Education for Chemical Engineers 24 (2018) 13–26

Contents lists available at ScienceDirect

Education for Chemical Engineers

journal homepage: www.elsevier.com/locate/ece

Teaching chemical product design using design projects

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ARTICLE INFO

Article history:
Received 13 June 2017
Received in revised form 17 April 2018
Accepted 6 June 2018
Available online 14 June 2018

Keywords:
Chemical product
Product design
Design methodology
Design project

ABSTRACT

Product design has been gradually taking hold in the chemical engineering curriculum at various universities. At present, it 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. To fill this gap, this paper presents a multidisciplinary, hierarchical procedure that guides students to design a chemical product – molecular, formulated, functional, and device in a systematic manner. It begins with a market study to gather market information, compare competing products, and identify the qualitative product attributes for satisfying consumer preferences. Then, these product attributes are converted to quantitative technical parameters through heuristics, mathematical models, experiments, tools, and databases. Next, a suitable manufacturing process is synthesized to produce the product with the required product specifications, followed by a financial analysis to evaluate product profitability. All of these concepts in the procedure are reinforced in a product design project. In conducting a design project, the students are encouraged to synthesize a novel product and to consult with other professionals such as business personnel, chemists, and material scientists to appreciate the multidisciplinary nature of product design. Two case studies are given in this paper to illustrate the learning process of, as well as the contents for, such a student project.

1. Introduction

The importance of chemical product design to the development of the chemical engineering profession has long been established (Stephanopoulos, 2003; Cussler and Wei, 2003; Hill, 2004; Gani, 2004a, 2004b; Seider and Widagdo, 2012). Many textbooks have appeared (Bröckel et al., 2007, 2013; Ng et al., 2007; Wesselingh et al., 2007; Wei, 2007; Cussler and Moggridge, 2011; Seider et al., 2017) to define the scope and approach to chemical product design. Despite all of this effort, it is difficult to apply a general approach, no matter how good it is, to chemical product design because the underlying technology platform (i.e., knowledge base and associated models) is usually domain specific and fragmented. For example, the designer has to understand the basic science about emulsions and possess the database of the functions, some complementary and some conflicting, of all the ingredients in a hand lotion before such a product can be formulated. Even for products in the same class, products with different product forms require different treatments. Consider the different devices for dispersing mosquito repellent in air. The repellent can be released to air by directly heating a porous mat saturated with the repellent. Alternatively, the repellent in a bottle can be transported to a heater using a ceramic wick (Seider et al., 2017). This is even more challenging for students in chemical engineering, as many processing techniques used in manufacturing chemical products such as impregnation, coating, and homogenization are not covered in a typical chemical engineering curriculum.

To guide students in chemical product design, a systematic design framework is essential. All aspects related to product design, including market information, materials selection, product structure, product manufacture, and financial analysis, are considered so that a product that meets the product specifications, satisfies the consumer needs, and generates profit can be realized. To facilitate the development of this systematic framework, the diverse chemical products can be classified into molecular, formulated, functional, and device based on the way in which they are designed (Gani and Ng, 2015). Molecular products are simply single molecules or blends of molecules with a desired property value. Formulated products are obtained by mixing selected components together to get the desired product attributes. Functional products and chemical devices are those chemical products with a number of components that perform a desired function. Normally, a device transforms a feed stream into an outlet stream and includes mechanical and/or electrical parts, whereas a functional product

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https://doi.org/10.1016/j.ece.2018.06.001
1749-7728/

Table 1
Formulated products, functional products, and chemical devices in different market sectors.

Market Sector	Formulated Products	Functional Products	Chemical Devices
Agriculture	• Balanced fertilizer • Herbicide mixture	• Controlled release herbicide	• Fertilizer injector
Automotive & Transportation	• Auto tire • Diesel exhaust fluid • Antifreeze • Motor oil	• Safety windshield • Sun control window film	• Catalytic converter • Catalytic ozone converter for planes
Building & Construction	• Paint • Anti-corrosion paint • Adhesives for panelling • Stucco	• Acrylic composite countertop • Moisture absorber • Weather barrier film • Active smart window • Foamed concrete	• Water cooler air conditioner • Air conditioner with green refrigerant • Energy recovery ventilator • Humidity sensor • Indoor catalytic air cleaner • Desiccant/refrigerant air dehumidifier • Refrigerator • Chiller • Magnetic refrigerator
Electronics	• Optically clear adhesive • Die attach adhesive • Copper nanoparticle ink/paste • Encapsulant	• Silver nanowire • Engineering plastics for electrical applications	• LED light • Touch panel
Energy	• Heat transfer fluid • Drilling mud • Battery electrolyte	• Engineering plastics for solar and photovoltaic systems • Current collector and polymer separator for battery	• Battery • Flow battery • Solar panel • Fuel cell • Supercapacitor
Environmental	• Air freshener • Coagulant/flocculant mixture • Anti-scalant mixture • Decoloring agent	• Adsorbents • Ion exchange resins • Aerobic granules for biotreatment • Filter media	• Water purifier • PM2.5/plasma air purifier • Respirator • Portable sea water desalination system • Portable water sensor • Water testing device (e.g. COD meter) • Membrane bioreactor • Reverse osmosis membrane module • Adsorption/filtration column • Biofilter • Advanced oxidation reactor • Ultra-violet irradiator system
Food & Beverage	• Ice-cream • Energy drink	• Powdered milk • Food packaging film • Textured vegetable protein (meat substitute)	• Wine aerator • Espresso coffee machine • Ice-cream machine
Personal Care, Health Care & Medical	• Sunscreen lotion • Insect repellent • Toothpaste • Bar soap • Hair spray • Laundry detergent • Shampoo • Fabric softener • Spray wound dressing • Spray plaster • TCM dietary supplement	• Mosquito repellent mat • Hand warmer • Disposable diaper • Deodorization and dehumidification latex insoles • Transdermal patch • Controlled release pharmaceutical granules • Pharmaceutical tablets	• Mosquito repellent dispenser • Medical diagnostic kit • Glucose biosensors • Haemodialysis device
Packaging & Printing	• Inkjet ink • Screen print paste • Toner for photocopier	• Food packaging film • Stretch film/Pallet wrap • LDPE shrink film • Adhesive packaging tape	• Flexo platemaking equipment

does not. Examples of these products classified by market sector are summarized in Table 1. Note that molecular product is not covered in this article, as its design principles are significantly different from others. A chemical product may not fall exactly into a specific category. It mainly depends on the design objective. For example, a pharmaceutical tablet can be considered as a formulated product if ingredients selection is the key step in product design, whereas it can be considered as a functional product if its physical properties such as mechanical strength and dissolution time are the primary concerns. Different products follow different design procedures, which are described in the next section.

Design procedure has been outlined for formulated product, functional product and chemical device by Seider et al. (2017). For formulated products, it focuses on how to fix the key ingredients in a base case formulation by heuristics, mechanistic models, computer-aided methods, and/or experiments, and how to iter-