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Process Synthesis applied to the food industry

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Abstract
Various differences between typical chemical products and food products limit the direct applicability of process synthesis methods to food products. The main differences are the internal structure of the products, the number of products produced in one process, and microbiological considerations. We present an example where a modified version of the process synthesis methodology led to an alternative process with reduced capital costs. Finally some key research challenges are identified.

Keywords: process synthesis, structured products, food products

1. Introduction

In the last decades a lot of developments took place in the field of systematic methods for designing chemical processes. A lot of examples are published were breakthroughs have been achieved by not looking at a process as a combination of unit operations, but by understanding the fundamental phenomena happening in the process.
Most applications of process synthesis were for traditional chemical product processes. Extending these methods to food product processes is not straightforward given the following clear differences between these products:

- Food products are typically structured products where the performance is determined by the internal microstructure of the product.
- The unit operations are quite different, less reaction and separation, more mixing, crystallisation and preservation.
- Food processes are generally multi product processes, so on the same line different products with different properties need to be produced.
- Cleaning is an essential part of the operational policy for food safety and product quality reasons.

Meeuse et al. (2000) were among the first to extend these methods to products with an internal structure. Since then various publications on the design of process for structured products have appeared, (e.g. Wibowo and Ng, 2001, 2002).
With this paper we want to give an industrial perspective on the application of process synthesis in the food industry. In the next section we comment on the popular topic of process design and product design. Then the procedure used for process synthesis is discussed, illustrated with a case study. Finally, some research challenges are presented.

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2. Process design vs. Product design

In the literature various ideas are presented on the relation between process design and product design. Cussler and Moggridge (2001) have presented a four-stage product design methodology where the manufacturing of the product is only considered after the selection of the product, so once the product design is finished. Linke and Kokossis (2002) have presented an example where the design of a solvent and the separation process were carried out simultaneously using an optimisation-based approach. Wei (2004) and Hill (2004) show that the industrial reality is somewhere in between these two extreme approaches. Ideally process engineering is already considered in the very first stages of the product design. In these stages the involvement will be rather limited, however it will be increasing over the next stages of the product design process.

This situation is remarkably similar to the topic of integration of process design and control system design. Three different approaches are generally considered: strictly sequential design, anticipating sequential design and simultaneous design (Lewin, 1999). Where the middle option solves some problems from the strictly sequential design (expensive and time-consuming iterations), but does not lead to the complex fully integrated design.

The risk of the strict sequential approach is that a product developer might come up with a product that fulfils the needs excellent but is very difficult or expensive to produce. Also within Unilever process engineers are usually involved in product development activities. They give processing input in the product development project. This is important since small differences in the product design can have a huge effect on the process design. However, this does not mean that product design and process design are fully integrated. They are still two sequential activities but during the product design the processing is considered explicitly.

The importance of considering the processing already from an early point in time is demonstrated by the following examples.

Example 1:
A completely new sauce like product was developed. The developed product contained small chunks of a specific, soft vegetable. This product made on the lab scale scored well in various tests. However, scaling up was very hard given the soft character of the vegetable pieces. The high shearrates in various parts of the processes (including the generally neglected filling machines) completely mashed the chunks. An alternative product without the chunks was much easier to produce. This alternative product also scored well with consumers, but significant time was lost before this was realised. Earlier involvement of processing considerations would probably have led to the same end result, but in a shorter time frame.

Example 2:
An emulsified product was developed that contained both fat with a melting point of about 40°C and oil. As a result the emulsification cannot take place at ambient temperatures, it should take place at temperatures above 40°C. The consequence was that the product could not be made in the equipment currently available in the factory. When the product was modified, the fat was replaced by liquid oil, the consumer liking

remained the same. However, significant less investment was required since the already available equipment could be used.
In the rest of this article we will focus on the process design and assume that the product specifications are already given.

3. Process Synthesis methodology

The method we are using is a combination of the hierarchical decomposition (Douglas, 1988) and means end analysis (Siirola, 1996) with an explicit consideration of the generic design steps (synthesis, analysis, evaluation), in each stage. The three first stages of the hierarchical decomposition are input/output structure, task blocks and unit operations.

3.1 Input/output structure

In this level we specify the input (raw material) and output (products) of the process. In this paper we will focus on single product processes only, but the method is not limited to this. The specification of the outputs includes a specification of the microstructure of the products, but also for example the flavour profile and the microbiological status of the product.

3.2 Task identification

In this level the fundamental tasks required to convert the raw materials into the final product are identified. All tasks are related to property differences. Siirola (1996) has presented the following hierarchy of property differences: molecular identity, amount, composition, phase, temperature/pressure, form. This list of tasks is not very well suited for food properties. Common tasks for food processes are decontamination (e.g. pasteurisation and sterilisation) structure formation (e.g. emulsification, size reduction of dispersed phase in an emulsion, crystallisation.)
It is not trivial to put these tasks in a hierarchy. Therefore the proposed way of working is to identify the tasks first and then, based on inside decide the order in which these tasks need to de resolved. This can be an iterative process between this stage and the next stage, unit operations.

3.3 Unit operations

The next step is to transform these tasks into unit operations. This does not mean that there is a one to one relation between a task and a unit operation. Often various tasks can be carried out in a single unit operation. The operating conditions of these unit operations should be designed such that the tasks are fulfilled. Similar to the method proposed by Douglas (1988), (short-cut) process and physical property models and heuristics are used for the decision making. For instance, assume that an identified task is to size reduce the droplets of an emulsion to a diameter of about 8 μm. For the selection of the emulsification device heuristics can be used, leading to the selection of a colloid mill. The model presented by Wieringa et al (1996) can then be used to design the colloid mill.

4. Example

Consider the following real life example of a process for a specific product "P". This product is an oil-in-water emulsion with a droplet size of about 2μm. The emulsion is stabilised by two different emulsifiers, "E1" and "E2". E1 is a so-called small emulsifier and E2 a so-called big emulsifier. The product developer specifies the levels of the oil, E1 and E2 and the water phase.
The existing process is shown schematically in Figure 1. It consists of the following processing steps:

- mixing of all ingredients
- homogenisation
- pasteurisation
- cooling
- maturation

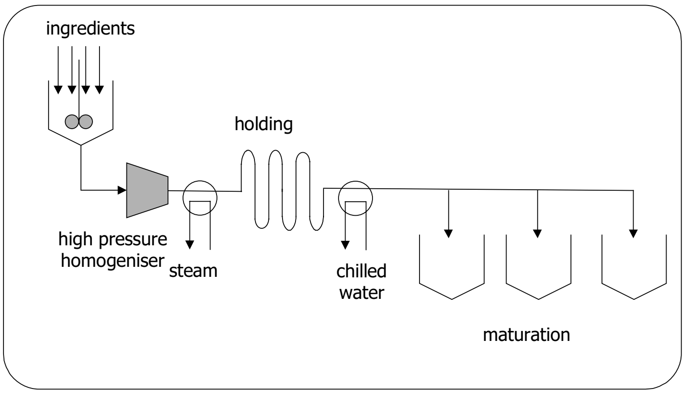

Figure 1. Process flow diagram

The maturation step was considered to be the bottleneck of the process. The residence time in this process takes up to 6 hours, limiting the flexibility of the plant. Moreover this capital costs for this part were expensive due to hygienic requirements

4.1 Input/output structure

We want to make a specific oil in water emulsion. The oil droplet size should be around 2μm. The emulsion is stabilised by two different emulsifiers, E1 and E2. The product developer specifies the levels of the oil, E1 and E2 and the water phase. The microstructure is shown schematically in Figure 2.

4.2 Task identification

A detailed study of the existing process revealed that the following tasks were associated to the processing steps:

- mixing of ingredients — dispersing of oil in water
- homogenisation — size reduction of the oil
- pasteurisation — bug killing
- cooling — cooling
- maturation — creation of the desired interfacial composition

Especially the last step, maturation, might need a little more explanation. The homogenisation takes place at elevated temperatures. It was found that at these temperatures E1 and E2 have the same interfacial activity. However, because of kinetic reasons the surface was almost completely covered with E1. At the temperature achieved after cooling the thermodynamic activity of E2 is preferred over E1. So after cooling part of E1 is desorbed from the interface and exchanged with E2. However in the current maturation process this exchange is a thermodynamically driven slow process. The final product after maturation has the thermodynamic optimum. So the maturation process would not be required if a limited amount of E1 is present during emulsification. The remaining E1 would then be post-dosed, after cooling. Figure 3 shows this process schematically.

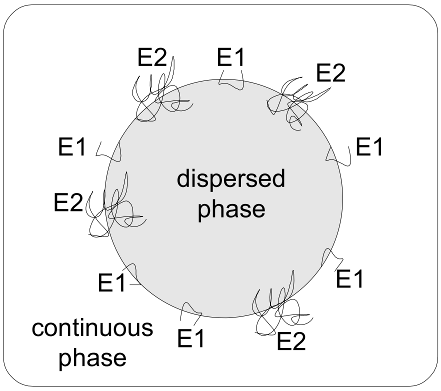

Figure 2. Schematic representation of product microstructure.

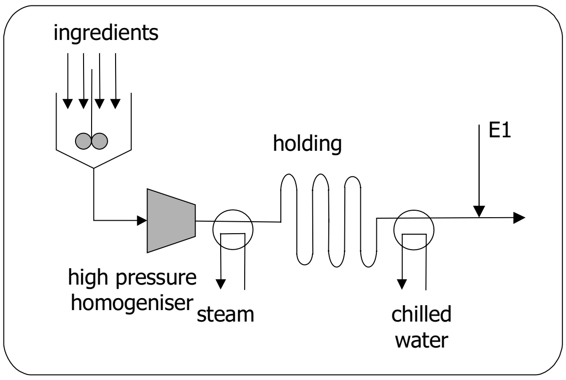

Figure 3. Schematic overview of alternative process

4.3 Evaluation

Some initial experiments have been conducted to show the feasibility of the alternative process. The results showed that the final microstructure is dependent on the level of E1 post-dosed. Too high levels of post dosing led to an emulsion with a too high droplet

size. However, at certain intermediate levels, similar product attributes were achieved without the maturation process.
An economic evaluation of this alternative process showed that for a grass roots design, the capital costs could be reduced with about 25% by applying the concept of process synthesis.

5. Research Challenges

The example presented in section 4 showed that process synthesis can have a huge value for the food industry. However there are still various hurdles for further introduction of this technology in the food industry:

- There is a need for process models that describe the product microstructure as a function of the processing conditions.
- The example presented was aimed at a single product process. Multi-product processes will increase the complexity of the problem. Especially when the different products also have different microstructures. Scheduling could become an essential aspect of the design process.
- The quality of the final product is partly determined by the hygiene/cleaning systems in the factory. So aspects like modelling of microbiological growth and decontamination and soil removal and the hygiene level in the process become essential.

Further developments in these area's will certainly lead to increased application of process synthesis within the food industry.

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