Intertwine product and process design

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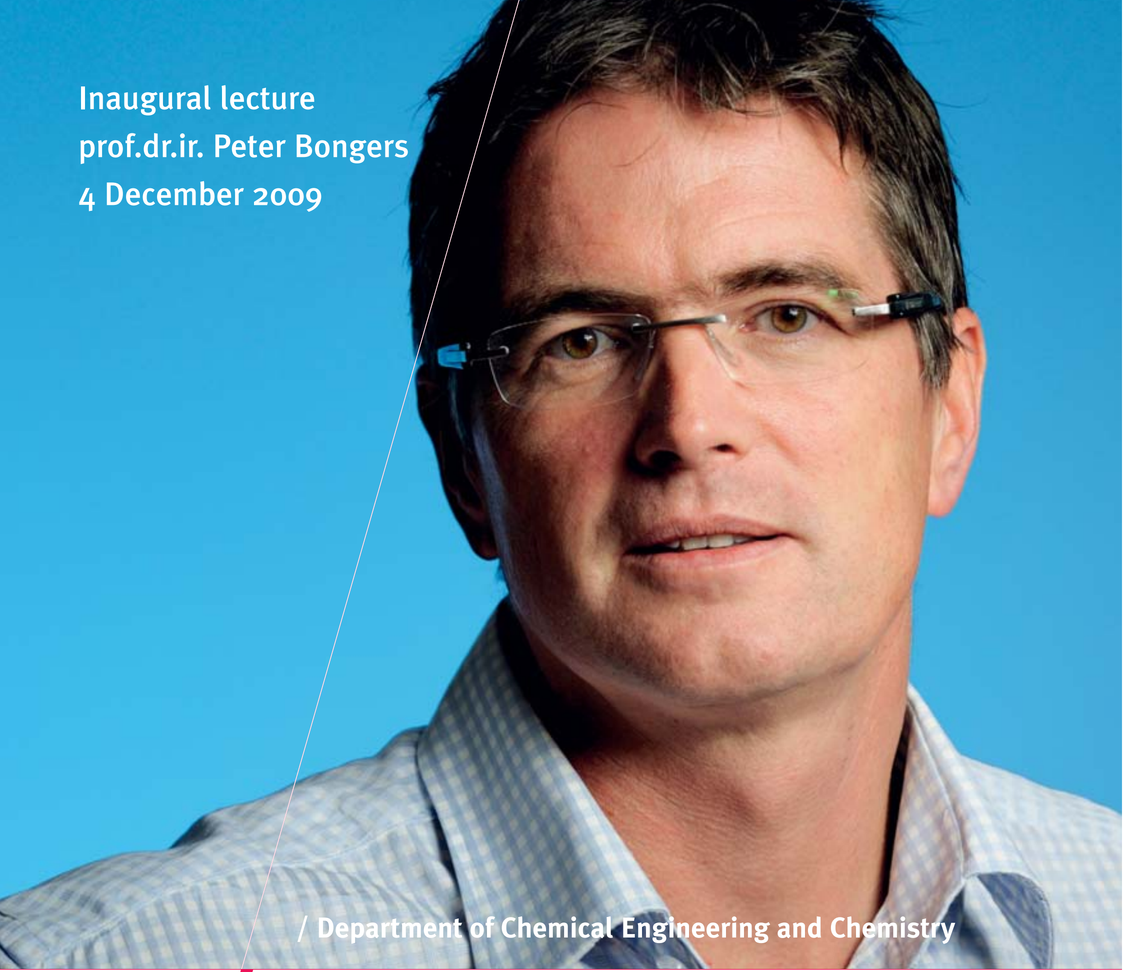
Inaugural lecture
prof.dr.ir. Peter Bongers
4 December 2009



/ Department of Chemical Engineering and Chemistry

Technische Universiteit
Eindhoven
University of Technology

Intertwine product and process design

Where innovation starts

Inaugural lecture prof.dr.ir. Peter Bongers

Intertwine product and process design

Presented on 4 December 2009
at the Eindhoven University of Technology

This part-time chair in Product-Driven
Process Engineering is funded by:

Hoogewerff-Fonds

Introduction

The mission of the Eindhoven University of Technology (TU/e) is to be a research-driven, design-oriented university of technology at an international level, with the primary objective of providing young people with an academic education within the ‘engineering science & technology’ domain. ‘Design-oriented’ means that the research is done with the design of a new product or a new process in mind.
But what comes first, the product, the process, or should they be designed simultaneously?
In classical petrochemicals the product properties are not so much dependent on the way they are produced as long as sufficient purity is achieved. However, complex products and complex materials like plastics, gels, ice cream, margarine, gels, washing powders, and the like are very much affected by what exactly happens in the manufacturing process. It therefore requires a Product-Driven approach of Process Engineering. Such an approach is relatively new and deviating from the classical approach of Process Engineering.
My appointment in Eindhoven concerns the Hoogewerff chair in ‘Product-Driven Process Engineering’. This chair was initiated by the Hoogewerff-Fonds in 2002 and is being sponsored for another term. My challenge is to further strengthen the scientific basis in this important new field and to provide its embedding in the broader domain of Process Systems Engineering, which is one of the focal areas of the Department of Chemical Engineering and Chemistry at Eindhoven.
(Grossmann and Westerberg, 2000) defined:

> *Process Systems Engineering as being concerned with the improvement of decision-making processes for the creation and operation of the chemical supply chain. It deals with the discovery, design, manufacture, and distribution of chemical products in the context of many conflicting goals.*

In this lecture I will address both the research as well as the educational aspects of the Product-Driven approach within the Process Systems Engineering domain.

Chemically structured products

Chemical components are not only the components made by (chemical) industries, but also all components existing in nature. As such we are surrounded by chemicals.

Seider et al. (Seider et al., 2009) grouped chemical products into basic, industrial and configured consumer products, as shown in Figure 1.

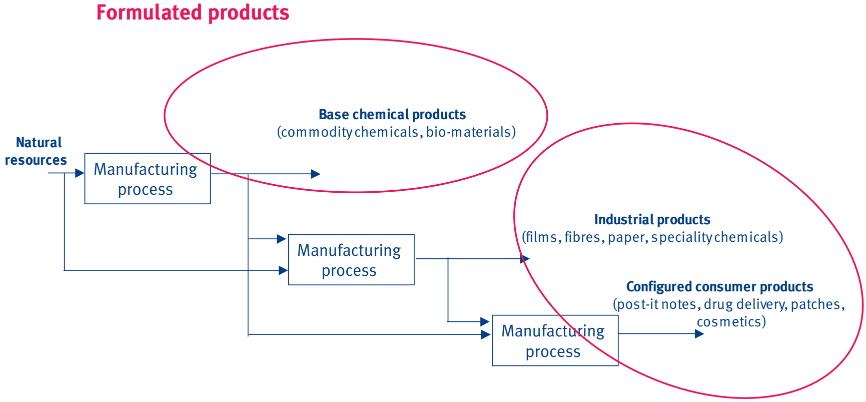


figure 1

Chemical product classification

1. Basic chemical products are manufactured from natural resources. They include commodity and speciality chemicals (e.g. ethylene, acetone, vinyl chloride), biomaterials (e.g. pharmaceuticals) and polymeric materials (polyethylene, polystyrene). They involve well-defined molecules and mixtures of molecules. They are mainly characterized by their composition and purities. As such we will call them formulated products.
2. Industrial products are manufactured from basic chemical products, and include fibers, paper, Active Pharmaceutical Ingredients, creams and pastes. Apart from their characterization by purity, they are often also characterized by their thermo physical and transport properties.

3. Configured consumer products are manufactured from basic chemicals and industrial products. They include cosmetics, detergents, composite food products, post-it notes and drug delivery patches. Unlike the basic chemicals and industrial products, they are sold directly to consumers and are characterized by properties dominant in satisfying consumer needs, including their microstructure and functional, sensorial properties.

An important factor for the industrial products, and a crucial one for the configured consumer products, is their microstructure. We will therefore name both groups chemically structured products.
Assembled products (like buildings, furniture, shoes and automobiles) are outside our domain. Although chemically structured products form their essential building blocks, these assembled products are the domain of for example Architects and Industrial Design departments.

What products are we looking at?

As mentioned before, we are mainly looking into structured products as opposed to formulated products. The chemically structured products are ubiquitous in the agricultural, chemical, food, beverage and pharmaceutical industries. Chemically structured products:

- Have formulations consisting of multiple components, which can be present in different phases
- Have their properties determined by the microstructure as well as by the formulation
- Have their microstructures often at non-equilibrium
- Exhibit a complex rheology

Let's have a look at various examples of chemically structured products and illustrate the richness of this broad area.

Fertilizers

According to Brockel and Hahn (2004), the world consumption of nitrogen fertilizer amounted to 80 million tons in 2000. Most fertilizers contain nitrogen as ammonium (NH_4^+) and nitrate (NO_3^-), of which the latter is subject to leaching. Stabilized fertilizers aim to reduce NO_3^- leaching by increasing the lifetime of $NH_4^+ - N$ in the soil from less than 1 week under normal conditions to 6–10 weeks. This will lead to a lower overall consumption of the fertilizer.

Product structure design needs to combine among others chemical and physical properties, environment-friendliness, stability with respect to mechanical stress and temperature, and enhanced handling properties by reducing dust formation and caking.

Some microstructures for solid fertilizers are shown in Figure 2. It can be seen that the left picture a) shows a porous microstructure on the shell, whereas the microstructure of the shell on the right b) is less porous, allowing less leaching and hence a longer lifetime of the fertilizer.

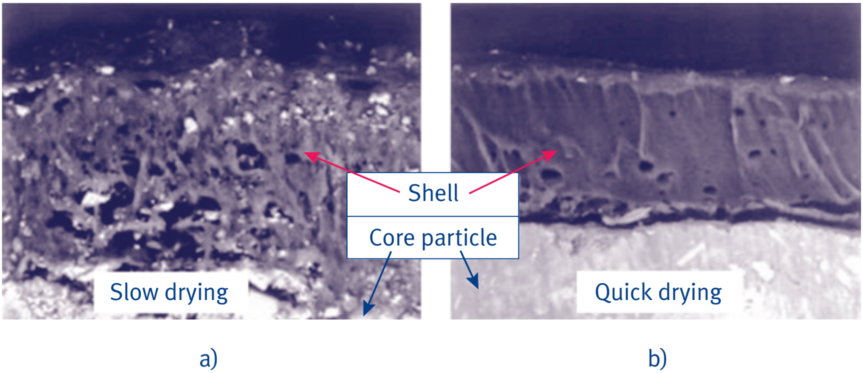


figure 2
Shell quality of fertilizer depending on drying conditions

Hair conditioners

Hair conditioner products are used to condition the hair. They have a complex formulation, consisting of *moisturizers*, whose role is to hold moisture in the hair; *proteins* to penetrate the hair and strengthen its structure through polymer cross-linking; *acidifiers* to create shine and elasticity; *polymers* to detangle the hair; *thermal protectors* to shield the hair against excessive heat, for example caused by blow-drying; *glossers*, light-reflecting chemicals which bind to the hair surface; *oils* (essential fatty acids), which can help to make dry/porous hair more soft and pliable; *surfactants* to strengthen the hair fibers; *sequestrates* for better function in hard water etc.

Apart from the complex formulation, the microstructure of the product is also important. (Hill, 2004) showed some microstructures of hair conditioners (Figure 3). While differences in product microstructure are obvious from the micrographs, a difference will also be apparent to the consumer as the viscosities (and hence how easy it is to rub the conditioner into the hair) of these products differ by an order of magnitude.

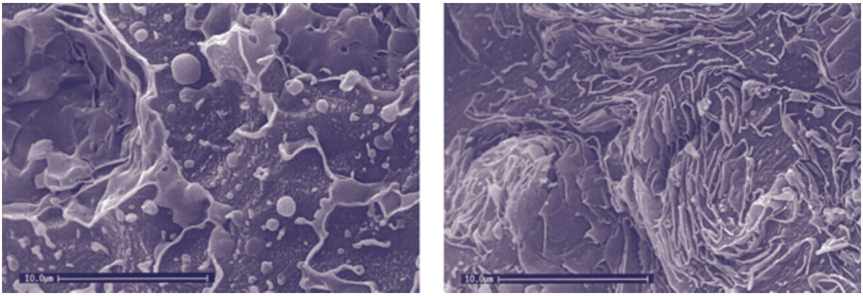


figure 3 a) b)

Cryo-SEM micrographs of a lamellar-structured hair conditioner manufactured under low deformation rates (a) and high deformation rates (b)

Ice cream

As described by Crilly et al. (2008), ice cream is a complex multiphase structure consisting of ice, air and fat as dispersed phases at a range of different length scales, all embedded in a continuous phase consisting of unfrozen sugar solution known as the matrix or serum. The entire structure is the result of both the ingredients and all the processes used in ice cream manufacture including emulsification, freezing, and aeration. It is thermodynamically unstable, and delivered quality can only be ensured at low and stable temperatures. Physicochemical processes during storage can lead to loss of quality by coarsening of the ice particles, disproportionation of the air, and loss of water from the matrix. Product design for specific sensory, stability, shape and, increasingly, nutritional properties, is a challenging task and must take account of all these aspects of the structure. Almost all properties are sensitive to the size, density and morphology of the dispersed phases as droplets, cells, crystals or even micelles. Finer structures, in general, result in more desirable organoleptic properties such as creaminess and smoothness but the interfacial dynamics are more rapid, leading to less stability. Even small changes in the relative densities of the dispersed phases, such as in the case of low-fat or fat-free products, can dramatically change key properties such as taste perception, mouth feel and rate of melt. The microstructure of a typical ice cream is shown in Figure 4.

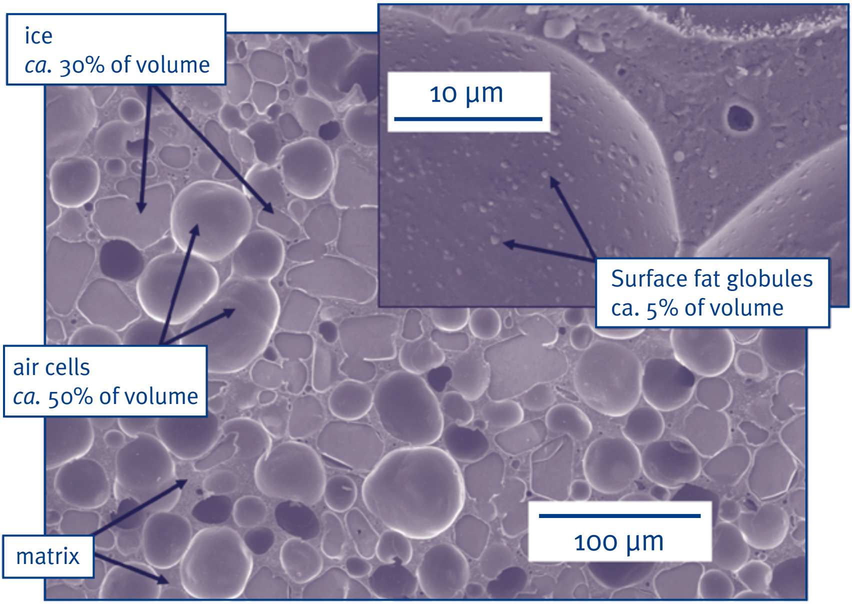


figure 4

Ice cream microstructure depicted by scanning electron microscopy (Crilly et al., 2008). The overall structure is determined largely by freezing and aeration process conditions. Complex interactions exist between the structural phases and between fat, protein and emulsifier. Shown in the inset, air is stabilized by a coating of fat droplets (Pickering stabilization) and because the 'matrix' is highly viscous.

To further illustrate the importance of the structuring process some meta-stable multi-phase food systems are shown in Figure 5, all with water and oil[1] as main ingredients.

Enterprises

The majority (in numbers) of chemically structured products are so called Fast Moving Consumer Goods (FMCG). These are the products that are sold quickly at relatively low cost. Although the absolute profit made on FMCG products is relatively small, they generally sell in large quantities, so the cumulative profit on such products can be large.

FMCG products are generally replaced or fully used up over a short period of days, weeks or months, and within one year. This contrasts with durable goods or major appliances such as kitchen appliances, which are generally replaced over a period of several years.

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[1] note that temperature differentiates oil from fat

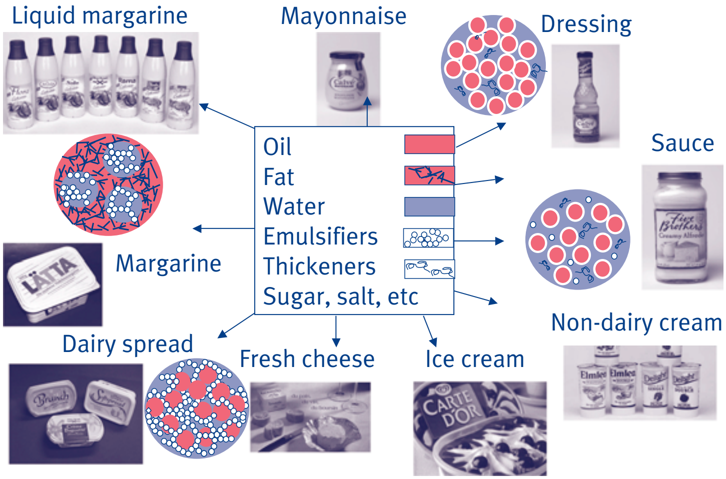

figure 5

Metastable multiphase food systems

Some of the best known examples of Fast Moving Consumer Goods companies include Anheuser-Busch, Cadbury, Coca-Cola, Colgate-Palmolive, General Mills, Friesland-Campina, H.J. Heinz, Kimberly-Clark, Kraft, Nestlé, Pepsi, Procter & Gamble, Reckitt Benckiser, Sara Lee and of course Unilever.
As these enterprises develop, manufacture, market and sell the majority of the chemically structured products, it is important to take their environmental changes into account.

Enterprise environment

Let me sketch the changing environment in which enterprises are operating, for which we have to prepare our students, and which will guide our research activities.

- *Profitability*. In order to sustain the business over longer periods, the business needs to be profitable. The profitability has to be seen in the wider supply chain network, concerning on-shelf availability, stocks, conversion costs, capital, utilization, cleaning, waste etc.
- *Increase of raw material costs*. Due to the continuing increasing demand in fuel compared with supply, energy prices will continue to rise. Bio-based fuels compete for crops that we need as raw materials for our products. The competition is directly for the oils and indirectly for the available acreage for crops. A significant increase in the efficiencies (reduction of wastage) of the conversion processes will therefore be important.

- *Naturalness*. An important consumer trend is the need for more natural and healthy products. Components of naturalness are the lack of ‘chemical’ additives for preservation, minimal processing of the raw materials, absence of chemicals in the processing, less time between the harvest and consumption etc.
  As E-numbers are also seen as non-natural, naturalness is also a consumer perception. A more variable feedstock has large impacts on the conversion process and supply chain. Healthy products in foods contain significantly less (added) salt, sugars and fats leading to alternative ways to structure the product, of which processing is one.
- *Personalization*. Consumers are demanding more choice in the product range and availability, always and everywhere. A larger product range implies lower volume per product; hence an increased flexibility in the manufacturing base is needed, but also more cleaning between the different products.
- *Sustainability*. This is part of our environmental vitality drive, which aims to reduce negative impact on the environment, for example packaging waste. The reduction in carbon footprint of our products can have a large impact on where the products are manufactured and distributed in relation to consumers. Reduction of water usage, both during processing as well as during cleaning, has a large impact on manufacturing.
- *Affordability*. As the largest consumer base is in D&E markets, affordability of products is important. During an economic downturn it is as important in the developed countries. Affordability can be increased by using less costly raw materials (often with more variability) and increasing the added value by the processing. The processing also needs to be low cost and robust for the raw materials.
- *Global marketplace*. For an increased number of companies the entire globe is the potential marketplace. Information travels around the globe at enormous speed, and products can be ordered by consumers on the internet from the other side of the world just as easily as from next door.
- *Rapid innovation*. The half-time of a product innovation (or time-to-market) in the early seventies was about 10 years, while currently, for products not requiring clinical trials, 2 years is already considered on the long side. This acceleration of innovation is the result of competitive pressures in the (global) marketplace. As a rough rule of thumb it is said that the first company to enter the market with a new product can get up to 60% of market share, so there is a high premium on being ‘first’. A drawback is that the investments are tremendous (Bruin, 2004).

Not all consumer trends are valid for all regions and/or markets; therefore it is important to determine accurately which trends need to be satisfied by the product. Product innovations need tremendous investments, which need to be recovered by product sales. Product affordability is negatively influenced by the investment for innovations. The goal is to increase the numbers of successful product innovations AND to reduce the investments.

Multiple scales

The performance of chemical structured products is determined by phenomena operating at various time and length scales. The performance of the products is determined by both the formulation and the microstructure. In most structuring processes, the product microstructure manifests itself at a scale that is almost 10^7 times smaller than the size of the equipment that forms the structure. The challenge is to reduce this gap and to understand how phenomena at a smaller length scale relate to properties and behavior at a longer length scale. This is the eternal triangle between molecules, product and process as advocated by my predecessor prof. Bruin (Bruin, 2004). On the other hand phenomena on a global scale influence the operational policies of plants and supply chains. Furthermore, in the supply chain (with typical length scales of 10^6 m and time scales of days-weeks-years), the microstructure of the (meta-stable) products needs to be maintained.

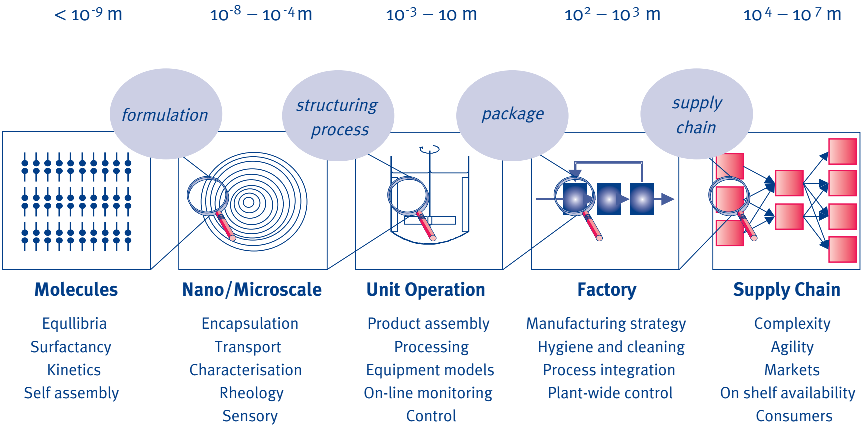

figure 6

Length scales for product-process design

Chemical engineering research challenges

Over the past years, chemical engineering has been hinged on some changing paradigms. The 1st paradigm was the concept of unit operations. The 2nd paradigm is the concept of transport phenomena, laid down in 1960 by Bird-Steward-Lightfoot (Bird et al., 2002). In the 1990s the community was looking for new horizons in chemical engineering. Charpentier (2002) refined Villermaux (1993) proposals to undertake simultaneous chemical engineering research in four parallel tracks:

a. to increase productivity and selectivity through intelligent operations via intensification and multiscale control of processes;
b. to design novel equipment based on scientific principles and new methods of production: process intensification;
c. to extend chemical engineering methodology to product-focused engineering, i.e. manufacturing and synthesizing end-use properties required by the customer, which needs a triplet of ‘molecular processes–product–process’ engineering;
d. to implement multiscale application of computational chemical engineering modeling and simulation to real-life situations, from the molecular scale to the overall complex production scale.

In recent years, chemical product design (similar to item c) has been suggested as a 3rd paradigm in chemical engineering (Costa et al., 2006; Hill, 2004). Later in this lecture I will illustrate that intertwining the chemical product design with process design is even more challenging.

Academic changes

The IROP/OSPT published a positioning paper on process technology in the Netherlands in 2008. In this paper they identified a gap in the process technology R&D value chain, as shown in Figure 7.

The core of the process systems engineering activities is within the applied research which, as indicated in Figure 7, is at the core of the identified R&D gap. There is a growing concern that, as a consequence of the academic focus on scientific publications, impact factors and decreasing subsidies for applied research, PSE groups suffer in maintaining the necessary pilot plant equipment

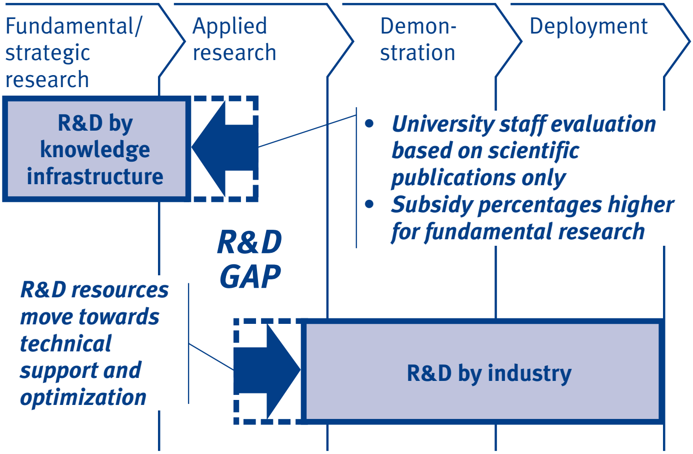

figure 7

Technology R&D value chain

(which consumes a large part of the overall costs) and attracting sufficient academic staff. However, PSE is an essential bridge between the fundamental research and industrial demonstrations.

Building block: sustainability

The Royal Academy of Engineering published 'Engineering for Sustainable Development: Guiding Principles' (Dodds and Venables, 2005) as a set of case studies to distil a set of general guiding principles that are encapsulated in or illustrated by the case studies. Edwards (2006) tailored these design principles to chemical products as:

- Product formulations should be chosen to minimize the quantities of raw materials. Renewable sources should used when appropriate.
- By selecting the best combination of formulation and process route, microstructures should be designed which minimize the quantities of active ingredients and structurants.
- The energy demand of processes and the emissions (including those from cleaning) from factories should be reduced.
- Transportation emissions should be minimized in moving the product through the supply chain to the user.
- The use of packaging throughout the supply chain should be minimized.
- Any damage to the environment during the product's use and disposal should be reduced.

Building block: process intensification

Process intensification is becoming more important as a field of research. In their paper Gerven and Stankiewicz (2009) present a fundamental vision on process intensification. The vision encompasses four approaches in spatial, thermodynamic, functional and temporal domains, which are used to realize four generic principles of PI. The approaches refer to all scales existing in chemical processes, from molecular to meso and macro scale. The four principles of process intensification are

1. *Structure*: maximize the effectiveness of intra- and intermolecular events.
   It is not only about aiming at processes limited only by their inherent kinetics; it is primarily about changing those kinetics. This is where the whole ‘evil’ of low conversions and selectivities, unwanted side-products etc. has its roots. According to the simplest collision theory, the factors responsible for the effectiveness of a reaction event include: number/frequency of collisions, geometry of approach, mutual orientation of molecules in the moment of collisions, and their energy.
2. *Energy*: give each molecule the same processing experience. Processes in which all molecules undergo the same history deliver ideally uniform products with minimum waste. Here not only macroscopic residence time distribution, dead zones or bypassing, but also meso- and micro-mixing as well as temperature gradients, play an important role.
3. *Synergy*: optimizing the driving force and maximizing the specific surface areas to which these forces apply. This principle is about the transport rates across interfaces. The word ‘optimize’ is used here on purpose as maximization of the driving force (e.g. concentration difference) is not always required.
   On the other hand, the resulting effect always needs to be maximized, and this is done by the maximization of the interfacial area to which that driving force applies. Increased transfer areas (or surface-to-volume ratios) can for instance be obtained by moving from the millimeter to the micrometer scales of channel diameters.
4. *Time*: maximizing synergetic effects from partial processes. It is evident that synergistic effects should be sought and utilized, whenever possible and at all possible scales. Most commonly such utilization occurs in the form of multifunctionality on the macro scale, for instance in reactive separation units, where the reaction equilibrium is shifted by removing the products in situ from the reaction environment.

Chemical process design

Now turn to process design. Siirola (1997) estimates that decisions made in the conceptual design phase of the chemical plant, which accounts for about two or three percent of the project costs, fix approximately eighty percent of the combined capital and operational costs of the final plant. So the success of a chemical plant, hence the chemical product, is to a large extent determined by the conceptual design.

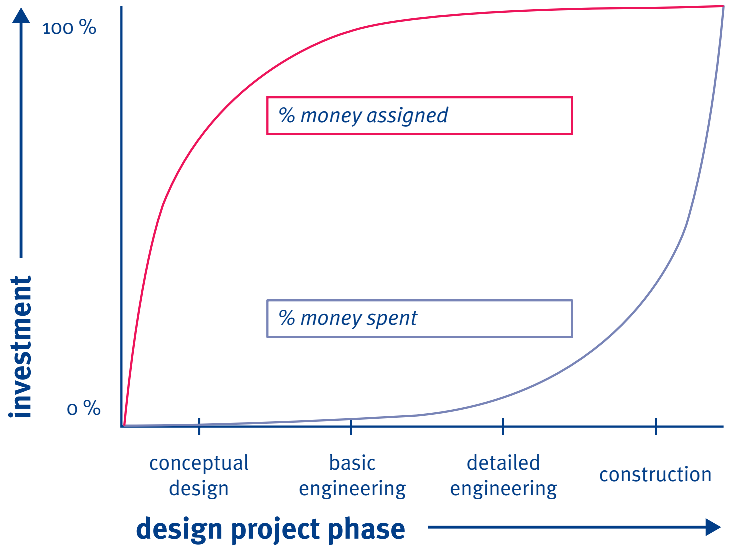

figure 8

Financial characteristic of conceptual process design (Meeuse, 2002)

Conceptual process design is a highly complex task because:

- a large number of alternatives are possible,
- a large variety of requirements need to be satisfied,
- large differences in time and length scales are involved.

The number of possible combinations can easily run into many thousands (Douglas, 1988). The process synthesis methodology is regarded in this context as a way to beat the problem of complexity.

Process synthesis was originally conceived to assist process and chemical engineers in the area of petrochemistry (Douglas, 1988;Siirola, 1996) three decades ago. Three fundamental approaches have been envisaged for the synthesis of chemical process:

1. Evolutionary modifications. Evolutionary modification starts with an existing flowsheet for the same or a similar product and then makes modifications according to the desired product.
2. Systematic generation is based on a hierarchical decomposition of levels of increasing level of complexity (Douglas, 1988; Siirola, 1996).
3. Superstructure optimization starts with a larger superflowsheet that contains embedded within it many redundant alternatives and interconnections as necessary (Papalexandri and Pistikopoulos, 1996).

In spite of its inherent complexity, the development of novel process synthesis methodologies has lately gained increasing interest from academia and industry. This phenomenon is reflected in the number of scientific publications focusing on process synthesis research issues and its applicability in industrial practice (Li and Kraslawski, 2004). For instance, the effective application of process synthesis in industry has led to large cost savings, up to 60% as reported by Harmsen et al. (2000), and the development of intensified and multifunctional units, e.g. the well-documented methyl acetate reactive distillation unit (Stankiewicz and Moulijn, 2002).

Towards a product-centered approach

It is a well-acknowledged fact by industry and academia that chemical industry focus has shifted from a process-centered orientation to a product-centered one (Hill, 2004). During the last decades we have experienced how the commodity chemical business is gradually releasing its dominant role towards higher-added value products, such as speciality chemicals and consumer products as shown by Cussler and Moggridge (2001) in the change in employment of graduates in the chemical industry (Figure 9).

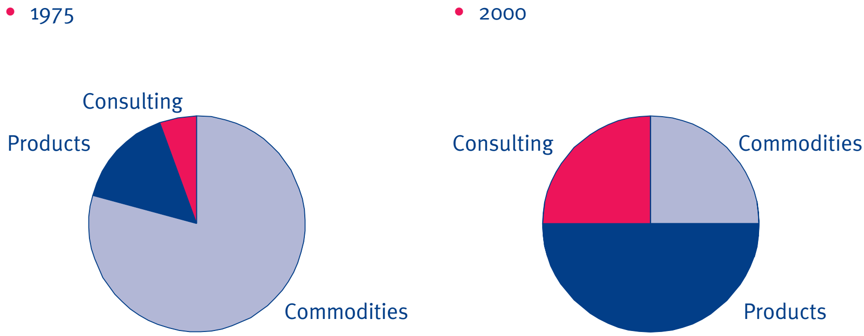

figure 9

Changes in employment

This trend is further reflected in the increasing number of scientific publications addressing product and process design (Edwards, 2006; Gani, 2004; Hill, 2004; Hill, 2009; Norton et al., 2009; Wibowo and Ng, 2001), and in textbooks for undergraduate/graduate courses in chemical process design (Cussler and Moggridge, 2001; Seider et al., 2009; Wesselingh et al., 2007)

Stretching the boundaries of the synthesis activity towards products has brought challenges for the chemical and process engineers. Those refreshing problems need the development of novel tools and methods, involving areas like the fundamental understanding of the product-process interactions, multilevel modeling of consumer products, property models for products with internal microstructure, prediction of consumer preference and its dependence on ingredients and processes etc.

Whether product design is embedded in the process design activity still remains a topic of debate. As mentioned elsewhere (Cussler and Moggridge, 2001; Moggridge and Cussler, 2000), if the emphasis is on product design, current methodologies of process design (e.g. the hierarchy of decisions by Douglas (1988) do not capture the product design space. It is therefore necessary to go beyond the process design hierarchy.

Table 1 shows the steps of process and product design as suggested by Douglas (1988) and Cussler and Moggridge (2001), respectively. This sequence of steps implies that process design is contained in the fourth step of the product design approach, and product design is prior to the first step of the process design approach.

Process design – hierarchy of decisions	Product design
1. Batch versus continuous	1. Identification of consumer needs
2. Input-output structure of the flowsheet	2. Generation of ideas to meet needs
3. Recycle structure of the flowsheet	3. Selection among ideas
4. General structure of the separation system	4. Manufacturing of product
5. Heat-exchange network	

table 1
Process design and product design steps

Despite the maturity of most process synthesis approaches for chemical products, they fall short when it comes to extending its scope and applicability to structured products. This drawback of current approaches is derived from the intrinsic differences between bulk chemicals and food products (and also hold for structured products), and include (Meeuse, 2005; Stappen, 2005):

- Food products are typically chemically structured products whose performance is determined by both the formulation and the internal microstructure of the product;
- Unit operations are quite different, involving less reaction and separation tasks and more structuring and stabilization (microbiological preservation) tasks;
- Food processes are generally multiproduct processes, where the same production line has to accommodate the manufacturing of different products with different properties;
- Cleaning (and possible sterilization) is an essential and non-negotiable task within the operational policy.

In contrast to bulk chemicals, structured products are therefore characterized not only by the formulation (the level of each ingredient, leading to a composition, purity, physical state, temperature, pressure etc.), but also by the relative spatial arrangement of each ingredient and performance behavior. All these features are responsible for the exclusive attributes of structured products (e.g. creaminess of an ice cream, spoonability of a mayonnaise, spreadability of a margarine etc.).

The first attempt to widen the scope of process synthesis to food products with internal structure was carried out by Meeuse et al. (1999).
More recent publications on food product and process design in foods are those by Almeida-Rivera et al., 2007; Bongers and Almeida-Rivera, 2009; Hill, 2004; Meeuse, 2005; Ridder et al., 2008; Stappen, 2005.

In most of the work, there is a sequential approach (also indicated in Table 1): first design the structured product (and obtain marketing approval for this product), followed by design of the process (Cussler and Moggridge, 2001; Grievink, 2002; Seider et al., 2008; Wesselingh et al., 2007). The main contribution of their work is to place more emphasis on, and provide methods for, chemical product design.

The above discussion is shown schematically in Figure 10, where the ultimate aim is to intertwine product and process design.

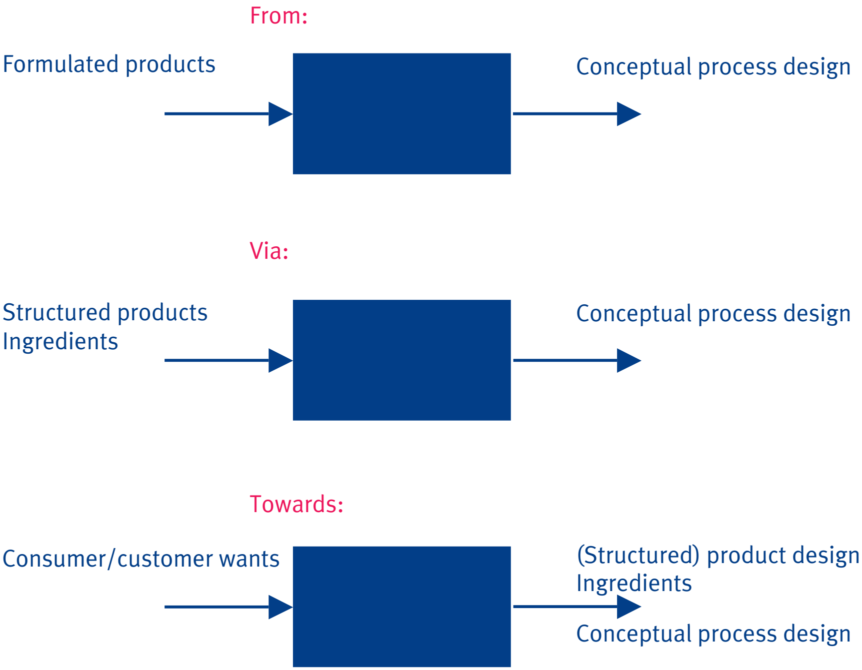

figure 10

Conceptual product-process design journey

Intertwine product and process design

While there is already a staggering mismatch between effort and impact for process design when the formulated product is known, the mismatch is even larger when we take the product design into account.
Especially for chemically structured products, a lot of the constraints in the process design are determined in the product design phase which, together with the process design, determines product opportunities. To overcome these limitations of a sequential approach, a paradigm shift, illustrated in Figure 11, is needed to intertwine process design and product design.

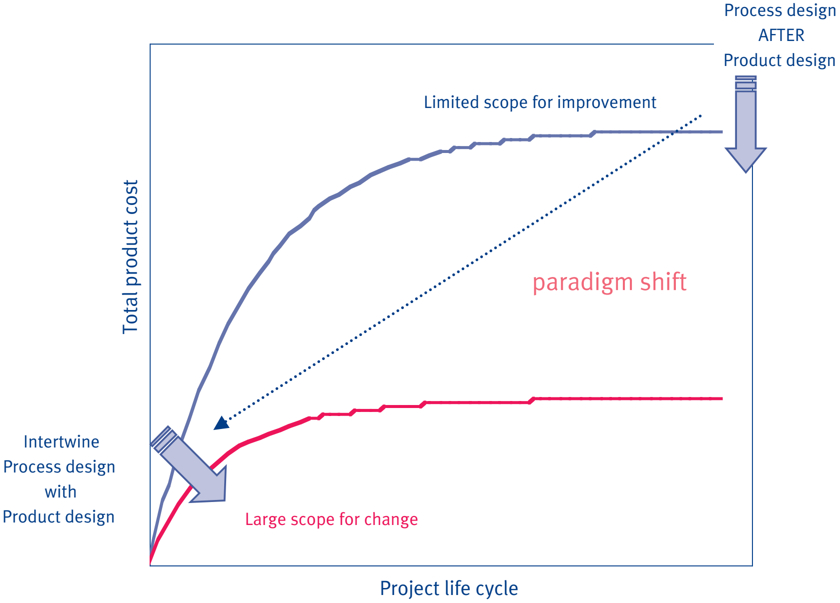

figure 11

Product cost

An example of how the ingredients and the process determine the product is shown in Figure 12. The left side (a) of the figure shows how the air cell size (for the same formulation) influences the perceived creaminess of an ice cream by consumers. The air cell size is determined by the process. The right side (b) of the figure shows how the fat level in the formulation (for the same processing) influences the perceived creaminess. Both fat level and process can be varied to determine the product attribute creaminess.

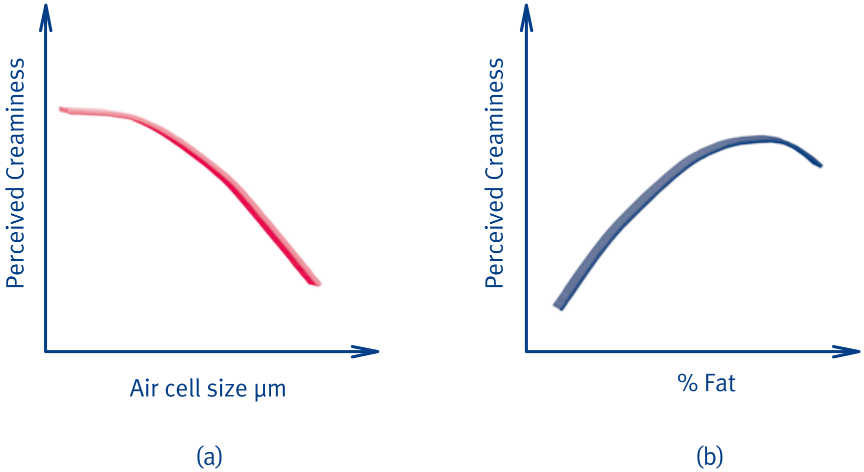

figure 12

Ice cream creaminess

Depending on the desired level of perceived creaminess, which should be derived from what the consumer wants, both the fat level and the process can therefore be manipulated to achieve the target.

Research within the chair

The research aim is to have a more structured approach to intertwine product and process design for chemically structured products. For this, we propose a product-driven process synthesis methodology. This approach exploits the synergy of simultaneously combining product and process synthesis workstreams, and is based on the systems engineering strategy.

Following the proposed methodology it should be ensured that the newly designed structured product can be manufactured on the most appropriate process with the desired properties at optimal costs.
As we propose that it would be beneficial to use the methodology in the very early stages of product design, when there is still a lot of uncertainty, the methodology should allow an efficient reduction of the complexity.

Decomposing the problem into a hierarchy of design levels of increasing refinement which has been derived from the pioneering work of Almeida-Rivera et al., 2004; Douglas, 1988; Grievink, 2002; Meeuse et al., 1999; Siirola, 1996; Stappen, 2005, is therefore proposed. The outline of the methodology is shown in Figure 13 where for each step (horizontal) towards the final product design, all levels (vertical) are performed.

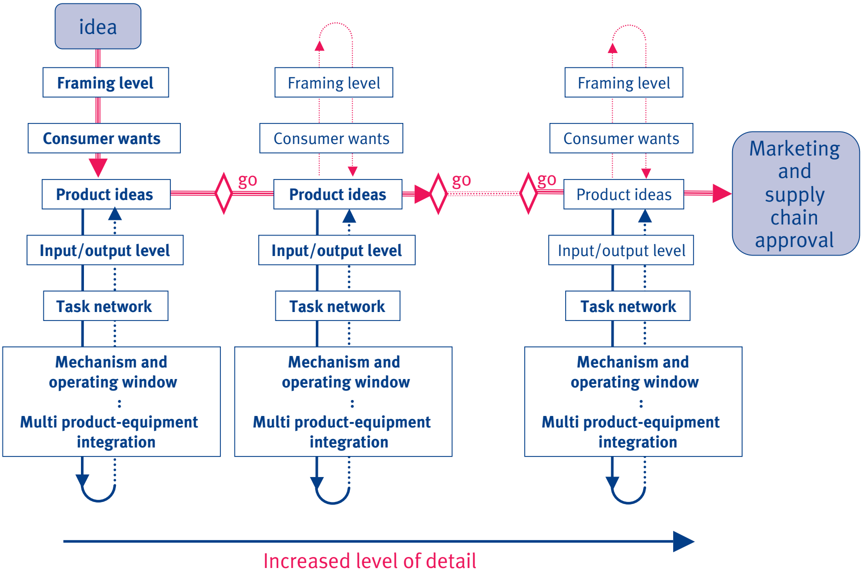

figure 13

Product-driven process synthesis methodology

As the level of detail about the product increases, all levels are in principle repeated. When new knowledge about the potential product becomes available, the previous assumptions need to be verified (which is indicated by the vertical dotted lines). The product is the 'tangible' communication vehicle with the marketing and supply chain. The result of following this methodology is that, together with the product concept that can be shown to marketing, an optimal 'potential' route to manufacture the products is ensured.
Each of the columns in Figure 13 is detailed in Figure 14.

Level	Description
0	Framing level
1	Consumer wants
2	Product function
3	Input/output level
4	Task network
5	Mechanism and operational window
6	Multiproduct integration
7	Equipment selection or design
8	Multi product-equipment integration

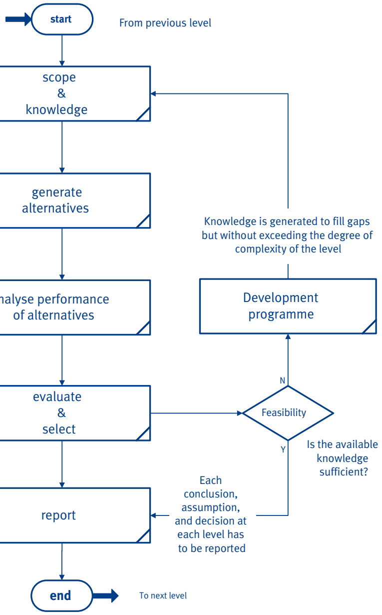

figure 14

Left: levels of the product-driven process synthesis methodology; right: activities at each level

Outline of the product-driven process synthesis methodology

For the whole methodology, it must be clear that, when starting with an initial idea for a chemically structured product, step 7 which is equipment selection or design can only be performed with very broad brushes.

By a similar argument, when the product design is almost finished, much more emphasis will be placed on the equipment design.

Although we will outline what needs to be done at each of the levels, how it can be done most efficiently still needs to be further investigated.

Framing level

The product-driven process synthesis methodology starts with the framing level. In this level, we embed the chemically structured product-process design into the overall project. For this, the background of the project, business context, market segmentation and overall supply chain considerations such as product portfolio, projected demand profiles and regional spread are of importance.

Consumer wants

The second step is translating consumer wants and *customer wants* into product attributes such as smoothness, whiteness and creaminess. Quality Function Deployment (QFD) or ‘House of Quality’ is often used at this stage. QFD is a team effort that starts with establishing WHAT the consumer/customer wants. This is done by interviews and so-called focus groups, and the result is a list of statements expressing wishes. The last activity in this level is to rank these so-called ‘WHATs’ by weighting them.

Product function

The next step is to deliver product functions that potentially satisfy WHAT the consumer wants. In this stage we need product ideas to potentially satisfy the product attributes from the previous level. Many ideas come from individuals, or from groups during creativity sessions, or from using tools like TRIZ (Orloff, 2006; Salamatov, 1999). QFD can be used to link the relevant product properties (measurable quantities) of the product ideas to satisfy the product attributes. While developing the product ideas, the previously mentioned sustainability guidelines, such as minimizing quantities of raw materials etc., need to be taken into account. As it is impossible to evaluate all ideas in detail, a first screening needs to be done. This could be done using a morphological analysis (Ritchey, 2006), complemented by multi-criteria decision-making (Ridder et al., 2008) to rank the ideas.

Input/output level

The fourth step is the input/output level. In this level a complete specification of the output (microstructure, flavor profile and microbiological status) and potential inputs (ingredients) to the process are made. This includes performance parameters such as quality, economic potential, hygienic considerations, controllability, flexibility, pumpability and availability. It is staggering to observe the lack of knowledge of how the microstructure influences the product attributes, and as a result which microstructures are desired.

Fundamental tasks

Next, the fundamental tasks needed to transform the inputs to outputs are identified. Tasks that require a certain sequence or that belong together without any doubt are grouped, to reduce the number of possibilities. Then a set of potential task networks is made. Either literature, heuristics or experiments are deployed to prune the set of networks. Research effort is needed to determine how future control objectives can be incorporated.

Mechanism and operational window

In step five we determine the mechanism and operational window that can be used to perform a task, this step includes the driving forces and kinetics. Furthermore, the operational window for the product (time, P, pH, shear, T etc.) is defined. In this step process intensification principles need to be incorporated.

Multi-product integration

Multi-product integration is important when the production line is used for more products than the one we are designing. Then the outcomes of the previous three steps for the different products are compared to look for overlap and possibilities to combine the production.

Equipment selection and design

In the equipment selection and design step, the operating units are selected. Integration possibilities (e.g. by combining tasks with the same driving force that are close together in task network) and controllability have be considered. The operational window from step five is compared with the operating boundaries of the unit. In this step, PI principles need to be applied as well as sustainability arguments. Then, the final design of the units (only of the key dimension) and final flowchart are made.

Multi-product-equipment integration

The last step is the multi-product-equipment integration. We optimize the interaction of the various unit operations in the flowsheet (plant-wide control). Multi-stage scheduling of the multiple products is applied, fed by the run strategy based on the product demand and portfolio.

Education

The previous part of the lecture has provided an outline of my research plans. However, the primary objective of the university is to provide young people with an academic education within the ‘engineering science & technology’ domain.

According to Thijssen (1965) in his 1965 inaugural lecture, the building of product technologies can be seen as a symphony orchestra giving a performance: process engineering is the conductor, and key parts are played by material science, process experience, transport phenomena, reaction engineering and mechanical engineering. Having stated this in 1965, product technology and the intertwining with process design is not a ‘mandatory’ part of the curriculum in our chemical engineering department.

Classes of processes

According to Bruin (2004) we can recognize four major classes of processes that are used to manufacture a chemically structured product. These four categories form two pairs that are each other’s opposites.

- **Separation processes**. The most important category of processes in the process industry is the class of disassembly or separation processes, in which a raw material is split into valuable intermediate products that are often used as raw materials for end-product manufacturing processes. Separation processes comprise distillation (e.g. oil refineries) and extraction processes (e.g. fractionation of vegetable oils and fats, milk fractionation), but also a host of mechanical separations in which mixtures or slurries of particulates are separated into fractions (e.g. treatment of ground ores, flour milling). These processes are very typical to the chemical process industry (large tonnages, bulk products, often continuous processing).
- **Structuring processes** are the opposite of separation processes. Man-made structured products use assembly, structuring or texturizing processes, for example crystallization and emulsification processes (e.g. margarines, mayonnaises, ice creams, paints, detergents), foaming (e.g. insulating materials, shaving cream, whipped creams), granulation, agglomeration,

extrusion processes, dough-making, baking etc. The end-product is often a complex microstructure of dispersed phases held together by binding forces and a continuous phase. The product microstructure leads to the desired product functionality in use.

- **Transformation processes**. The most important process step in all the branches of the chemical industry is the conversion of reactants into a product. (Bio-) converted foods often use highly complex conversion processes in which either chemical or biochemical conversions are applied to raw materials, yielding ingredients, flavors, fermented products, roasted products (black tea, coffee) and the like.
- **Stabilization processes** are the opposite of transformation processes. Two major processes can be identified. The first, encapsulation, provides a barrier between two reacting species. The second, to combat spoilage, is rather typical for the food industry and pharmaceutical products. Naturally structured foods often use preservation or stabilization processes in which the main aim is to eliminate microbial, enzymatic or chemical spoilage of the raw materials, which are usually food tissues (fish, meat, vegetables).

An actual total manufacturing process is usually built up of combinations of these basic four processes. Education on both separation processes and transformation processes is well embedded in the curriculum. Structuring processes and stabilization processes are essential in conceptual process design for chemically structured products. However, they have very limited attention in the current curriculum. The profile of structuring processes and stabilization processes needs to be raised, in order to prepare our students for the wide variety of enterprises hiring them.

Acknowledgements

In this inaugural lecture I hope I have given you an impression of the challenges that I plan to address in the field of Product-Driven Process Engineering. I would like to conclude my lecture by expressing my gratitude and addressing some people.

Of course I would like to thank the Executive Board of Eindhoven University of Technology and my colleagues in the Department of Chemical Engineering and Chemistry for placing their trust in me and providing me with the facilities to initiate and execute my research program.

The board of the Hoogewerff-Fonds, who continued this chair for product-driven process engineering, for placing their trust in me to shape this chair at the Eindhoven University of Technology.
Solke Bruin, who I first met when I joined Unilever in 1994 and later when he held the Hoogewerff chair in Eindhoven. André de Haan for his hospitality in having this chair in his Process Systems Engineering group.

The whole thinking on product-driven process synthesis is not a one-man band. It has been a joint effort of a number of colleagues for over more than a decade, and we are still only at the beginning of this journey: Michel van de Stappen, Michiel Meeuse, Clive Marshman, Micheal Hill, Johan Grievink, Solke Bruin, Bas Bakker and last but not least Cristhian Almeida-Rivera.

I would like to thank the various boards of Unilever, who not only approved this part-time role in Eindhoven but also positively support it. At this stage a special thanks to Ardjan Krijgsman is appropriate.

Preceding this inaugural lecture we organized a mini-symposium on ‘Dutch product and process design’. For their efforts in preparing lectures and their contribution to this special occasion, I would like to express my great appreciation to my colleagues prof. Bruin, prof. van den Berg, prof. Boom, prof. Grievink and dr. Almeida-Rivera.

Rector Magnificus, ladies and gentlemen, I've tried to provide you with an overview of how to intertwine product-process design and why it is of importance. Taking future processing into the product design arena will influence the final product structure, while at the same time taking the product into the process design arena will influence the final process.

Finally I would like to conclude by expressing my gratitude to all of you for having made the effort to be present today.

I have said.

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Curriculum Vitae

Prof.dr.ir. Peter Bongers was appointed part-time professor in chemical process engineering in the Department of Chemical Engineering and Chemistry of Eindhoven University of Technology (TU/e) on 1 March 2008.

Peter Bongers graduated in mechanical engineering (1986) at Delft University of Technology. He gained his PhD (1994) in systems and control theory with a thesis on 'Modelling and identification of flexible wind turbines and a factorisational approach to robust control'. He joined Unilever Research Vlaardingen in 1994 to work in the area of process modelling and control. In 1998 he transferred to the Unilever Ice Cream Research in the United Kingdom. Afterwards he moved to the Hellendoorn ice cream factory to lead a project to implement novel process technology and subsequently led the roll-out in Europe. From 2005 he was responsible for the process systems engineering skill base in Unilever Food Research in Vlaardingen. In March 2008 he was appointed part-time professor in the Hoogewerff chair in product driven process engineering in the Department of Chemical Engineering and Chemistry at Eindhoven University of Technology. His research interests are process design and optimisation over various length scales (product structure, unit operations, manufacturing lines and supply chains). In his current work he is responsible for processing and manufacturing science within Unilever Research.

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