Sustainable Production of Food

Prof. dr *ir.* Albert van der Padt

Inaugural lecture upon taking up the post of Special Professor of Sustainable production of food at Wageningen University on 13 March 2014

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Rector Magnificus, colleagues, family and friends

The mission of the Wageningen University, our University, reads: *'To explore the potential of nature to improve the quality of life'*. To reach this goal, research at the Wageningen University covers the food chain from farm to fork. Plant and Animal Sciences are aiming at optimal production of crops and livestock in a sustainable manner. Land and water management is being optimized at Environmental Sciences aiming at minimal soil losses caused by farming. The transformation of agro-materials into food, feed, consumables and/or fuels is explored at the Agrotechnology & Food Science Group. Part of this group is the Food Process Engineering Group, host of the chair: Sustainable Production of Food. As depicted, Food Process Engineering is only a tiny link in the food system, but an essential link that enables us to pick our food with our fork.

The Food Process Engineering Group searches for sustainable food processing techniques, both for isolation and purification of food components as well as for structuring of food. For this, knowledge is gained on morphology, physics and thermodynamics of food. This knowledge is then utilized to understand the process phenomena, leading to new separation and structuring principles. Integrating these new systems with conventional systems and translating them into the food manufacturing chain is the focus of the chair on Sustainable Production of Food.
To arrive at a more sustainable production of food, two topics are essential:
1) complete utilization of the agro-feedstock and
2) running each separation or conversion step at the best operation point at the right location in the processing network.

To find the optimal operation set point of the different processes within the food manufacturing network, we will make use of the approach developed in the Food Process Engineering Group headed by Prof. Boom. Based on the knowledge of the morphology, physics and thermodynamics of the product, the window of operation of the current technologies may even be stretched wider, and new operating set points may be found. The search for the most eco-effective agro-industry network can be adapted from the chemical industry. The ambition is to adapt this methodology as developed for chemical processing, the so-called product-driven process synthesis, and redirect it to the sustainable production of food, optimized for optimal agro-material usage. Not only for the primary food production itself, but also for all the other streams.

First, I will look back into the history of food industry and I will discuss the current situation thereof. Next, I will compare it to the developments in the chemical industry. Finally, I will discuss how we can evolve these methodologies to enable the sustainable production of food.

The food process engineering roadmap in retrospect

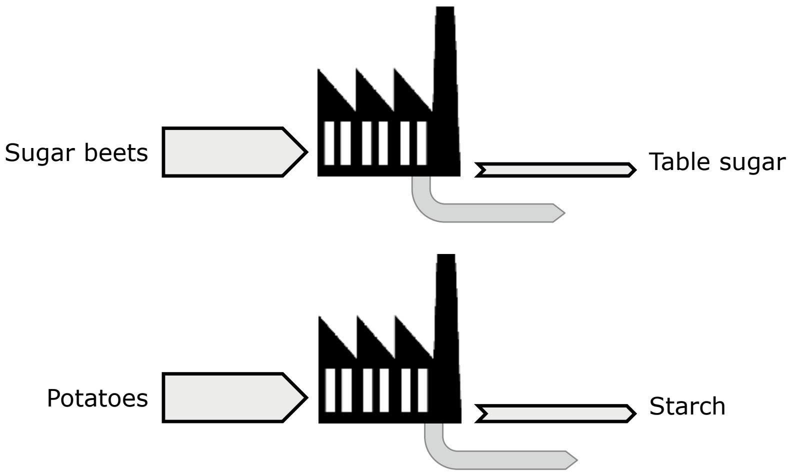

Figure 1. Conventional business model was focussed on a single product, this resulted in a food system with (single) products and many by-products.

Traditionally, food process engineering is about the transformation of agro-feedstock into nutritious and safe food. In the early 20th century the general concept was to extract only one product from the agro-feedstock, for example, sugar from sugar beets, starch from potatoes, while the remainder was regarded as waste. In Europe at that time, there was no need to intensify the use of the agro-feedstock since the population density was relatively in balance with the local production; there were hardly any environmental restrictions and there were ample resources. In the midst of the 20th century the population increased in the so-called western world and the food chain was forced to increase in capacity. Increasing knowledge led to further optimization of the concept of one crop – one product; beets for sugar, potatoes for starch (Figure 1).

Although the world population has doubled since 1960, the mechanization, pest management and availability of fertilisers have enabled an increased food production while the agro-feedstock prices dropped [6]. This induced a drop in consumer prices. The margins in the industry became very tight. This forced the food industry to become more efficient. However, the infrastructure of the food industry was based on the concept of one crop for one product, and therefore, the industry chose for optimization of unit operations that lead to better yields of the same product to get more out of the same agro-feedstock. This is indicated by the top arrow in Figure 2.

However, there is only a certain amount of primary product available in a raw material. To get even more value out of the raw material, the next logical step taken was to look at the other streams. Sugar beet pulp became used for yeast production and later on for ethanol production, potato proteins out of the potato fruit juice, and food-grade whey products out of whey. In addition, the industrialisation and the growing population put more and more stress on the environment, and therefore the industry was forced to further reduce its waste streams. The traditional food process engineering solutions failed, and a switch in mind set was required.

The industry started to think in components, these components could be used further downstream for the formulation of end products (Figure 2, centre arrow). This development made it possible to switch from the traditional agro-industry to an industrial approach of product assembly, that does not rely on harvested crops or cattle, but on the use of ingredients that can be purchased at the global market. Examples thereof are Unilever, Nestlé and Coca-Cola.
For the food assembly industry, a raw material utilization of 100% is theoretically achievable. This segment of the food industry started to use the concept of product-driven process synthesis for the production of food [3,5]. This methodology starts with assessing the consumers' needs, and then systematically maps and optimizes the most efficient routes to arrive at these products. Not only the process is optimized, also the sourcing of raw materials is taken into account.

However, the agro-industry cannot pick its raw materials: it is based on the processing of a single resource. Sugar beets do not contain only sucrose but also other sugars, proteins, cellulose, lignin and salts [10]. To arrive at sustainability in the food industry, all those components need to be used for high-value products. Thus the agro-feedstock usage must become eco-effective [4]. This implies that not only the quality of the primary product must be safeguarded, also the quality of all other components must be maintained or enhanced to enable the usage of those components to produce other high-value products. Since all components of the raw material are used as input for other products or processes, no waste streams are

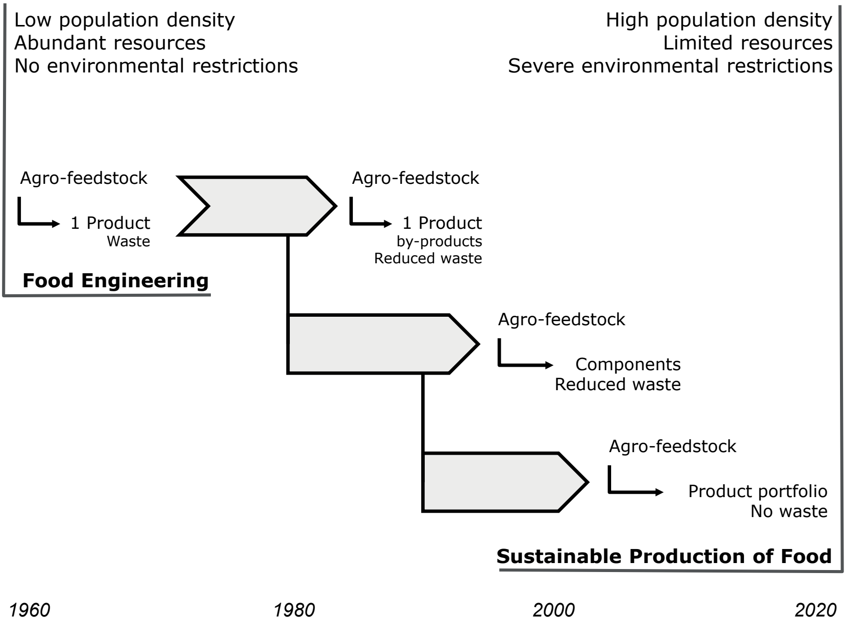

Figure 2. Plot of development of food engineering towards sustainable production of food.

produced. This cannot be done by simply adding extra steps at the end of current processes. The food industry must find new routes to arrive at a new product portfolio resulting in no waste (shown at the bottom right of Figure 2). This implies that the agro-industry must change and extend its core business; from food commodity supplier towards multi-product supplier of both food and non-food products, ingredients and/or materials.

However, there are no common practices for the food industry to achieve this. It is a gap in the field of food process engineering. Therefore, it is good to look at other disciplines and learn, for instance, from chemical engineering.

Developments in chemical engineering

At the first half of the 20th century, the process industry was built on the unit operation concept as well. The chemical industry focussed on the production of single products (base chemicals, industrial materials or final products) and could optimize the whole process chain by making use of a production network of optimized unit operations.

This methodology was introduced by Arthur D. Little in 1915. A unit operation is a standardized basic step, that does one specific task: for example, distilling a mixture in two different mixtures; heating or cooling a stream, or drying a slurry into a powder. The concept is that a production process consists of a number of these unit operations in series. The strength of this methodology is that, since a unit operation does only one task, it can be optimized easily. Combining a series of these well-optimized unit operations then will arrive at a well-optimized production process.

Therefore, at the first half of the 20th century, most of research into processes was related to these unit operations, and it was approached as well-defined sub-problems at the so-called meso-scale [11]. New designs for unit operations were based on previous solutions, combined with guessing and some extra experimental work on how the system might work better (Figure 3).

In the midst of the 20^{th} century, competition forced the industry to start utilizing effluent streams instead of simply discarding them. Chemical factories were adapted to deliver a limited set of by-products besides the major product. However, unit operations are always optimized for the prime product. But if a manufacturing network needs to make more than one product, each unit operation influences the performance of the others. Therefore, a simple series of individual optimized unit operations does not lead to the optimal process anymore.

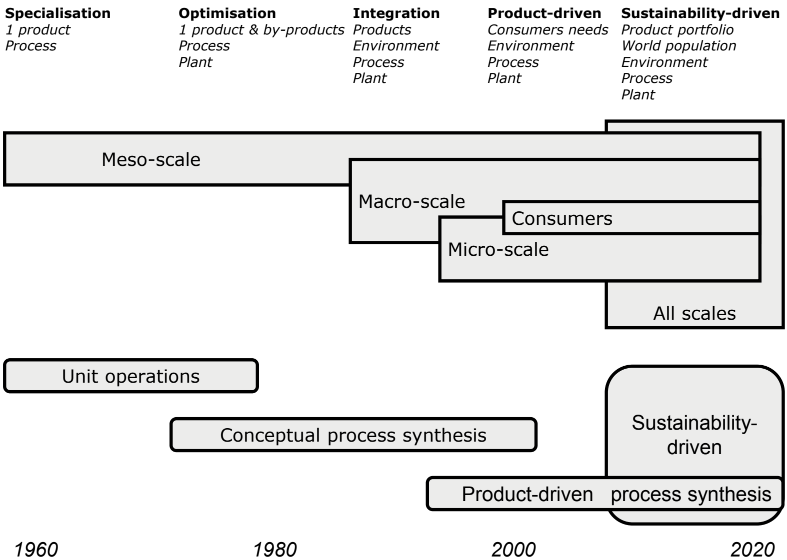

Figure 3. Process synthesis history.

Conceptual process synthesis was developed and used for the integral optimization of product and by-product streams. This approach is based on systematically evaluating possible conceptual flow sheets of a superstructure of them [7, 13]. In the 1990's, the stricter environmental legislation induced the method in conceptual process synthesis to take into account how the production would affect the environment of the process, this is known as conceptual process synthesis at macro-scale level [11]. Since then, the manufacturing network should include processes or precautions that reduce the impact on the environment and their effect on the cost function.

At around the beginning of the 1990, it was assumed that the equipment and operating data were given. Therefore, many process flow sheets were available and could be analysed. However, if only product specifications are known and no manufacturing process has been conceived yet, or none of the existing equipment can meet the environmental restrictions that are posed, new processes and new manufacturing routes must be found. This development coincided with significant scientific breakthroughs at the micro-scale. Better insight at the molecular level contributed to the development of intensified processes and consumer-tailored products [11]. This made that the conceptual process synthesis field was changed into the product-driven process synthesis [8].

These developments were headed by the chemical industry; even though around 1990 the food industry picked up these technologies [5] and the methodology was further developed by Bruin and co-workers at the Technical University of Eindhoven for the business-to-consumer food industry. Bongers and co-workers added the appreciation of the product by the consumers and coupled these to the desired product attributes [2, 3]. They showed that for consumer food products, both the micro- and nano-structure are very important for the appreciation of the product by the consumer. Therefore, these attributes must be considered in the determination of the optimal manufacturing route. For the food industry that assembles the products from ingredients, and thus create the micro- and nano-structure, product-driven process synthesis is the search of the proper processes combined with the search for available components and/or ingredients to arrive at these adequate structures. This route works for the assembly industry, for both the production of food and non-food. It helps finding the most effective way to satisfy the wishes of consumers, the optimal plant can be designed from gate to gate.

In other words, product-driven process synthesis is the search for the optimal starting point and production route to finally obtain the desired consumer product. This is analogous to a navigation system: you put in exactly where you want to

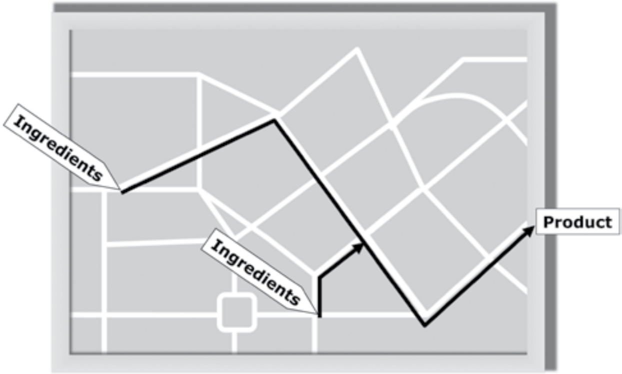

Figure 4. Product-driven process synthesis is like a navigation system, you determine the final product, the method determines where to start and how to go.

arrive, and then the navigation system determines your starting points, the means you need to have (a car, bike or plain) and the route you have to go for (Figure 4). Such a methodology is possible for a system that produces a single product. For the total agro-food production system, however, the question arises whether this is the most effective way for ensuring complete high-value usage of the agro-materials.

To meet our future societal challenges on sustainability and eco-effectiveness, all input materials must be converted into valuable products. Hence, neither degraded streams nor waste streams will be allowed. The agro-industry must thus find new routes to arrive at a new product portfolio that only includes high value products and no side streams. This is illustrated in Figure 5, here, a new multi-path navigation

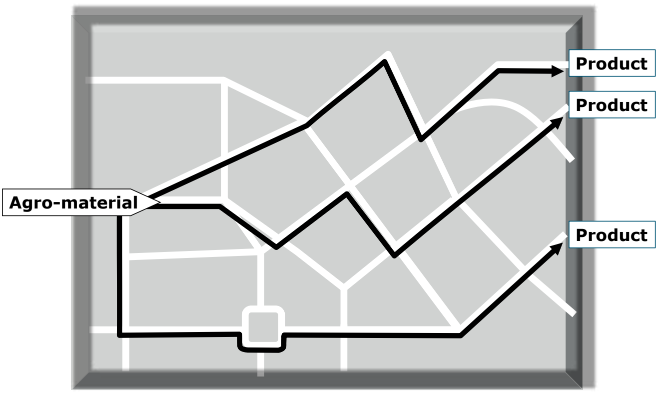

Figure 5. Sustainability-driven process synthesis is like a multi-path navigation system determining the optimal set of routes arriving at the product portfolio that best utilizes all parts of the agro-material.

system determines the optimal set of routes arriving at the product portfolio that best utilizes all parts of the agro-material. However, in most cases, not all parts of the crop are suitable for food. Those other parts can be used for the production of feed, as input for the pharmaceutical industry, the fibres could be used for the production of paper or fabrics and it could be used as input for the production of chemicals and of fuels; in other words for the bio-based economy.

For the sustainable production of food, we need to develop a systematic approach to find new routes to arrive at the most eco-effective product portfolio for a specific agro-material. This approach I will call: 'sustainability-driven process synthesis', and this finalizes our overview of the history of process synthesis as given in Figure 3. To be successful, it is essential to first extract those fractions with the highest value, but in this case one should not destroy the quality of the remaining fractions. Here lies the challenge for the sustainable production of food, to revise agro-material processing such that all of the raw material is used in highly valuable products, by mild processing, sequentially separating the fractions with the highest value, such that all fractions find use as food, feed or non-food products (Figure 6).

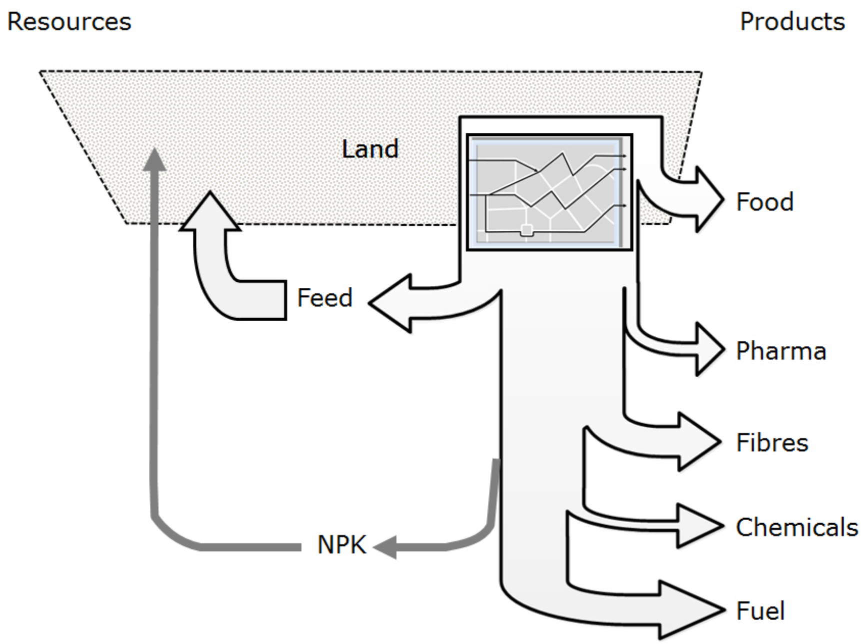

Figure 6. Optimal agro-feedstock usage for food, feed and non-food applications.

Ambition for the sustainable production of food

We can only achieve complete and sustainable use of all the raw materials, by integrating the agro-food production chain. The agro-material must be the starting point to abstract the most eco-effective product portfolio. This portfolio is the input for the design of the processing network. In this way, we reverse the product-driven process synthesis as described by Bongers and co-workers [2, 3]. We intend to evolve this into a sustainability-driven process synthesis. For this, we collaborate with the group of Professor van der Vorst, of the Operations Research and Logistics Group of this University. The objective here is to develop a methodology to systematically synthesize the optimal routes for processing agro-materials into the most optimal product portfolio with minimal degradation and (almost) no low-value side streams.

In my opinion, the product portfolio that can be potentially created out of a given raw material is hidden in the composition and structure of that raw agro-material and could be described by its key functional properties. These functional properties of both the agro-material and its associated product portfolio will be defined and developed together with the industrial partners of the ISPT cluster on Complex Molecule Separation and Protein Processing. The functional properties of the agro-material will be input for a decision support system determining the potential of the agro-material and from this it will derive the associated product portfolio (Figure 7). This is the first step of sustainability-driven process synthesis.

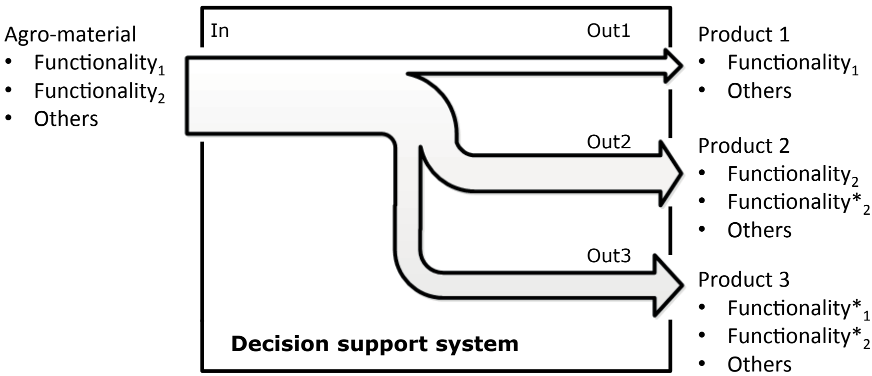

Figure 7. Sustainability-driven process synthesis starts by defining the functional properties that is based on the composition and structure of the raw agro-material. A decision support system determines the associated product portfolio.

Next, a production network has to be designed that can convert the agro-materials into the identified product portfolio (Figure 8). This could be done using four major classes of processes as identified by Bruin [5]: separation (or fractionation), structuring, transformation and stabilization:

Separation processes are needed to take apart the raw material into fractions that contain the right functional properties needed to arrive at the perceived product portfolio. Typical processes for the food industry are centrifugation, classification, extraction, filtration, membrane based processes and chromatography.

Structuring processes are of major importance for the properties of a food. When ingredients or components are combined that are not molecular soluble, a micro- and nano-scale structure is created using a structuring or texturizing processes. This internal structure is often key for the desired product functionality. Classic structuring processes are for example crystallization, homogenization, foaming, granulation, agglomeration, spray drying and extrusion.

Transformation processes involve reactions to convert the raw material in a digestible appreciated food. Typical conversion processes that are used are baking, cooking, roasting or fermentation, but one may also think of enzymatic synthesis of oligosaccharides or protein hydrolysates, important ingredients for infant formulae. Here the biofunctionality is changed adding value to the raw material.

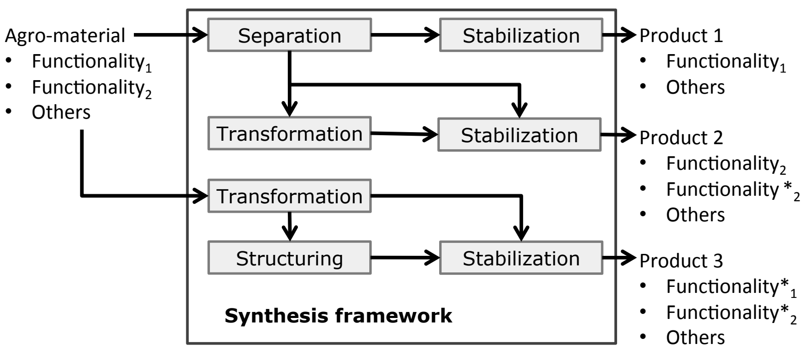

Figure 8. A design analysis and synthesis framework helps to systematically combine separation, structuring, transformation and stabilization into a system that optimally produces a range of high-quality products.

Stabilization processes protect the food from spoilage. In the food industry often heat is applied to eliminate microorganisms and destroy residual enzyme activity. However, one sees more and more milder processes, such as microfiltration membranes or the application of high pressure processes or electric pulses. Another approach is to reduce the water activity to such a level that no spoilage will occur.

A design analysis and synthesis framework will be created to systematically combine these processes into conceptual systems that optimally convert the agro-material into the associated product portfolio while retaining the native quality and functionality of the constituents. This is the second step of sustainability-driven process synthesis. Now, for each of the four process classes, scenarios of various separation, structuring, transformation and stabilization processes must be identified. This must include existing processes, but many of those processes do not allow the required conversions without degrading the materials at the same time. Therefore, also new processes that are still under development have to be included, as well as new targets for current technologies. This will guide us not only to new process targets and manufacturing networks, but might also identify process steps that are not yet available.

The construction of the production network could be done using heuristics to select and construct scenarios. The resulting superstructure that comes from these heuristics can then be optimized analogous to the methods as developed for process system engineering [7]. Here we should combine three classes of criteria:
1) product (portfolio) quality and functionality,
2) cost-effectiveness and
3) eco-effectiveness.
This is the final step of sustainability-driven process synthesis leading to truly sustainable processing of agricultural products into highly valuable products.

The optimization of such a superstructure, will only converge towards the best processing network if the effect of each process on the product properties and its functionality is described properly. These process – product interactions determine the efficiency of the system and the window of operation. For an adequate description a proper understanding of these changes is vital. The product of course will obey the laws of thermodynamics and will stay within the physical boundaries. But for agro-materials, thermodynamics and physics are often not so easy to quantify, this is due to their complex micro- and nano-structure that is so important for their appreciation by the consumer.

Figure 9. Wordle™ compiled from the titles of the papers on membrane filtration found by Scopus, leaving out the Scopus search keywords. The size of the words is proportional to number of papers it is mentioned in the title (Scopus search (last 10 years) on ('Membrane' and 'Filtration') hits on over 40000 papers, if this search is narrowed down by adding AND ('food' OR 'dairy' OR 'enzyme' OR 'protein') 20000 hits remain.

For products that are treated with membrane separation, this is illustrated by the Wordle™, compiled from the titles of the papers on membrane filtration in Scopus (Figure 9). Three words attract the attention: fouling, water and desalination.

- Water is the major component that is handled with membrane processing, not the food components themselves.
- Many papers deal with fouling, which is the clearest example of process - product interaction. Due to the membrane properties and the processing conditions, the product degrades and fouls the membrane, which degrades the process efficiency in turn. Most publications discuss the modification of the membrane to reduce the interaction with the product to overcome fouling for this membrane.
- Desalination is of course all about water but also deals with thermodynamics of minerals: their insolubility induces scaling and the osmotic pressure that they induce has to be overcome by the transmembrane pressure. Again, process – product interaction *pur sang*.

It is remarkable that these studies describe the process – product interactions based on the direct interaction of one of the constituents with one part of the process, in this case, the membrane. There is hardly any attempt to create a more comprehensive idea of the properties and behaviour of the feedstock during processing, if this is known, you could then adapt the processes to avoid degradation of product and process. However, many researchers are focussed on circumventing these physical hurdles and thus stretching the window of operation. For this an additional driving force is implemented and integrated in a process. For example, one may use additional shear fields in membrane systems to reduce fouling and thus increasing capacity [9], or one can apply an electrical potential over a membrane system or over an ion exchange column to increase its selectivity and/or capacity [1, 14], or use ultrasound that is combined with pasteurisation, drying, membrane filtration or freezing systems to increase the capacity and in other cases to reduce the harshness of the conditions that are needed to achieve stabilization [12]. These papers show that for some applications this approach is effective, but for others it is not.

In the last 15 years, the Food Process Engineering Group took another approach to develop new sustainable food processes. As mentioned before, the starting point is the processed material. The morphology, physics and thermodynamics of the feedstock are studied and this knowledge is applied to underpin the process dynamics. These insights are then translated towards new processes for sustainable production of foods and food ingredients.

This approach can also be used for existing processes to extend the window of operation. To find new set points for separation processes, an inventory of the physical parameters that determine the mobility of the molecule of interest in the matrix must be made and the essential physical phenomena must be measured and modelled. Based on the properties of the agro-material and its behaviour during processing, the movement of the target component in the process system is then described.

Knowing these phenomena, optimal process conditions and the right equipment size for successful fractionation can be derived, and it would not surprise me that these are far away from the present settings. In addition, this knowledge gives input on the decision which additional driving force could be effective to outperform the current window of operation. Whether this is shear, vibration, ultrasound, or an electrical potential cannot been foreseen at this moment in time, but this will arise naturally from understanding the dynamics of the components in the feedstock.
We will apply this strategy to develop a mild fractionation bio-refinery of solid raw materials, to put membrane fractionation systems and chromatographic systems at work for agro-materials at high viscosities. These projects will be done together with dr van der Goot and dr Janssen of the Food Process Engineering Group, guaranteeing a strong base in this group. These projects are financed by the Institute of Sustainable Process Technology. Within this framework we will collaborate with dr Boon and

dr Bussmann of TNO on chromatography and we are ensured of industrial input via the industrial partners of the cluster Complex Molecule Separation and Protein Processing.

Education responsibility

I just described that my research will be focused on the transition of an efficient food process chain towards the sustainable use of food raw materials, an eco-effective step within the agro-material processing chain. The crux is to make 100% usage of the agro-material, not only for the food itself, but also for all other streams.
As described above, the methodology of sustainability-driven process synthesis is not straightforward. In fact, it is not even here, yet. So, how should we educate the new scientists and researchers that should realize this concept in industry. Should we wait until it is there and ready to be implemented in an advanced course? Or is there already a way to begin?

I think that we should basically achieve a change in mind-set. This must also be our aim in education, starting even at BSc level. Last year we have changed the approach of the traditional Food Process Engineering course. Instead of teaching the mass transfer and energy balances of four important but classical unit operations, we now teach what the properties of the agro-materials are, and how they behave while being processed. So we start with an agro-material and its main components, water, fat if any, protein, carbohydrates, salts and fibres and from understanding their basic functionalities, the students design themselves a production network that fully utilizes the agro-material and converts it into a certain product portfolio. Very simple, very basic, but it points towards the future. We discuss and assess different scenarios based on the amount of energy that is required for the production of the various product portfolios. By doing this themselves, students learn to understand that for a certain agro-material there is an associated product portfolio and they know that you have to evaluate different process scenarios to arrive at a sustainable portfolio of products from a certain raw material.

Ladies and gentlemen, today I discussed the transition that is needed to arrive at the sustainable production of food. For this, we will develop the sustainability-driven process synthesis methodology to systematically design eco-effective production networks for safe food. To reach optimal production, new set points for the processes must be derived based on knowledge of the properties of the agro-material and its behaviour during processing. Currently, we are implementing a very basic version of this line of thought in our education programme. This way of education will prepare our students for the challenges of tomorrow. Here, I conclude my lecture.

Acknowledgement/Dankwoord

I gratefully thank the board of the University and the Appointing committee for giving me the honour and opportunity to take the position of special professor at the Wageningen University. I feel proud and privileged to be in this position and I thank Remko Boom for his support and never-ending enthusiasm to get me on board.
I want to thank the Food Process Engineering group for their warm welcome and all the help to get me on track. I want to thank Anja Janssen, Marlies Geerts, Atze Jan van der Goot and Jacqueline Bloemhof, Jochem Jonkman and Jack van der Vorst for joining my research programme even before it started.

Special thanks for my colleagues at FrieslandCampina, to start with Tom van Hengstum who made it possible for me to be here. I want to thank Emmo Meijer for having confidence in me and giving me the chance to set-up my own field of research at the Wageningen University. Colleagues of Global Process Technology R&D, Innovation, DGS and MVA, thanks for your continuous support and for being here today.

For the final part of this acknowledgement, allow me to switch to Dutch.
Ik wil mijn familie en vrienden bedanken voor jullie steun en interesse, niet alleen vandaag, maar juist door de jaren heen. Fijn dat jullie erbij zijn.

In het bijzonder wil ik mijn ouders bedanken voor het feit jullie altijd hebben geloofd in mijn kunnen en vertrouwen hebben gehad in mijn keuzes. Mede door jullie inzet is het, ondanks het schooladvies, geen Lagere Tuinbouwschool geworden.

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Tenslotte, Mieke, jou wil ik bedanken voor je steun door dik en dun, voor je oprechte mening en voor de talloze mooie momenten die we samen hebben.

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'Traditionally, food process engineering is about the transformation of an agro-material into one specific food product. The challenge for Sustainable Production of Food, is to revise this way of food manufacturing towards an eco-effective production network for safe food, taken into account the streams that will be used for the bio-based economy. Development of Agro-material based Product portfolio driven Process Synthesis methodology is essential and will lead to new routes with a new product portfolio and hardly any waste.'

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