Capstone Chemical Process and Product Design Courses: Emphasis on Product Manufacturing

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This paper attempts to explain the rare participation of chemical engineering students on interdisciplinary design teams. It discusses the distinctions between chemical engineering design education and the design education in other engineering curricula. Chemical engineering students learn how to design processes to manufacture chemical products. Other engineering students focus on how to create new products – not how to manufacture them. Having presented these distinctions, this paper concludes with issues (problems) to be addressed in seeking to create better balanced interdisciplinary design teams.

Undergraduate chemical engineering curricula cover material and energy balances, chemical thermodynamics of processing systems, transport phenomena (fluid mechanics, and heat and mass transfer) in chemical processes, separation processes, and the design of chemical reactor processes. In their capstone design course(s), nearly all curricula cover process design; that is, the design of manufacturing processes using the basic principles taught in the core chemical engineering courses. Over the past decade, capstone design courses have begun to introduce strategies for the design of chemical products (e.g., thin-glass substrates for LCDs, microfluidic labs-on-a-chip, and hemodialysis devices); that is, strategies for designing chemical products that satisfy consumer needs. While many chemical engineers design these products in industry, however, due to time-constraints and difficulties generalizing their complex technology platforms, most capstone design courses focus on process design alone, integrating engineering science concepts to design manufacturing processes.

In contrast, other engineering curricula focus on the design of new *prototype* products, often multidisciplinary in nature, involving mechanical, materials, biotechnology, electrical and computing system components. Their students create working prototypes, but don't design the processes to manufacture them, permitting an assessment of their economic feasibility. Due to these differences in design emphasis, opportunities for the participation of chemical engineering seniors in interdisciplinary design projects are limited.

Keywords: Product design, chemical process design, interdisciplinary design teams, manufacturing

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Introduction

Over the past half century, chemical engineering design courses have focused on process design strategies for commodity chemical products, such as ethylene, vinyl-chloride (for polyvinylchloride, PVC), and tetrafluoroethylene (for teflon). Because these are well-defined chemical products, no searches for molecules to satisfy customer specifications are required.

Usually, chemical engineering science courses concentrate on basic principles reinforced with practical problem solving. Due to time limitations, idealized systems are normally covered, involving ideal gases, ideal liquid phases, Newtonian fluids, and perfectly stirred chemical reactors.

Given these limitations, capstone design courses often cover missing concepts, as needed; e.g., heat exchanger design and non-ideal phase equilibrium. Also, most capstone design courses show how processing concepts are integrated to give promising process designs. Emphasis is placed on process synthesis; i.e., the synthesis of alternative process flowsheets followed by process simulation, equipment sizing and costing, and profitability analysis. Such process design courses show how to generate trees of processing alternatives, and how to select the most promising processes from amongst many alternatives.

As an example, consider the design of a process to manufacture the well-known chemical, vinyl-chloride – the monomer commonly polymerized to PVC, primarily for plastic tubing. Because the vinyl-chloride product is well understood, a search for a new chemical product to meet customer needs (i.e., the role of product design) is not carried out. Rather, chemical engineers concentrate on designing a low-cost manufacturing process (i.e., carrying out process design). For this purpose, many alternatives are considered during each of several synthesis steps and an inverted tree of alternatives is generated, as shown in Figure 1 (Seider et al., p94)[1]. As shown for the manufacture of vinyl-chloride, five chemical reaction paths are considered, two of which are rejected. Then, for each reaction path, alternative distributions of chemicals (involving the recycle of unreacted chemicals) are considered. Subsequently, alternative separation operations are considered, then temperature, pressure, and phase change operations, and finally task integrations. Each of the branches in the tree corresponds to a different manufacturing process, one of which is sketched in Figure 2 (Seider et al., p92)[1]. The challenge in process design is to select the best alternative flowsheet – normally having low cost, easy controllability, safe processing operations, and the like. To achieve this, equipment is sized, costs are estimated, and profitability measures are considered. Note that these manufacturing processes integrate the so-called unit operations – heat exchangers, pumps, furnaces, distillation columns, chemical reactors, and the like. For the well-known vinyl-chloride product, no prototype is needed. Also, prototypes (pilot plants) of the manufacturing process cannot be created by capstone design teams.

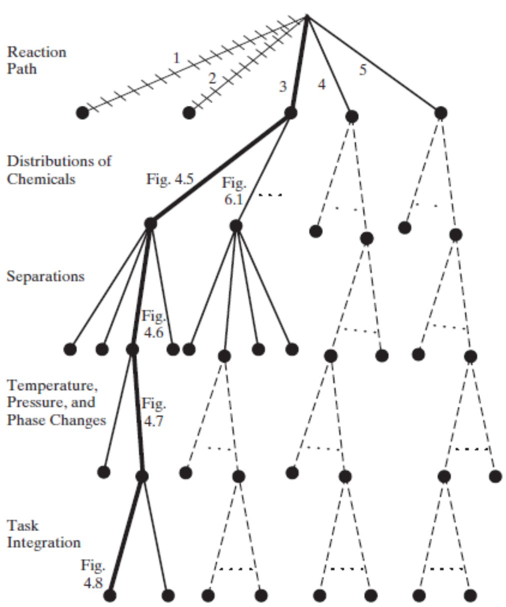

Figure 1 Inverted synthesis tree for processes to manufacture vinyl chloride
(Seider et al., p94)[1]

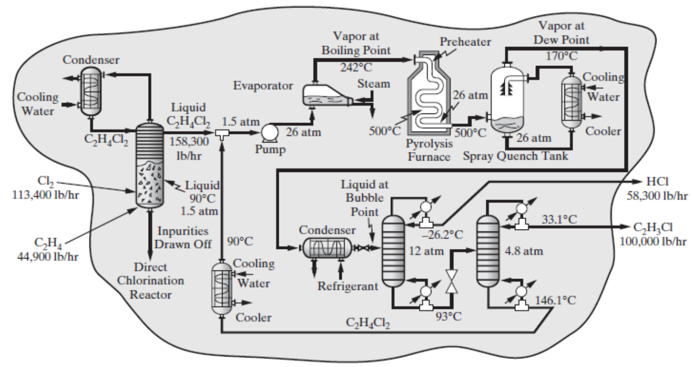

Figure 2 Promising process alternative for manufacture of vinyl chloride
(Seider et al., p92)[1]

Chemical Product Designs

As mentioned above, in chemical product design, emphasis is on creating new chemical products that satisfy customer needs. Often molecular structure design is carried out to synthesize candidate molecules to achieve specified chemical properties. For example, it's often desirable to locate a molecule(s) that evaporates rapidly (has a low latent-heat of vaporization), is in the liquid phase (has a high boiling point and a low freezing point), is partially miscible with water, doesn't form an azeotrope with a particular solvent. Another example is a hollow-fiber module to remove urea from blood; i.e., a hemodialysis device (artificial kidney). Here, polymer fibers must be selected and low-cost mass-exchangers created for use by patients at hemodialysis centers. Yet, a third example is a lab-on-a-chip that uses microfluidic channels to process nanoliter quantities of potential drugs, such as kinase inhibitors to inhibit the phosphorylation reaction of just one of 500 human kinase enzymes. For this purpose, pharmaceutical companies generate families of inhibitor molecules (often one million per day) to be tested on lab-on-a-chip, high-throughput screening devices.

During the second half of the 20th Century, process engineering in the chemical industries and in chemical engineering education grew rapidly. But, relatively few chemical engineers concentrated on product engineering, that is, product design, and chemical engineering courses provided little coverage of chemical product design strategies. Of course, several chemical companies were well-recognized for their array of new chemical products sold directly to consumers; for example, 3M Company, General

Electric, Proctor and Gamble, and L'Oreal. But, most chemical engineers worked as process engineers for chemical companies that manufactured commodity and specialty chemicals usually not sold to consumers; for example, DuPont, Monsanto, Exxon/Mobil, and Air Products and Chemicals. Gradually, more positions became available in companies that produce pharmaceuticals, electronic materials, batteries, and fuel cells; principally, the newer chemical products. This evolution was documented in papers that presented perspectives on the design of chemical products and approaches for teaching product design subjects (Seider et al.[2], Cussler et al.[3], Favre et al.[4], Costa et al.[5], Hill[6].)

These papers clearly document chemical products that often involve complex technology platforms beyond those normally covered in undergraduate chemical engineering courses. Hence, to permit undergraduate design groups to carry out such product designs, some preliminary training is required – usually provided by a faculty adviser and his/her research group. Furthermore, an increasing number of chemical engineering departments are introducing product design strategies in either separate product design courses, or more often, by adding topics to process design courses.

In recent years, a few books have been written covering chemical product design. These include Cussler and Moggridge[7] and Wei[8]. Just one book has been written to cover strategies for both product and process design[1]. Its next edition is intended to better integrate the teaching of product design concepts in traditional chemical process design course(s)[9]. For this purpose, simpler technology platforms are being selected, permitting undergraduate seniors to carry out engineering problem-solving to arrive at more easily manufactured and optimized product designs.

Given the clear shift toward product engineering in the chemical industries, a key question concerns the response of chemical engineering educators. This has been assessed in 2012 using a survey prepared by the AIChE Education Division distributed to design instructors worldwide, with 68 responses received[10,11]. Of the many issues assessed, probably of most interest here, is the chart on Topics Covered in Figure 3. As seen, coverage is heaviest in process design-related subjects. Product design-related subjects show significantly less coverage; for example, product design, brainstorming methods, uncertainty analysis/six sigma, innovation maps, product prototypes, and molecular structure design. There is an increase in the coverage of product design-related subjects relative to informal surveys in the early 2000's, but the emphasis is clearly on process-design related subjects.

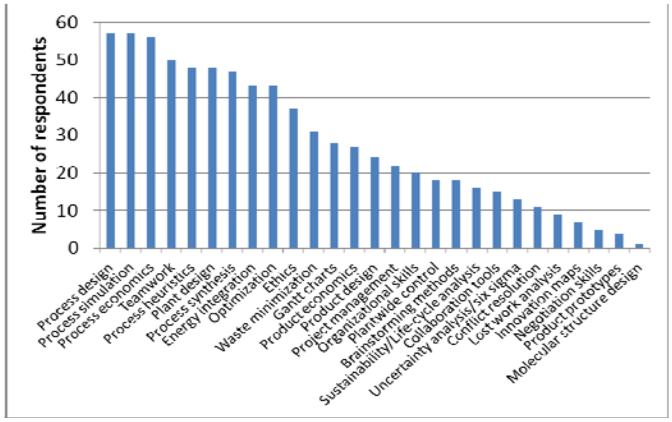

Figure 3. Topics taught in 2011-2012 in chemical engineering design courses

Interdisciplinary Design Projects

Most advanced chemical products are designed by interdisciplinary design teams. In these teams, chemical engineers are often joined by various combinations of materials, mechanical, electrical and systems, computing, and biological engineers. For hemodialysis devices, polymeric materials engineers would be appropriate, and for labs-on-a-chip, experts on soft-polymer materials, enzyme biochemistry, fluorescent light-detection cameras, and high-speed data transmission and processing, would be very helpful.

At the recent 2012 Capstone Design Conference[12], several interdisciplinary design project courses were described at large engineering schools – including those at Georgia Tech, Vanderbilt, and Purdue. Often, these projects are provided by commercial companies, with funds (on the order of $10,000 per project) permitting student travel to companies for orientation sessions and interactions with company engineers, and covering the costs of creating and testing product prototypes. Some projects are provided by national design competitions; e.g., the International Environmental Design Contest by WERC and the Shell Eco-Marathon.

Not surprisingly, most of the projects in 2012 didn't have a significant chemical engineering component and no chemical engineers were involved. In all cases, product prototypes were designed and demonstrated; e.g., robotic devices, smart-devices for detecting product mal-functions, and small missiles. In no cases were manufacturing facilities designed, including cost estimates and profitability analyses.

A key question – Shouldn't all engineering design projects include manufacturing facilities and economics evaluation – especially since products must often be redesigned to facilitate low-cost manufacturing? In my opinion, the failure to consider manufacturing misses a key aspect of product design.

An observation – Perhaps, as other disciplines broaden their design perspectives to include manufacturing processes, chemical engineering participation in interdisciplinary design projects will increase. For now, most chemical engineering students are expected to opt for chemical process design projects.

Another question – How should chemical engineering faculty encourage and help facilitate chemical engineering students to participate on interdisciplinary design teams? Several personal views are offered next. Initially several approaches are possible, including: (1) respond positively to ad-hoc requests for participation, permitting students to work on an interdisciplinary project rather than a typical chemical process design project, (2) formulate an interdisciplinary project that involves both product and process design and encourage students from other departments to participate. After achieving these successes, participate actively in organizing and assisting student design teams in an interdisciplinary project course. In my opinion, at least initially, while students from other engineering departments don't design product manufacturing processes, continue to require chemical engineering students to take a process design course.

Concluding Remarks

A dichotomy exists between chemical engineering students who concentrate on manufacturing chemical products, and students in other engineering disciplines that focus on product design. Gradually, the former have been learning to create prototype chemical product designs. Perhaps eventually interdisciplinary design teams, including chemical engineering students, will successfully design prototype products and processes to manufacture them.

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