, biodegradable plastics, microfluidic sensors, and computer chips, in the undergraduate curriculum. It is also evident that undergraduate students are requesting and beginning to receive training in the new technologies that enable them to design new chemical products.

For design researchers at the FOCAPD-2024 Conference, we began with an observation and an important question:

Observation – in our engineering schools, engineering departments other than ChE are focusing on the design of new products, mostly using exciting new technologies.

Question – in recent years, ChE enrollments have been declining, while other department enrollments are increasing, especially in bioengineering and computer science. Is our decline related to students' perception that opportunities to design new products using the latest new technologies are fewer in the ChE profession?

While considering this observation and its related question, the need for ChE education to keep pace with the advancement of the chemical engineering profession seems clear. Then, how can we create a widely-accepted model for teaching product design? To initiate this, we propose the following specific steps universities can take to update their curricula in response to evolving industry needs. First, departments should encourage regular discussions on incorporating emerging technologies, such as AI, sustainability practices, and life-cycle analysis, into existing courses – with each department having research concentrating on topics such as these. Second, universities can develop elective course sequences that prepare students for product design projects in specialized areas, such as pharmaceuticals, renewable energy, and consumer products. Third, faculty members should create and share product design problem statements that reflect current industry challenges, enabling students to work on meaningful and impactful projects. Fourth, collaboration with industry partners should be strengthened to provide students with experiential learning opportunities, including hands-on prototyping and real-world case studies. Finally, universities should integrate AI and machine learning into design courses to help students optimize product designs efficiently, preparing them for a technology-driven workforce.

7.1. Reflections of Professor Ed Cussler - an early promotor of teaching product design

When predicting the future, consider these reflections: "I began my interest in product design after 1980, concerned about the dominance of the huge petroleum industry – interested in the scientific details of petroleum processing – a business that was intellectually stagnant – concentrating on sustaining and not on innovating. In 1995, I felt new directions were needed – that supplement unit operations, with product design supplying some. Today, I would like to point to new opportunities for chemical engineering efforts beyond the existing chemical industry, with possible new areas including: a new sustainable power grid with chemical energy storage (batteries, etc.), chemical heat pumps without moving parts, pharmaceuticals emphasizing drug discovery, producing food without emitting CO_2, and the like. These are examples where chemical product design will become important." Note: a complete letter has been attached to the CACHE report on page 73 (see Supplemental Materials).

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ece.2025.04.002.

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