PRODUCT CENTERED PROCESS DESIGN

Christianto Wibowo
ClearWaterBay Technology, Inc., Walnut, CA 91789, U.S.A.

Ka M. Ng
The Hong Kong University of Science and Technology, Hong Kong

Keywords: Process design, Process development, Product engineering, Consumer products

Contents

Summary

This chapter presents a framework for product-centered process design and development, which is particularly useful in designing chemical-based consumer product manufacturing processes. The objective is to provide directions and guidelines towards the development of a process for manufacturing a product with the desired performance in reduced time and cost. The product performance, represented by several quality factors, is related to the product ingredients and structural attributes, and then to the process flowsheet and operating conditions. Process alternatives are systematically generated and unit operations as well as operating conditions are properly selected. Various related issues in each development phase, from formulation all the way to processing in the production scale, are considered with an emphasis on how to manufacture a product with the desired qualities rather than how to design the product to be manufactured. The framework is illustrated using an example on the development of a new shampoo product.

1. Introduction

As the scope of the chemical processing industry broadens to include high-value-added chemicals in addition to the traditional commodity chemicals, today’s chemical engineers are playing increasingly important roles in the manufacture of products such as creams and pastes, structured liquids, devices/packages, as well as appliances that are based on chemical technology. The term 'chemical-based product' will be used throughout this article to refer to both commodity chemicals and consumer products consisting of multiple ingredients and having clearly defined size, shape, and structure. With trends indicating an ever-increasing demand for new products with improved performance and shorter product life cycle (Tanguy and Marchal, 1996; Pisano, 1997; Villadsen, 1997; Wintermantel, 1999), faster and more effective development of manufacturing processes for chemical-based products is highly desirable to enhance competitiveness.

The development of chemical-based products and their manufacturing processes often involves a considerable amount of trial-and-error, which can become a bottleneck and lead to costly delays in product launching (Pisano, 1997). Another potential problem is the difficulty in scaling up a laboratory procedure to large scale commercial production. To tackle these problems, a few approaches have been taken towards systematizing the process development of chemical-based products. For example, Moggridge and Cussler (2000) proposed a procedure for chemical product design, in which different products are conceptualized, based on market needs and screened to identify the best candidates. The manufacturing process of these products should then be developed. Wibowo and Ng (2002) proposed a product-oriented process synthesis and development procedure for the manufacture of chemical-based consumer products. Product quality is the central theme and is closely linked to the manufacturing process. Along the same line, Ulrich and Eppinger (2000) described the product and process development for products such as power tools, ink jet printers, cellular phones, and mountain bicycles, the manufacturing of which are normally handled by mechanical and industrial engineers.

In this chapter, a framework for product-oriented process synthesis and development for manufacturing chemical-based products is presented. The objective is to provide directions and guidelines for developing an optimal manufacturing process in reduced time and cost. Process alternatives are systematically generated and unit operations as well as operating conditions are properly selected. Various related issues in each development phase, from formulation all the way to processing in the production scale, are considered. This approach calls for a high degree of integration of process systems engineering with other basic sciences and close collaboration among engineers and scientists of different backgrounds. Emphasized are the issues of how to manufacture a product with the desired qualities, rather than how to design the product to be manufactured.

2. Systematic Framework for the Manufacture of Chemical-Based Products

The spectrum of chemical-based products covers various product functional forms, ranging from molecules to structured products. Table 1 depicts the various product functional forms, along with examples in major application areas. The molecules can range from small molecules such as refrigerants to complex functional molecules such as drugs. Structured products include gas and aerosols, liquid and liquid mixtures, semi-solid products such as creams and pastes, simple and composite solids, as well as ready-to-use devices/packages and appliances. A structured product is usually a mixture of one or more key ingredients responsible for its functionality, which will be referred to as the *active ingredients*, and some *supporting ingredients* for enhancing its performance. Depending on the application, different *delivery systems* can be chosen to deliver the active ingredient.

Regardless of the functional form, the product performance, characterized by a set of attributes referred to as the *quality factors*, is determined by two factors (Figure 1). The first one is the material properties of the ingredients, such as dielectric constant, viscosity, and so on. For example, a thickener such as xanthan gum is normally used to induce strong shear-thinning behavior in cosmetic creams. Obviously, material properties are selected by appropriately choosing the ingredients. An active ingredient is typically selected according to the desired product functionality, while supporting ingredients are picked in such a way that other quality factors can be met. The second factor is the product microstructure, which is characterized by structural attributes such as particle or droplet size distribution, phase volume fraction, and particle shape. They can be controlled by properly designing and operating the manufacturing process. For example, micron-sized particles can be obtained by selecting appropriate size reduction equipment (such as an air jet mill), and the particle size can be manipulated by adjusting the air velocity.

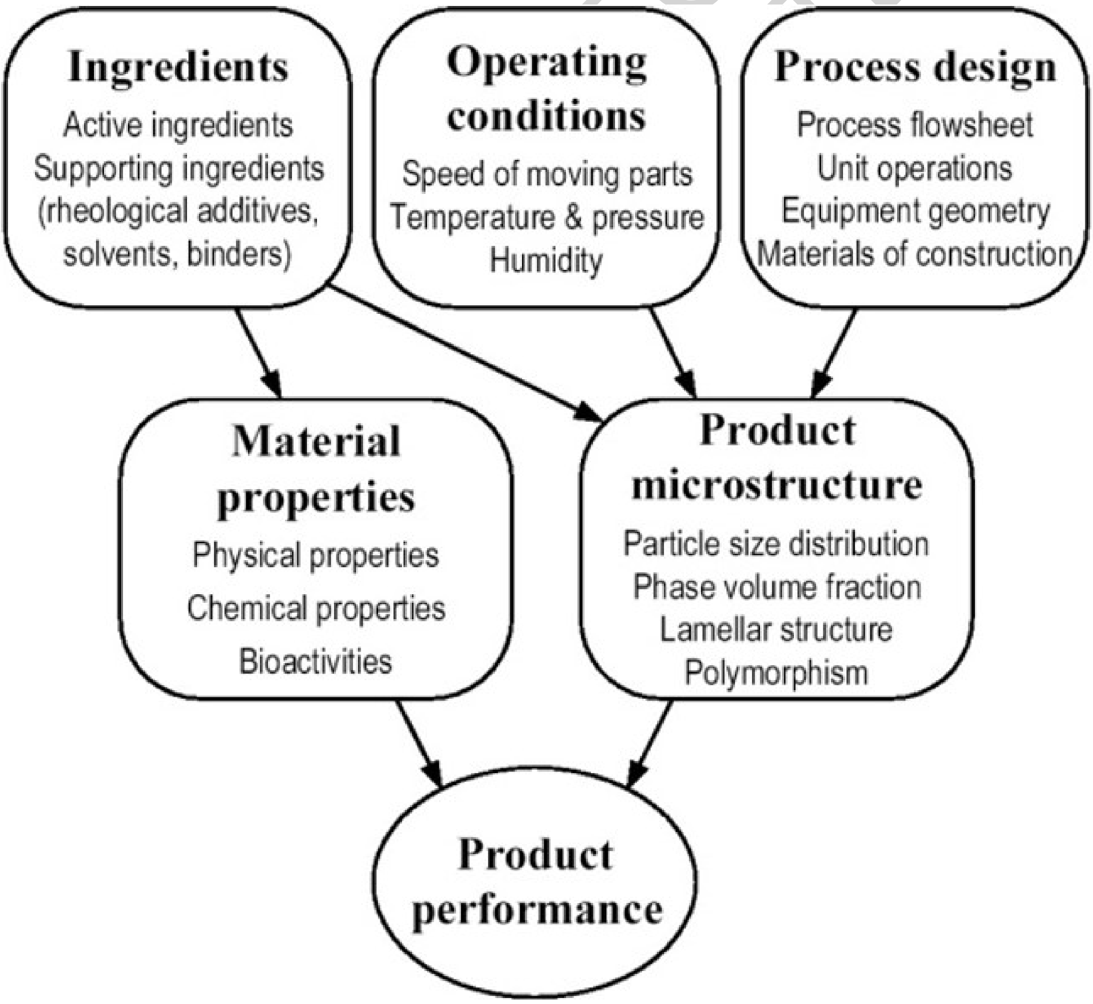

Figure 1: Factors determining product performance (after Wibowo and Ng, 2002)

Product Forms	Molecules		Structured / Multicomponent Products					
Industrial Sectors / End Users	Small Molecules	Functional Molecules	Gas and Aerosol	Liquid and Liquid Mixture	Cream and Paste	Simple and Structured Solids / Solid Mixture / Nanoparticle	Device / Package	Appliance, Equipment
Specialty Chemicals	Refrigerants, Fire Suppressants, Lubricants	Dyes, Conditioners	Arsine	Solvent mixtures	NA	Metal sodium	NA	NA
Agrochemicals	NA	Herbicides Pesticides	Liquid herbicide	Liquid fertilizers	NA	Controlled release herbicides, Balanced fertilizers Mosquito mat	Insect trap, Mosquito mat heater	Fertilizer granule spreader
Pharmaceuticals and Healthcare Products	NA	Active pharmaceutical ingredients	Inhalant	Syrups	Pharmaceutical creams	Injectable powders, Tablets Dietary supplement formulations	Transdermal patch	Diagnostic kits
Foods, Flavors and Fragrances	NA	Sugar esters, Non-absorbing fat	Air freshener	Juice concentrate, Herbal extracts, Cooking oil	Ice cream, Tooth paste, Ketchup	Chocolate bar, Candies	Microwave ready food	Ice cream maker, Expresso machine,
Personal Care Products, Cosmetics	NA	NA	Hair spray	Shampoos, Hand antiseptics	Sunscreen lotions, Moisturizing cream	Powdered detergents, Bar soaps	Diapers, Adhesive dressing	??
Home and Office Products	NA	Colorant	Natural gas	Thinner	Polishing wax, Paint formulation	Toner, Paper, Glue stick, Low gas permeability film	Nanocomposite tennis balls, Gas sensors	Indoor catalytic air cleaners, Self-cleaning glass, Solar powered lamp
Industrial Products	Benzene, Toluene, Xylene	Surfactants	Nitrogen, helium, oxygen	Heat transfer fluid	Petroleum wax	UF membranes	Gas meters	Fuel cells, Batteries

Table 1: Classification of Chemical Products by Functional Form and Industrial Sector/End User with Examples

A general procedure for product-oriented process synthesis and development is summarized in Table 2. First, the product is conceptualized based on consumer needs and market trends. The appropriate product form, including a suitable packaging, is selected. Second, the desired product performance is defined in terms of quality factors. Third, necessary ingredients and product microstructure are selected based on the desired quality factors. Fourth, process alternatives for manufacturing a product containing the selected ingredients and having the desired microstructure are identified. Equipment operating conditions are also selected. Limitations on product quality imposed by the manufacturing process are also identified. Finally, both the product and process are evaluated to ensure that a product of the desired performance is produced in an efficient manufacturing process.

Step 1	Product conceptualization
Step 2	Identification of product quality factors
Step 3	Selection of ingredients and product microstructure
Step 4	Generation of process alternatives
Step 5	Product and process evaluation

Table 2: Systematic procedure for product-oriented process synthesis and development

3. Product Conceptualization

Clearly, the very first step towards manufacturing a product is defining the product itself. In doing this, consumer needs and market trends, represented by typical issues depicted in Table 3, need to be captured. Among typical trends are the expectations that a product would last longer, cost less, be safer, and be more environmentally friendly. Consumers also tend to like a product that combines several complementary ingredients (Kirschner, 1996). For example, two-in-one shampoo and conditioner mixtures are among the leading hair care products since the 1990s (Reisch, 2000). Another example is bleach containing detergents, which account for more than 30% of the U.S. powder detergent business (McCoy, 2000).

Market trends may not present themselves so obviously. Therefore, innovation and creativity are among the key ingredients for success in product development. It is often the case that the development of a groundbreaking product begins with a creative inventor's desire to make life simpler, followed by tireless efforts to realize the idea. Market research among potential customers is also useful in conceptualizing the product and confirming the need. For example, the conception of diaper absorbents comes about because of some people's dislike of changing cloth diapers. As confirmed by research among mothers, the need for a new product which can absorb and retain moisture without passing it back to the skin was identified.

Consumer wants and needs
• The product should last longer and/or cost less
• Products performing complementary functions should be combined in one product
• The use of a personal care product should be a pleasurable experience

•	The product should be smaller in size, easy to carry when travelling
Product safety	
•	The product should not contain toxic solvent or allergenic materials
•	The product should not contain dangerous chemical for little children
•	The product should contain more natural ingredients
Legal and environmental issues	
•	It is preferable that the product is biodegradable
•	Refillable container should be used to reduce waste

Table 3: Examples of typical market trends to be considered in chemical-based product development

Product conceptualization involves the selection of the appropriate form in which the key ingredients should be delivered, including product packaging. The packaging may greatly affect consumer perception of the product, and therefore should be considered carefully. The choice of packaging may put additional constraints on the product. For example, the choice of using a flip-cap bottle for a viscous product, such as shampoo, leads to the requirement that the product can flow through the small hole on the cap with ease.

4. Identification of Product Quality Factors

The next step towards realization of the product in question is to identify the desired performance in terms of quality factors. The desired product functionality is described in more detail. If the product is to be used in a specific device, such as a photocopier or a washing machine, it is important to understand how the device works in order to properly define the quality factors. Consumer satisfaction is not only affected by the ability of the product to perform a certain function, but also by other issues such as convenience of use, sensation, and product durability. For example, protection effect and ease of spread are equally important quality factors for a cosmetic cream.

Depending on product form or delivery system, the desired quality factors can be different. For example, rheology is an important issue for emulsions, but obviously not for tablets. On the other hand, mechanical strength is a key issue for composite materials, but not relevant to solutions. Thus, additional quality factors may need to be specified after the ingredients are selected in the next step, and cannot be anticipated at the moment.

Since most of these quality factors are qualitative, a set of *performance indices* is used as a measure of product performance. Table 4 shows examples of representative performance indices and standard methods of measurement for typical product quality factors that chemical-based consumer products are expected to possess. By nature, sensorial quality factors are perceptions that can be quantified only by using an arbitrary scale. An index is assigned to reflect the level of satisfaction in using a product. This index is then related to material properties and structural attributes via psychophysical models. Some other quality factors can be satisfactorily quantified using physical properties such as tensile strength, melting point, and viscosity. Yet some others can be quantified using dimensionless numbers. For example, flow properties of a powder can be related to material properties and structural attributes by defining the flow number (Wibowo and Ng, 2001b).

-
-
-

Bibliography

Baravetto, J. T., E. M. Schrader, T. W. Coffindaffer, and S. M. Guskey, "Conditioning Shampoo Composition," U. S. Patent 6,174,522 (2001). [The ingredients of the conditioning shampoo claimed in the patent include solid particles].

Bergmann, W., (1995), "Conditioning Shampoo Composition and Method of Preparing and Using The Same," U. S. Patent 5,456,863. [An example in the patent describes a typical method for comparing the quality of shampoo products].

Bhagat, P., (1990) "An Introduction to Neural Nets," *Chem. Eng. Prog.*, 86(8), 55. [A general introduction to the basic concepts of neural network].

Block, L. H., (1996), "Pharmaceutical Emulsions and Microemulsions," *Pharmaceutical Dosage Forms: Disperse Systems*, 2nd ed., vol. 2, H. A. Lieberman, M. M. Rieger, and G. S. Banker, eds., Marcel Dekker, New York, p.47. [A comprehensive discussion on various properties of emulsions and microemulsions].

Diepen, P. J., O. S. L. Bruinsma, and G. M. van Rosmalen, (1997), "Crystal Size Engineering in Melt Suspension Crystallization," *Ind. Eng. Chem. Res.*, 75, 171. [This article describes an approach for controlling the crystal size distribution in melt suspension crystallization].

Floyd, A. G., and S. Jain, (1996), "Injectable Emulsions and Suspensions," *Pharmaceutical Dosage Forms: Disperse Systems*, 2nd ed., vol. 2, H. A. Lieberman, M. M. Rieger, and G. S. Banker, eds., Marcel Dekker, New York, p.261. [This includes a discussion on the development of pharmaceutical suspensions].

Kirschner, E. M., (1996), "Producers Raise High-Tech Stakes in Personal Care Ingredients, Markets," *Chem. Eng. News*, 74, Jul. 1, 13. [An overview of the market situation of personal care products].

Levere, R. D., N. G. Abraham, M. L. Schwartzman, and M. W. Dunn, (2000), "Vitamin B12 Containing Scalp and Skin Treatment Compositions," U. S. Patent 6,110,472. [This patent provides examples of ingredients that would alleviate exfoliation].

Lochhead, R. Y., The Rheology of Hair Products, (1993), "*Rheological Properties of Cosmetics and Toiletries*, D. Laba (ed.), Marcel Dekker Inc., New York, p.275. [This includes a list of quantitative criteria for rheological properties of hair products].

McCoy, M., (2000), "Soaps and Detergents," *Chem. Eng. News*, 78, Jan. 24, 37. [An overview of the market situation of soaps and detergents].

Mitsui, T., (1997), *New Cosmetic Science*, Elsevier, Amsterdam. [A comprehensive guide to ingredients and compositions of cosmetic products].

Moggridge, J. D., and E. L. Cussler, (2000), "Introduction to Chemical Product Design," *Chem. Eng. Res. Des.*, 77, 5. [This article proposes a systematic approach to chemical product design].

Pisano, G. P., (1997), *The Development Factory*, Harvard Business School Press, Boston, MA. [This book outlines the typical development of a pharmaceutical product and some general guidelines for conducting such a development project].

Princen, H. M., and A. D. Kiss, (1989), "Rheology of Foams and highly Concentrated Emulsions – IV. An Experimental Study of the Shear Viscosity and Yield Stress of Concentrated Emulsions," *J. Colloid Interf. Sci.*, 128, 176. [This article proposes a model relating emulsion viscosity to droplet size].

Reisch, M. S., (2000), "Hair Care Products," *Chem. Eng. News*, 78, Mar. 20, 15. [An overview of the market situation of hair care products].

Schmitt, W. H., (1992), "Skin-care Products," *Chemistry and Technology of the Cosmetics and Toiletries Industry*, D. F. Williams and W. H. Schmitt (eds.), Blackie Academic & Professional, London, p.99. [This includes a discussion on typical cosmetic ingredients and their functions].

Snyder, M. A., B. L. Hill, E. Inman Jr., S. M. Guskey, and R. L. Wells, (2001), "Styling Shampoo Compositions with Improved Styling Polymer Deposition," U. S. Patent 6,248,317. [This patent discusses in detail the ingredients of a shampoo product and their functions].

Tanguy, D., and P. Marchal, (1996) , "Relations between the Properties of Particles and Their Process of Manufacture," *Chem. Eng. Res. Des.*, 74, 715. [A perspective on the importance of controlling the crystallization process to produce particles of desirable properties].

Ulrich, K. T., and S. D. Eppinger, (2000), "Product Design and Development," second edition, Irwin McGraw-Hill, Boston. [A general discussion on product design and development for products that are not typically handled by chemical engineers].

Villadsen, J., (1997), "Putting Structure into Chemical Engineering," *Chem. Eng. Sci.*, 52, 2857. [A proceeding of an industry/university conference on structured chemical products].

Wibowo, C. and K. M. Ng, (1999), "Synthesis of Bulk Solids Processing Systems," *AIChE J.*, 45, 1629. [A step-by-step procedure for synthesizing bulk solids processing systems guided by heuristics and modeling].

Wibowo, C. and K. M. Ng, (2001a), "Product-Oriented Process Synthesis and Development: Creams and Pastes," *AIChE J.*, 47, 2746. [A systematic approach for designing a process for manufacturing creams and pastes].

Wibowo, C. and K. M. Ng, (2001b), "Operational Problems in Solids Processing Plants: Systems View," *AIChE J.*, 47, 107. [An approach for solving operational problems in solids processing plants by considering the basic phenomena responsible for the problems].

Wibowo, C., W.-C. Chang, and K. M. Ng, (2001), "Design of Integrated Crystallization Systems," *AIChE J.*, 47, 2574. [A step-by-step procedure for designing a crystallizer together with the downstream solid-liquid separation units to avoid operational problems].

Wibowo, C., and K. M. Ng, (2002), "Product-Centered Processing: Chemical-Based Consumer Product Manufacture," *AIChE J.*, 48, 1212. [This article proposes a general approach to the development of chemical-based consumer product manufacturing processes].

Willey, A. D., M. E. Burns, and J. H. Collins, (1995), "Bleaching Compounds Comprising N-Acyl Caprolactam and Alkanoyloxybenzene Sulfonate Bleach Activators," U. S. Patent 5,405,412. [This patent lists the ingredients of a laundry detergent product and their functions].

Wintermantel, K., (1999), "Process and Product Engineering: Achievements, Present and Future Challenges," *Chem. Eng. Res. Des.*, 77, 175. [This is a transcript of a lecture that emphasizes the relationship between product quality and microstructure].

Biographical Sketches

Christianto Wibowo is a senior engineer and Training Course Coordinator at ClearWaterBay Technology, Inc., Walnut, California, USA. He holds a B.S. degree from Bandung Institute of

Technology, Bandung, Indonesia and a Ph.D. from the University of Massachusetts, Amherst, both in chemical engineering. He is currently involved in various consulting projects on general process development as well as the design of crystallization and solid-liquid separation processes. Prior to joining the company, he conducted research in solids processing and crystallization process development, and worked as a Post-doctoral Research Associate at the Hong Kong University of Science and Technology. He is a member of the American Institute of Chemical Engineers, from which he received the Process Development Division Best Student Paper Award in 2002.

Prof. Ka M. Ng is CEO of Nano and Advanced Materials Institute Ltd., Chair Professor of Chemical Engineering, and Director of the Consortium of Chemical Products and Processes at the Hong Kong University of Science and Technology. He obtained his B.S. degree from the University of Minnesota in 1976 and his Ph.D. from the University of Houston in 1980. From 1980-2000, he served as Professor of Chemical Engineering at the University of Massachusetts, Amherst. He joined the faculty in Hong Kong in 2000 and served as Head of Department from 2002-2005. He held visiting positions at DuPont, MIT, and the National University of Singapore. His research interests center on product and process design, involving reactions, separations, and solids processing.
He serves as a consultant, technical advisor and independent non-executive director for various companies and government bodies around the world, and is at present the Corporate Science and Technology Advisor of Mitsubishi Chemical Corp. He is a member of the editorial board of the Korean J. Chem. Eng., Chinese J. Chem. Eng., and Computers & Chemical Engineering.

Professor Ng is the recipient of the General Electric Outstanding Teaching Award in 1992. He is a fellow of the American Institute of Chemical Engineers where he received the Excellence in Process Development Research Award in 2002.