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Quantitative environmental and economic sustainability analyses of food supply chains: The case of novel dairy products

Verena Depping

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Abstract

Environmental sustainability of supply chains is playing an increasingly important role within the food industry. The present thesis covers three food-related topics and quantitatively investigates environmental sustainability and integrated environmental and economic sustainability along the supply chain. It addresses sustainability at an early stage of product development, in order to attenuate products' undesired impacts. The thesis is based on an interdisciplinary research project that developed novel milk concentrates as substitutes for milk powders, one of the current key intermediate products in the dairy sector.

The thesis, firstly, analyzes the environmental-impact reduction potential of milk concentrates. For this purpose, a comparative, attributional life cycle assessment was conducted. The findings highlight the environmental-impact advantage of most milk concentrates compared to milk powders. The best concentrate option saves up to 35% of the cumulative energy demand. Concentrates are found to be environmentally advantageous, even if they are trucked up to 1,000 km. The introduction of milk concentrates, however, causes a significant reduction of product shelf life that is common for more environmentally sustainable manufacturing processes. Therefore, this thesis, secondly, evaluates the impact of shelf life on the tradeoff between economic and environmental objectives with the aid of a multi-objective optimization model and a rolling horizon scheme that captures product price uncertainty. Results show that the economic value of shelf life is only 1.1% and therewith not a strong argument against the substitution of powders with more environmentally sustainable concentrates. Since fractionation is increasingly applied in the process industries, this thesis, thirdly, evaluates the environmental impacts of fractionated milk concentrates and their non-fractionated counterpart. For this purpose, a generic scope-definition framework was developed that tackles multi-product processes, such as fractionation processes, and is separated into attributional life cycle assessment and consequential life cycle assessment. Findings show that the environmental assessment of milk fractionation depends on the respective application (milk-casein-based products vs. lactose-free products).

Overall, this thesis demonstrates the value of applying quantitative sustainability assessments to product development and processing-technology selection. It identifies the frame within which milk concentrates are an environmentally and economically advantageous substitution for milk powder and explores potentials and limitations for comparing fractionated and non-fractionated products under the criterion of environmental sustainability.

Zusammenfassung

Nachhaltige Wertschöpfungsketten spielen eine zunehmend wichtige Rolle in der Lebensmittelindustrie. Die vorliegende Dissertation betrachtet Nachhaltigkeit in einem frühen Produktentwicklungsstadium und bewertet neue Prozesse und Produkte hinsichtlich ihrer Umweltwirkungen und Profitabilität. Zentrale Grundlage der Arbeit ist ein interdisziplinäres Forschungsprojekt im Milchsektor im Rahmen dessen neuartige Milchkonzentrate als Ersatz für derzeit marktübliche Milchpulver entwickelt wurden.

Die Arbeit untersucht zunächst Umweltentlastungseffekte durch neuartige Milchkonzentrate mit Hilfe einer vergleichenden Umweltbilanzierung. Die Ergebnisse verdeutlichen die ökologische Überlegenheit von Milchkonzentraten gegenüber Milchpulvern. Bei einer Weiterverarbeitung am selben Standort kann durch Milchkonzentrate bis zu 35% des kumulierten Energiebedarfs eingespart werden; sie sind bis zu einer Transportdistanz von ca. 1000 km ökologisch vorteilhaft. Allerdings geht die Einführung umweltfreundlicherer Milchkonzentraten mit einer reduzierten Produkthaltbarkeit einher. Dieser Zusammenhang kann oft bei der Herstellung von Lebensmitteln beobachtet werden. Für die strategische Auswahl neuer, umweltfreundlicher Prozesse und Produkte ist deshalb entscheidend, den Einfluss der Produkthaltbarkeit auf ökonomische und ökologische Ziele zu bestimmen. Das hierfür entwickelte Analysekonzept beinhaltet ein mehrkriterielles Optimierungsmodell, eine Methode zur Zielreduktion und einen rollierenden Zeithorizont. Die Ergebnisse zeigen, dass der ökonomische Wert von Produkthaltbarkeit mit 1.1% kein starkes Argument gegen die Einführung von Milchkonzentraten ist. In einer weiterführenden Analyse wurden fraktionierte Milchkonzentrate betrachtet, da Fraktionierung zunehmend in der Prozessindustrie eingesetzt wird. Die Arbeit stellt einen generischen Ansatz vor, der eine vergleichende Umweltbilanzierung von fraktionierten und nicht-fraktionierten Produkten ermöglicht. Für Milchprodukte zeigen die Ergebnisse, dass die ökologische Tragfähigkeit fraktionierter Milchkonzentrate von deren jeweiliger Anwendung abhängen. Der Ansatz ist für zukünftige Studien interessant, die sich mit Mehrproduktprozessen in Umweltbilanzierungen befassen.

Die Arbeit verdeutlicht den Wert einer frühzeitigen Nachhaltigkeitsbeurteilung von Produktdesigns und Verfahrensentwicklungen. Sie identifiziert den Rahmen, innerhalb dessen eine Substituierung von Milchpulvern durch Milchkonzentrate ökologisch und ökonomisch vorteilhaft ist. Darüber hinaus ergründet die Arbeit, welche Möglichkeiten und Grenzen Umweltbilanzierungen bieten, um fraktionierte und nicht-fraktionierte Produkte zu vergleichen.

Acknowledgments

At the end of this project, I would like to thank all the people who contributed along the way.

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Throughout my PhD project, I supervised various thesis students with who I enjoyed discussing, among others, Franziska Roth, Florian Grodeke, Christian Kürzl, Christina Gschwendtner, Christian Jonas, and Lukas Wiesmeier. Thank you for your contributions and commitment!

In addition, I would like to thank all industry contacts, including contact persons at several dairy companies and plant manufacturers, in an anonymous format. Applied research lives from realism; thank you for granting the option of on-site measurements at the dairy plants, for providing data, or for supervising common theses.

I am most grateful to have wonderful friends and family, who supported me throughout this endeavor. Thank you – Lisa, Julia, Carina, Franziska, Caro, Felix, Bode-Bode^2, and Altevers^4 for always holding a keen interest in my pursuits and for making life colorful. I particularly would like to thank my parents; my father for inspiring to take on a scientific perspective early in life and for sharing wholeheartedly and my mother for continuously creating additional time windows to work on this project by picking up our little son. I also would like to thank my family-in-law, Evi, Rainer, and Haiko, who have been rather a second family than in-laws for half of my life. My deepest thanks goes to Jan though, who ironically emphasizes that he did not contribute anything. This might be true, except for all the love through turbulent and happy times. Finally, I would like to thank our son Basti for the never ending source of laughter and happiness we enjoy – or as he himself would frame it: “Ich bin nicht happy, nur glücklich”! In that sense!

Thank you!

Verena Depping

Oberhaching, June 2019

Contents

1 Introduction

1.1 Environmental and economic sustainability of food supply chains

Environmental concerns are playing an increasingly important role for decision makers in companies. Students participating in the Fridays for Future movement and other parties are urging a change in course with regard to climate policy in order to conserve healthy conditions for life on earth. In 2019, the earth overshoot day, which marks the date when humanity's demand for ecological resources in a given year exceeds what earth can regenerate in that year, is estimated to be July 29th (Global Footprint Network, 2019). For the remainder of the year, humanity lives in ecological debt, compromising future generations' ability to meet their needs. In face of the rapidly growing world population, ensuring future healthy living conditions will become even more challenging.

In this context, enhanced environmental sustainability of products is gaining increasing significance in marketing and product sales. Within the food industry, a range of environmental food labels are already available in the B-to-C sector to satisfy novel customer needs or pave the way for acquiring new customers. Prominent examples are food labels that target environmental aspects next to organic production. Moreover, several food labelling schemes focus on CO_2-emissions, such as the *Carbon Reduction Label* that displays the carbon footprint of a product and declares that this footprint will be reduced within the next two years (Ecolabel index, 2018). Several large corporations even have created private food labels that address environmental sustainability (see Greenpeace, 2019).

Environmental sustainability, however, is also becoming more relevant in B-to-B relations, since environmental impacts of final products need to be documented throughout the entire supply chain. Its increasing importance is supported by new technological means of tracking products or product components from their origin to final customers. In addition, monetary incentives and regulations foster the shift towards more sustainable products and processes. Energy-intensive companies, for instance, are partially exempted from the German EEG apportionment and are refunded part of their energy and electricity taxes, in case they gain the DIN EN ISO 50001 certification or an equivalent certificate (UBA, 2018). Certification according to DIN EN ISO 50001, for example can require a reduction of the company-wide energy consumption of 1% per year. Tax reductions are thus coupled with energy-cost reductions. Optimizing on energy efficiency and environmental sustainability therefore often goes hand in hand with profit maximization for the involved companies. This connection will be strengthened, if energy provision becomes more expensive or CO_2-levies are charged.

The interrelation between environment and profit is also visible for food waste. Food waste remains a major challenge in food production. In Germany, a total mass of around 11 million tons of food are wasted per year, of which a share of approximately 22% are related to the production stage (BAFU, 2018; Hafner et al., 2012). Moreover, considering the dairy sector, the loss of 1 liter milk equals the wastewater load of one German citizen for 1.9 days, when assuming a chemical oxygen demand of 230 g per liter milk and a daily average chemical oxygen demand of 120 g per citizen (Gujer, 2007; IFC, 1998). As a consequence, it is essential to find options to reduce food waste from an environmental perspective. These options can consist, for instance, in the optimization of existing processes, the acquisition of new plants, or the development of new and more sustainable products or processing variants. Food-waste reduction, while enabling a more comprehensive utilization of raw materials, therefore can also be a cost factor for companies. When considering food waste, environmental sustainability thus can be in line with economic reasons or constitute a trade-off situation. One recent quest, which addresses both environmental and economic sustainability, is the development of so-called tailor-made products (cf. van der Goot et al., 2016). Tailor-made products require a low degree of processing and a comprehensive usage of product streams by also valorizing potential side or waste streams. These products thus provide means to tackle the challenge of eco-efficiency improvements that companies within the food industry are facing.

Against this background, the present thesis analyzes the possibility to enhance the environmental and economic sustainability of food supply chains. At the core of this thesis is a joint, interdisciplinary research project that developed a new tailor-made product within the dairy sector (Kulozik et al., 2016). The project was conducted in cooperation with the chair of Food and Bioprocess Engineering at the Technical University of Munich as well as two German dairy companies.

1.2 Food industry case from the dairy sector

The goal of the conducted interdisciplinary research project was to substitute milk powders by novel milk concentrates. Milk powders are one of the current key intermediate products in the dairy sector that demand particularly large amounts of energy. Their production includes a drying stage that consumes around 50% of the total energy demand, although product volume is reduced by only around 10% in this stage (Ramírez et al., 2006). Moreover, milk powders are reconstituted before being processed into final products in various applications thereby restoring water removed during energy-intensive drying stage. One alternative to milk powders are milk concentrates, which require no energy-intensive drying. Concentrates can in principle be applied wherever powders are currently being reconstituted, for example when producing yoghurts, ice cream, filled bakery products, or finished meals. Within the research project, a range of different processing variants were developed, using novel combinations of existing processing technologies such as concentration and heating technologies (Dumpler et al., 2018; Dumpler et al., 2017a, 2017b; Dumpler and Kulozik, 2016, 2015). Milk concentrates were designed with various dry-matter contents, such as 20%, 25%, 30%, or 35%.

The developed new product – milk concentrate – exhibits several key trade-offs compared to the current product – milk powder – along the supply chain. Firstly, resource consumption and waste rates differ along the whole supply chain of the products, since manufacturing, storage and transportation (i.e., modes and volumes), as well as downstream processing at the customers are altered. Secondly, the shelf life of the new product is significantly lower. Depending on the selected processing variant, the shelf life of concentrates ranges from 9 to 50 days under predominantly chilled storage conditions. By contrast, milk powders have up to two years shelf life and can be stored under ambient conditions. Thirdly, the various environmental indicators required next to the economic indicator to comprehensively analyze the transition to the new product, can be non-congruent. For an evaluation of the products and processing variants, it is consequently important to account for these inherent trade-offs. Figure 1.1 illustrates the supply chains of milk powders and milk concentrates.

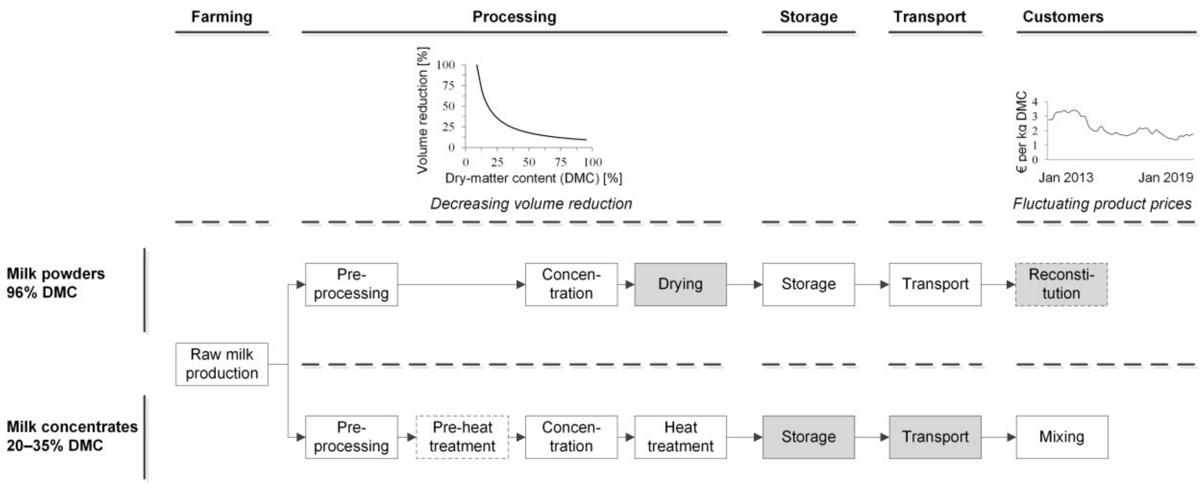

Figure 1.1. Overview of the supply chains for milk powders and milk concentrates. Gray boxes are processes that are particularly important for the trade-off between milk powders and milk concentrates, boxes with dashed lines represent optional processes.

From this project, a follow-up project resulted that considered fractionated milk concentrates. Fractionation is increasingly applied within the dairy sector to extract specific product components. The resulting specified products can be potentially sold to different customer groups and increase the value of the identical input material – milk. Skim milk, for instance, can be fractionated to produce *micellar-casein concentrate*, *whey-protein concentrate*, and *lactose*. While the fractionated-protein products are typically supplied in a powdered form, liquid concentrates also have been investigated recently (Marx et al., 2018; Marx and Kulozik, 2018a, 2018b). The choice between fractionated or non-fractionated milk concentrates therefore constitutes a future trade-off.

1.3 Research objectives

The overall goal of this thesis is to extend knowledge on the sustainability of food supply chains with the aid of quantitative analyses. The thesis covers three topics that address either environmental sustainability or integrated environmental and economic sustainability by considering cases of new product developments in the dairy sector.

Early consideration of sustainability in product development can achieve significant environmental benefits. The food industry is particularly suitable for attenuating products' undesired environmental impacts at an early stage, since new products are often generated by combining and operating existing processing steps in novel ways. This is also the case for milk concentrates, which can be produced with a range of different processing variants to different final dry-matter contents. The environmental impacts resulting from a switch from milk powders to milk concentrates thus can already be analyzed in product development. Applying a supply-chain perspective is essential when comparing the products, since both downstream stages (i.e., transportation and processing at the customers) and upstream stages (i.e., raw milk production) are affected by the transition. Transportation to the customer moreover is a major variable in this product comparison. This thesis therefore addresses the following research question:

RQ1: Are novel milk concentrates environmentally advantageous compared to traditional milk powders along the supply chain? Which product option should be chosen and to what extent does the optimal product choice depend on the transportation distance?

The introduction of new and more sustainable manufacturing processes often goes along with a reduction of product shelf life. This is also the case when more moderate heat treatments are applied, like for the replacement of milk powders with milk concentrates. In case of price fluctuations, shelf-life-reduced products can negatively affect the economic performance due to limited storage duration. These products thus offer a reduced possibility to delay sales until higher price levels are reached. For milk powders and milk concentrates the economic value of shelf life is particularly relevant, since product prices on the dairy market have been fluctuating strongly in the past years (Eurostat, 2016). By contrast, the environmental impacts of products increase with longer shelf lives and longer storage durations. For the strategic choice of more environmentally sustainable processes and products, it is thus necessary to comprehensively determine the impact of shelf life on the trade-off between the economic and environmental performance. This results in the next research question:

RQ2: From an integrated economic and environmental perspective, should traditional milk powders be substituted with novel milk concentrates? Is the decision impacted by the value of shelf life?

Fractionated products typically are the results of multi-product processes. When applying life cycle assessments (LCA) to comprehensively assess environmental impacts along the value chain, two key issues arise relating to multi-product processes: functional-unit definition and by-product handling. Addressing these issues is particularly difficult for the special case of comparing fractionated and non-fractionated products. Since fractionation processes can yield specific functionalities that might be obtained exclusively by the respective process, a trade-off has to be found between functionality and comparability within the functional-unit definition. Challenges related to joint multi-product processes moreover have to be addressed differently for attributional LCA (ALCA) and consequential LCA (CLCA). The case of fractionated and non-fractionated milk concentrates exemplifies the inherent challenges. This leads to the final research question in this thesis:

RQ3: How can fractionated and non-fractionated products be compared with the aid of life cycle assessment? Are fractionated milk concentrates environmentally viable?

1.4 Thesis outline

The thesis is organized as a collection of three research papers that focus on the raised research questions. Figure 1.2 gives an overview on the sustainability dimensions for which the two food industry cases from the dairy sector are evaluated in the present thesis.

Chapter 2 investigates whether novel milk concentrates are environmentally advantageous compared to traditional milk powders along the supply chain. This chapter therefore focuses on answering the first research question. For this purpose, a comparative, attributional life cycle assessment (ALCA) is conducted. The ALCA considers individual processing steps that can be combined and operated in various ways to generate a multitude of different milk concentrates. Environmental sustainability is evaluated by determining the cumulative energy demand, global warming potential, acidification potential, and eutrophication potential of milk powders and milk concentrates.

Chapter 3 explores the impact of shelf life on the trade-off between the economic and environmental performance of milk powders and milk concentrates. It thus addresses the second research question. The developed framework includes a multi-objective optimization model, a method for objective reduction, and a rolling horizon scheme.

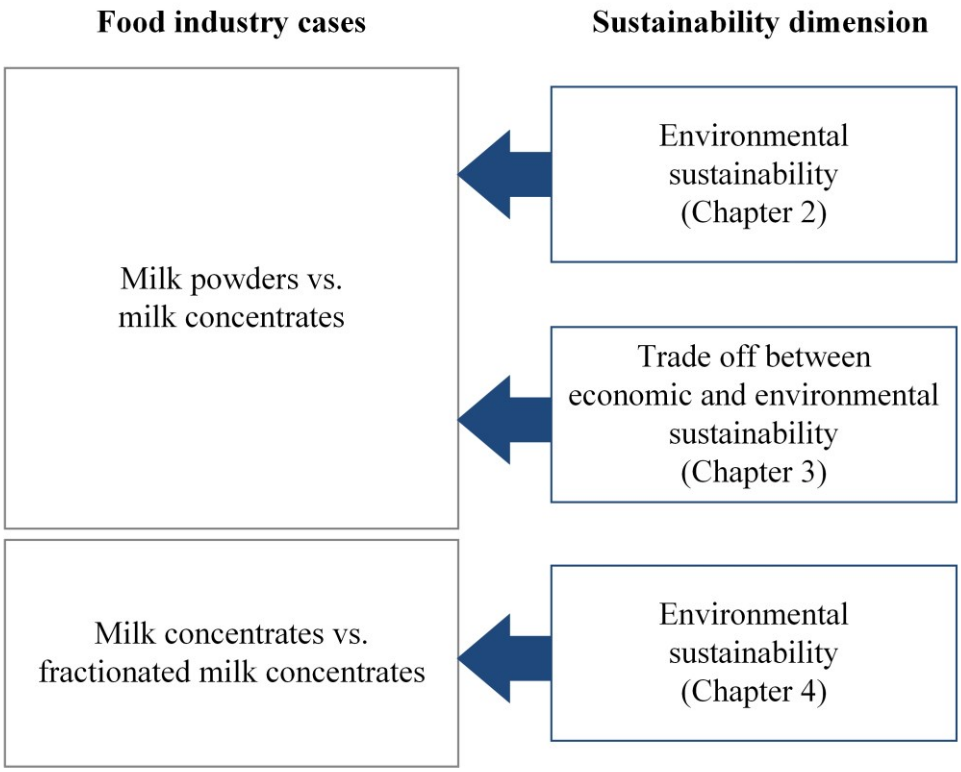

Figure 1.2. Overview on sustainability dimensions used to evaluate the industry cases from the dairy sector.

Like in company practice, price fluctuations are considered by periodically updating price information. The economic value of shelf is determined under *a priori* perfect price knowledge and price predictions with futures.

Chapter 4 compares fractionated and non-fractionated products with the aid of LCA. This chapter thus aims at answering the third research question. For this purpose, a generic scope-definition framework for multi-product processes is developed. Considering the potentials and limitations of ALCA and CLCA, the framework addresses the choice of an appropriate functional unit and allocation method. It is applied to new, fractionated dairy products – *micellar-casein concentrate*, *whey-protein concentrate*, and *lactose* – and their non-fractionated counterpart *skim-milk concentrate*.

Chapter 5 concludes the thesis with a summary of the main findings. Insights for practitioners and research challenges are discussed and an outlook for future research in this area is provided.

1.5 Included publications

Chapters 2 to 4 of this thesis have been published in scientific journals. The chapters are therefore also readable as individual contributions to the presented research questions that concern the environmental and economic sustainability of novel food products. They have been published as follows.

Chapter 2: Depping, V., Grunow, M., van Middelaar, C., Dumpler, J., 2017. Integrating environmental impact assessment into new product development and processing-technology selection: Milk concentrates as substitutes for milk powders. Journal of Cleaner Production, 149, 1–10.

Chapter 3: Stefansdottir, B., Depping, V., Grunow, M., Kulozik, U., 2018. Impact of shelf life on the trade-off between economic and environmental objectives: A dairy case. International Journal of Production Economics, 201, 136-148.

Chapter 4: Depping, V., Grunow, M., Kulozik, U., 2020. A methodological framework for comparing fractionated and non-fractionated products in life cycle assessments: The case of milk concentrates, Journal of Cleaner Production, 257, 120478.

2 Environmental assessment of milk concentrates and milk powders

This chapter is based on an article published as:

Depping, V., Grunow, M., van Middelaar, C., Dumpler, J., 2017. Integrating environmental impact assessment into new product development and processing-technology selection: Milk concentrates as substitutes for milk powders. Journal of Cleaner Production, 149, 1–10.

2.1 Abstract

Environmental-impact reduction potential is great early in new product development. To exploit this potential, this study evaluates novel combinations of existent processing technologies. Process engineering is combined with an environmental product assessment along the supply chain.

In the dairy sector, drying milk into milk powders is a highly energy-intensive process. This study investigates whether switching from *milk powders* to new products known as *milk concentrates* diminishes the overall environmental impact along the supply chains of dairy-containing products. A comparative life cycle assessment (LCA) is conducted, which considers individual processing steps that can be combined and operated in various ways to generate a multitude of different skim milk concentrates. For relevant environmental indicators such as cumulative energy demand, global warming potential, eutrophication potential, and acidification potential, concentrates were found to have a lower environmental impact than powders, even if the former are trucked up to 1000 kilometers. This break-even distance is a conservative estimate. It depends upon the environmental impact of raw-milk production. The concentrate with the lowest environmental impact is produced by a combined concentration with reverse osmosis and evaporation to a dry-matter content of 35% and preservation via subsequent pasteurization. This holds for all indicators except eutrophication potential, for which this concentrate is the second-best option.

This study identifies the frame within which milk concentrates are an advantageous substitution for milk powder and demonstrates the value of applying environmental assessment to product development and processing-technology selection.

2.2 Introduction

Early consideration of sustainability in product development can achieve significant environmental benefits. Evaluating the impact of potential product designs at this early stage is generally difficult, since manufacturing processes and supply-chain operations are still undefined. Product design, however, is closely integrated with process-technology selection in process industries. New products are often generated by combining and operating existing processing steps in novel ways. Decision support for product design can be provided in such contexts because environmental impact data for the potential processing steps is obtainable.

Increased consumer awareness has made environmental sustainability particularly important in the food sector. A high degree of fractionation of required intermediate products negatively influences overall product sustainability to a large extent here (van der Goot et al., 2016). Energy demand per kilogram of water removed rises nonlinearly with increasing dry-matter content (DMC) when processing food products. An example is highly processed and fractionated milk powder, one of the current key intermediate products in the dairy sector that demands particularly large amounts of energy (Kessler, 2002; Ramirez et al., 2006). Milk powders are reconstituted before being processed into final products in various applications thereby restoring water removed during energy-intensive drying. Drying milk products into powders followed by reconstitution should be avoided in line with market pressures and legislative efforts such as EU Energy Efficiency Directive 2012/27/EU intended to systematically enhance sustainability across the manufacturing industry. That in the EU around 12% of raw milk was processed into milk powder in 2015 (CLAL, 2016; Eurostat, 2016) indicates the significance of the saving potential. One alternative to milk powders are milk concentrates, which require no energy-intensive drying. Concentrates can in principle be applied wherever powders are currently being reconstituted, for example when producing yoghurts, ice cream, filled bakery products, or finished meals. Typical for the food industry, this new product can be produced using novel combinations of existing processing technologies such as concentration and heating technologies. Although technological challenges in combining processing steps and determining operating conditions are briefly addressed, this paper focusses on analyzing the environmental impact of potential processing variants for milk concentrates.

Applying a value-chain perspective for evaluating the transition from one product design to another is essential because product design affects transportation mode and volume as well as downstream processing at the customers, and thus environmental impacts there also. Milk concentrates' greater water content will increase volumes significantly when they replace milk powders. Concentrates may also need cooling during storage and transportation. Life cycle assessment (LCA) under ISO standards (ISO 14040, 2006; ISO 14044, 2006) was applied to comprehensively assess environmental consequences along the value chain. A lack of detailed manufacturing-process information typically hinders early integration of LCA into product design (Millet et al., 2007); however in process industries, product design generally requires a choice of processing technologies and their operating modes. If new products are manufactured using existing processing technologies, detailed data is already obtainable early in product development. This stage typically offers ample opportunity to reduce future production systems' environmental impact. No pertinent case studies on integrating LCA and product design have been published thus far despite the suitability of the process industries for attenuating products' undesired environmental impacts.

A product's environmental impact depends heavily on the selected processing variant, the product's design, and the product itself (Azapagic, 1999; Jacquemin et al., 2012). Several LCA studies have compared the impacts of different production processes in process industries such as the chemical industry (e.g., Cespi et al., 2014), cement manufacturing (e.g., Huntzinger and Eatmon, 2009), and waste treatment (e.g., Arafat et al., 2013). In the energy sector, Pérez Gil et al. (2013) and Brentner et al. (2011) also considered the possibility of combining options at different processing stages to determine the environmentally optimal route. However, LCAs analyzing different processing variants are scarce in the food industry. The authors found only one study comparing different preservation technologies for a dish (Pardo and Zufía, 2012). This study, however, is restricted to only one of the product's processing steps and focuses on underlying technologies.

Numerous LCA studies have been conducted that analyze existing dairy products based on the current processing variant. Products considered include fluid milk (e.g., Daneshi et al., 2014), yoghurt (González-García et al., 2012), butter (e.g., Flysjö, 2011), and cheese (e.g., van Middelaar et al., 2011). Djekic et al. (2014) also analyzed a combination of these products. Some initial work about milk powder has been published. In 2000, a Dutch consultancy assessed the specific energy consumption (SEC) per kilogram of milk powder among twelve Dutch dairy plants (Arcadis IMD, 2000). Their results formed the basis for the analyses by Ramirez et al. (2006) and Xu and Flapper (2011). More recently, two studies focusing on several products' greenhouse-gas emissions, including those involved in the production of milk powder were published (Finnegan et al., 2017; Vergé et al., 2013). Both studies are, however, macro-scale LCAs considering the Irish and Canadian dairy sectors as a whole. A first step toward comprehensively analyzing the environmental impact of milk-powder production across several dairy plants was taken by Müller-Lindenlauf et al. (2014) in their final project report to the German Federal Office for Agriculture and Food. In it, they documented the environmental impact of producing milk powder by evaporation and subsequent drying. Nonetheless, their study fails to compare different processing variants for producing milk powder.

No study to date has analyzed the environmental impact of novel combinations of processing stages required for designing new products in the food industry, here exemplified by milk concentrates. Nor have the environmental impacts of the benchmark product, milk powder, been comprehensively assessed.

In this study, LCA and product design were integrated by analyzing the environmental impact of several novel combinations of existing milk-processing technologies including different operating modes (processing variants). The new products analyzed were shelf-stable *milk concentrates*, which were compared to the current benchmark product, *milk powders*. Different combinations of the processing steps concentration, spray drying, and heat treatment were investigated as processing variants. Concentrates with a range of different final DMCs were also evaluated. Implications for the supply-chain stages before and after processing were derived to compare the resulting product designs.

2.3 Methods

2.3.1 Type of life cycle assessment

To compare the environmental impacts of milk powders and milk concentrates, and thus of well-established and new products, an attributional LCA (ALCA) was performed. An ALCA describes the environmental impact of a product system in steady state thereby providing insight into the average environmental impact of a product over its life cycle at a certain point in time (Hospido et al., 2010; Thomassen et al., 2008). Inputs and outputs were assessed for each processing step along the supply chain. Doing so enabled different processing variants based on individual processing steps to be compared.

Our analysis was conducted in cooperation with two mid-sized German dairy plants: one performing upscaling experiments on ways to produce shelf-stable milk concentrates and one deciding whether to switch to milk concentrates as an ingredient. As the experiments at the dairies were conducted for skim milk concentrate (SMC), the comparison in this study was restricted to this product and its equivalent, skim milk powder (SMP). Nevertheless, the results are considered to be entirely transferable to full milk concentrates and powder.

The LCA methodology used in this analysis was based on ISO standards (ISO, 2006a; ISO, 2006b). Calculations were performed with the LCA software tool SimaPro 8.0.5 (PRé, 2015).

2.3.2 Functional unit

Milk powders and milk concentrates are used as ingredients in a variety of food products. For this purpose, milk powders are reconstituted and milk concentrates are diluted in either skim milk or water to specific DMCs. Powders (concentrates) that are reconstituted (diluted) in skim milk to a DMC of around 12.5% are needed for yoghurt production. Powders (concentrates) that are reconstituted (diluted) in skim milk or water to a DMC of 30% or 35% are used, for instance, in ice cream, finished meals, or filled bakery products.

The following functional units (FUs) were defined based on these applications: 1 kg of skim-milk concentrate ready to be further processed at the customer stage, with a DMC of

- 12.5%, reconstituted/diluted in skim milk (FU1)
- 30%, reconstituted/diluted in skim milk (FU2) or water (FU4)
- 35%, reconstituted/diluted in skim milk (FU3) or water (FU5).

These functional units allow a comparison of the environmental impact of different SMPs and SMCs along the supply chain.

2.3.3 System under study

The system under study was restricted to those parts of the chain that differ between the old (*milk powder*) and new (*milk concentrates*) system (Hospido et al., 2010). Since switching from milk powders to milk concentrates affects processing efficiency, upstream processes such as the production of raw milk also had to be included in the analysis. The system was split into a foreground system involving self-assessed data and a background system involving data from literature and databases. The foreground system comprises SMP and SMC production as well as preprocessing at the customer, whereas the background system includes raw milk production and resource provision and disposal. Industry data has been compiled as annual averages of the year 2012. Figure 2.1 depicts the system studied.

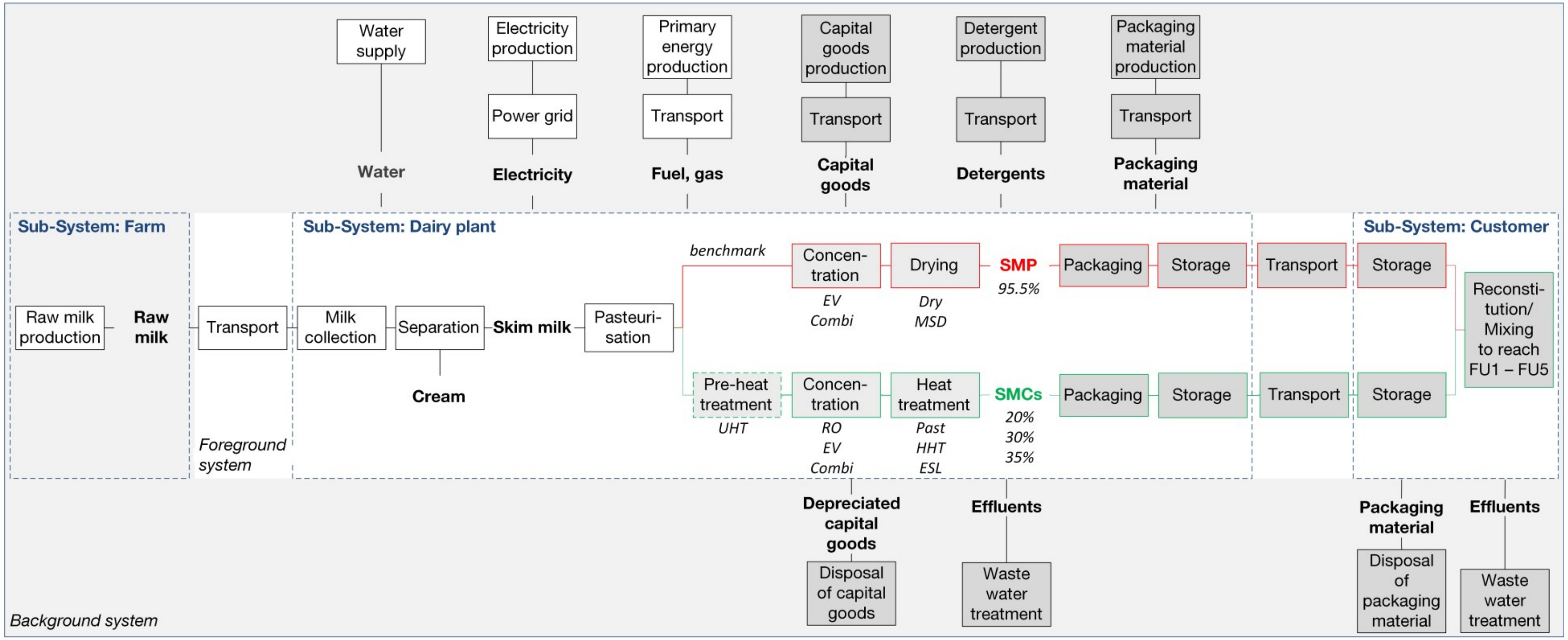

Figure 2.1. Overview of the skim-milk powder (SMP) and skim-milk concentrate (SMC) supply chain. The white area displays the foreground system and the gray area represents the background system. White boxes are common processes, patterned boxes are processes with several processing options, and gray boxes depend on the respective processing option or combination of processing options (i.e., processing variants).
Abbreviations: RO—reverse osmosis, EV—evaporation, Combi—reverse osmosis and subsequent evaporation, Dry—spray drying, MSD—multistage drying, Past—pasteurization, HHT—high-heat treatment, ESL—extended shelf life, UHT—ultrahigh temperature, FU—functional unit.

Raw milk is produced at the supplying dairy farms. The raw milk is transported to the dairy plant, where cream is separated from skim milk. After the skim milk is pasteurized, the SMP and SMC production processes take different routes. A typical industrial SMP manufacturing process currently comprises two- to three-stages. More recently, it includes a facultative skim-milk preconcentration step involving reverse osmosis (DMC approximately 28%), multiple-effect evaporation (DMC approximately 45%), and subsequent immediate (multistage) drying. These SMP processing options belong in the hatched boxes “concentration” and “drying” in figure 2.1.

While SMP has a DMC of around 96%, SMCs can be produced with various final DMCs. This study considered three concentrate DMCs: 20%, 30%, and 35%. The latter two DMCs correspond directly to the FUs, whereas a 20% DMC is generally regarded as the minimum required degree of concentration. The three degrees of concentration can be achieved by reverse osmosis, evaporation, or in case of a final 35% DMC, by a combination of the two (DMC after reverse osmosis is approximately 28%). Besides concentration, SMCs are heated after, and optionally before, concentration to extend their shelf-lives. Heat treatments considered include ultrahigh temperature (137 °C, 5 s), extended shelf life (125 °C, 2 s), high-heat treatment (120 °C, 5 s), and pasteurization (72 °C, 25 s). SMC processing options belong in the hatched boxes “pre-heat treatment,” “concentration,” and “heat treatment” in figure 2.1.

Several technological challenges such as sedimentation, crystallization of calcium phosphate, age-gelation, and bacterial growth had to be investigated when combining different processing options to produce SMC with DMCs greater than that of condensed milk (18%–20%). In addition, heat treatment of SMC is limited due to undesired protein coagulation when certain temperature-time-total solids combinations are exceeded. Dumpler and Kulozik (2015, 2016) have recently published a detailed analysis on feasible heat treatments for different skim-milk concentration levels. An additional restriction on heat-treatments exists for specific applications. SMCs requiring high native whey-protein content do not allow high-heat treatments. This is the case for concentrates used in yoghurt production. Therefore, only processing variants including pasteurization were considered for FU1. In addition, since the use of concentrates with a 20% DMC is restricted to FU1, these concentrates can be exclusively preserved via pasteurization. Table 2.1 shows the resulting feasible combinations of processing options (processing variants) together with the shelf-lives of the generated products. This table illustrates the different product design options.

Table 2.1
Considered processing variants and their characteristics.

DMC	Processing variants	Storage condition	Shelf life (days)	Reason for spoilage
Powder	*Concentration—Drying*			
95.5%	EV—Dry	ambient	≤ 730	Caking
	Combi—Dry	ambient	≤ 730	Caking
	EV—MSD	ambient	≤ 730	Caking
	Combi—MSD	ambient	≤ 730	Caking
Concentrates	*(Preheat treatment)—Concentration—Heat treatment*			
20%	RO—Past	chilled	9	MO—vegetative cells
	EV—Past	chilled	9–15	MO—vegetative cells
30%	RO—Past	chilled	14	MO—vegetative cells
	EV—Past	chilled	14–20	MO—vegetative cells
	RO—HHT	chilled	20	MO—bacterial spores
	EV—HHT	chilled	20	MO—bacterial spores
	UHT—RO—ESL	ambient	22	Age-gelation
	UHT—EV—ESL	ambient	22	Age-gelation
35%	RO—Past	chilled	19	MO—vegetative cells
	EV—Past	chilled	19–30	MO—vegetative cells
	Combi—Past	chilled	19–30	MO—vegetative cells
	UHT—RO—HHT	chilled	50	Age-gelation
	UHT—EV—HHT	chilled	50	Age-gelation
	UHT—Combi—HHT	chilled	50	Age-gelation

Abbreviations: DMC—dry matter content, RO—reverse osmosis, EV—evaporation, Combi—reverse osmosis and subsequent evaporation, Dry—spray drying; MSD—multi stage drying, Past—pasteurization, HHT—high-heat treatment, ESL—extended shelf life, UHT—ultrahigh temperature, MO—microbial growth.

SMP is packaged into bags and SMC is packed into bags in boxes, palletized, stored intermediately, and finally shipped to customers. At the customer stage, both products are stored until their use as ingredients. Bags of SMP are cut open and the powder is added to tanks via funnels. Here, the powder is reconstituted to obtain the desired FU. Typical problems connected with powder reconstitution are dust formation (during funnel filling) and foam development (during reconstitution), both of which lead to product losses. By contrast, concentrates may be added directly or mixed to reach the FU without losses.

2.3.4 Environmental impacts and allocation method

The analysis covered the following environmental indicators: cumulative energy demand (CED), global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP). Indicators were selected for their importance to the dairy products' supply chain (de Vries and de Boer, 2010).

The environmental impact of raw-milk production was allocated to skim milk and cream based on their relative volume of milk solids. Milk solids were assumed to represent economic drivers for environmental impacts in the upstream production chain (Thoma et al., 2013a). Milk solids were calculated to pass over to cream and skim milk at 38% and 62% respectively.

2.3.5 Life Cycle Inventory

Detailed life cycle inventory data for the present study can be found in appendix B. To couple this data with environmental impacts, corresponding ecoinvent v3.1 (2014) processes were chosen (for a list, see appendix C). The remainder of this section points to several of the present inventory's specifics.

Raw milk production and collection. Data on the raw milk production stage was based on the work of Guerci et al. (2013). This publication considers milk production at 12 farms in Denmark, Germany, and Italy, and includes all processes up to the farm gate. Lower limit (LL) and upper limit (UL) of raw-milk environmental impacts in Guerci et al. (2013) were assumed to represent the impact range related to raw-milk inflow at the partnering German dairy. In accordance with Guerci et al. (2013), raw-milk inflow was expressed in kilogram energy corrected milk (Sjaunja et al., 1990). The average round trip distance to collect the milk was calculated based on farm distribution around the cooperating dairy plant.

Dairy plant. At the partnering dairy, data on the following was gathered for each of the SMPs' and SMCs' processing steps: (1) product losses; (2) energy intake as electricity and directly from natural gas or other fuel; (3) fresh water and cleaning-agent consumption; (4) wastewater generation; (5) deployed capital goods; and (6) packaging types and materials. The assessed *product losses* of inputs and outputs were combined with the volume reduction factors (for concentration stages) and resulted in the respective inflow amounts needed. *Energy intake* was determined during both runtimes and cleaning cycles. The dairy plant burned natural gas to produce steam for both thermal processing and equipment cleaning, whereas electricity was used for cooling and other plant processes. The *cleaning agents* applied at the partnering dairy consisted of acidic solutions containing phosphoric and nitric acids and alkaline solutions containing sodium hydroxide. To decrease *tap-water* use and cleaning-agent demand, the dairy partly reused them in several unit processes. The required production and transport amounts of active substances for cleaning agents were taken as a proxy and coupled with the environmental impacts from ecoinvent v3.1 (2014, see appendix C). *Wastewater* containing residues of milk and cleaning agents is forwarded from the dairy to the local municipal sewage treatment plant. To determine the environmentally relevant flows associated with these effluents, municipal wastewater treatment was modelled using the tool from Doka (2008). For this purpose, the wastewater's input composition of BOD, nitrate, total Kjehldahl nitrogen, phosphate, and particulate phosphate was determined for each unit process at the dairy plant. The resulting inventory data and corresponding ecoinvent processes were then imported into SimaPro. Since *capital goods* investments and usage differ for SMP and SMC, equipment production was included in the present study. For the inventory of capital goods, the production and transport of the raw materials involved was taken as a proxy. Environmental impacts of capital goods were linearly depreciated over their lifetime according to German depreciation rules (German Federal Ministry of Finance, 2015). Both bags and bags in boxes for SMP and SMC *packaging* consisted of kraft paper with plastic inlays made of low-density polyethylene. The packaging options, however, differed with regard to material thickness (see appendix B). Production and transportation of kraft paper and plastic foil were considered for the environmental impact.

Distribution and customer. In line with previous research on food transportation, it was assumed that cooling SMCs during transportation increases the engine's fuel consumption (cf. Tassou et al., 2009). The related ecoinvent v3.1 (2014) dataset was adapted accordingly. *Product losses* occur during funnel filling and reconstitution of SMP at the customer stage. Deposited dust was removed daily in the surrounding area. Foam losses were found to rise if the final concentrate DMCs increased from 12.5% to 30%, whereas a further increase to 35% had no effect (see appendix B). Due to foam, the tank required pre-cleaning before the cleaning-in-place (CIP) operation could start. By contrast, SMC adding is loss-free. *Energy* was dissipated while storing SMCs under cooled conditions. An average storage duration of three days was assumed based on a six-day week at the customer with weekly delivery. By contrast, storage at ambient temperatures was considered to be environmentally neutral. During reconstitution/dilution, the energy intake for stirring and pre-cleaning was assessed.

The applied *cleaning agents* contained phosphoric acid as an active component. *Wastewater*, *capital goods*, and *packaging disposal* were also assessed at this stage.

2.3.6 Impact assessment method

In the present study, the same impact assessment method and characterization factors were used as those in Guerci et al. (2013) to ensure compatibility with the raw-milk production impacts. The methods specified in EPD (2008) were applied for this purpose. The CED indicator was restricted to non-renewable-energy use and the characterization factors of the CML-IA 2001 method were applied for the indicators GWP, EP, and AP. A 100-year time horizon and the IPCC factors from 2007 were used to calculate the GWP.

2.4 Results

The results achieved by comparing SMPs and SMCs along the supply chain are first presented for the indicator CED, due to the significant role energy consumption plays in evaluating these products. The indicator results for GWP, AP, and EP are subsequently analyzed.

2.4.1 Cumulative energy demand

Figure 2.2 illustrates the CED of different processing variants for SMP and SMC produced at an integrated dairy plant, which does the processing in-house (i.e., without transport from the dairy plant to the customer) for FU2. The SMC *Combi-Past-35%* option has the lowest CED of all products. For this FU, its CED is 2.29 MJ (34%)—lower than the CED of the best SMP option (*Combi-Dry*). Results showed that from an energy perspective, combining reverse osmosis and evaporation is preferable for both concentrates and powders. Nevertheless, concentrates generally outperformed powders during in-house processing, due to the latter's large energy intake during drying and greater product losses at the production-and-reconstitution stage. An exemption is the concentrate *UHT-EV-ESL-30%*, which is stabilized with two heat treatments and concentrated with evaporation, resulting in a larger CED than the best powder option.

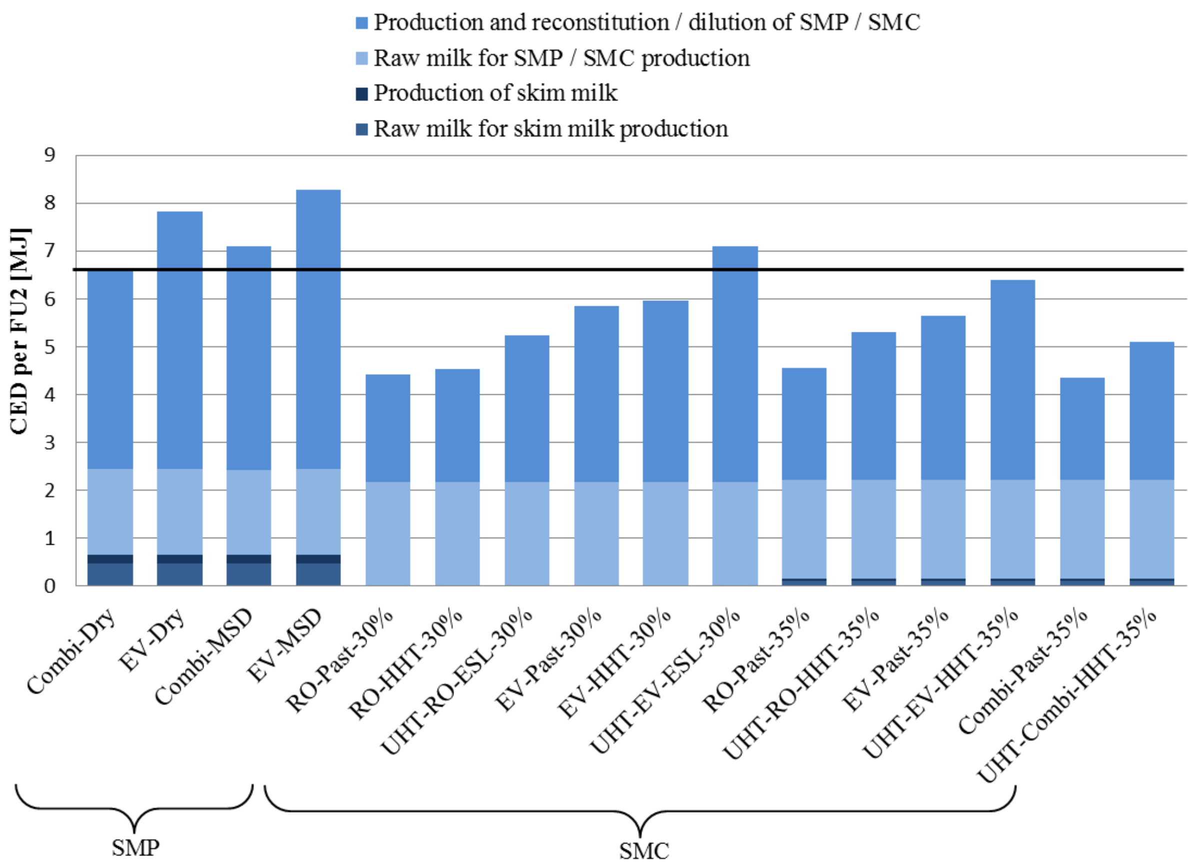

Figure 1.2. Cumulative energy demand (CED) of different skim milk concentrates and powders for FU2 if transportation is disregarded. Results are based on the lower limit of raw-milk impact.

For the production of powders, single-stage spray drying is environmentally preferable to multistage drying. This effect originates mainly from the multistage dryer's greater electricity intake, which outweighs its lesser natural gas consumption. In addition, results show that SMCs produced by reverse osmosis have a higher CED for a DMC of 35% than for a DMC of 30% (*RO-Past-35%* vs. *RO-Past-30%).* This finding, which contradicts the results for SMCs produced by evaporation, stems from the properties of the reverse osmosis plant. Whereas the plant is close to its optimal operating point for a DMC of 30%, its run times are reduced by 58% for a DMC of 35%, implying a significantly greater cleaning frequency.

Since transportation to the customer is a major variable in this product comparison, the extent to which the optimal product choice depends on transportation distance was investigated. For this purpose, the break-even distances of the different SMCs with the best SMP option for FU1–FU5 were analyzed. The concentrates show different increases per unit transportation distance in their environmental impact. The differences in increases result from differences in the selected transportation mode (cooled vs. ambient-temperature transport) and the required transportation volumes (i.e., the amounts needed for reconstitution or dilution of the respective FU).

Figure 2.3 shows the break-even distances of SMCs with the best SMP option *Combi-Dry* for FU2. Note that the CED values from figure 2.2 constitute the intercepts. As depicted, the concentrate *Combi-Past-35%*, which has the lowest CED in the case of in-house processing, can be transported up to 1044 km before a break-even point is reached. It can also be observed that the ranking for the processing variants *RO-Past-30%* and *RO-Past-35%* is inverted at a transportation distance of 186 km. Beyond this distance, the lower transportation mass of *RO-Past-35%* (13.79% by weight) compared to *RO-Past-30%* (17.06%) outweighs the CED disadvantages in production. While a DMC close to the optimal processing point of the reverse-osmosis plant is preferable for small transportation distances, a greater DMC does become preferable for larger distances.

Table 2.2 shows a comprehensive overview of the break-even distances for the LL and UL of raw-milk impacts across FU1–FU3. Regardless of the use of LL or UL, the product ranking remains constant within each FU. Yet due to greater product losses along the supply chain, powders require more raw milk than do concentrates. Hence the difference in impact between powders and concentrates is higher for the UL and the break-even distances are larger. The LL thus gives a conservative estimate of the distance up to which SMCs are environmentally preferable to SMP. Moreover, the break-even distances increase from FU1 to FU3. Rising SMP losses from foam development cause this increase when SMP is reconstituted to higher DMCs. The break-even distance of the best SMC option, *Combi-Past-35%*, increased from 919 km to 1048 km for the LL of raw-milk impact, and from 1007 km to 1291 km for the UL of raw-milk impact.

If final concentrates with 30% and 35% DMC are obtained by reconstitution dilution in water (FU4 and FU5) instead of reconstitution/dilution in skim milk, then the CED of the corresponding SMP (SMC) options rises by 10%–16.5% (1%–3%) for the LL of raw-milk impact. This finding reveals that using skim milk is preferable because the required amount of highly processed SMP or SMC is reduced. The finding holds even if the required skim milk is transported over long distances (several hundred up to several thousand kilometers to the customer, depending on the different powders and concentrates). Only the results for reconstitution/dilution of skim milk (FU1–FU3) are presented for subsequent analysis of impact categories GWP, AP, and EP.

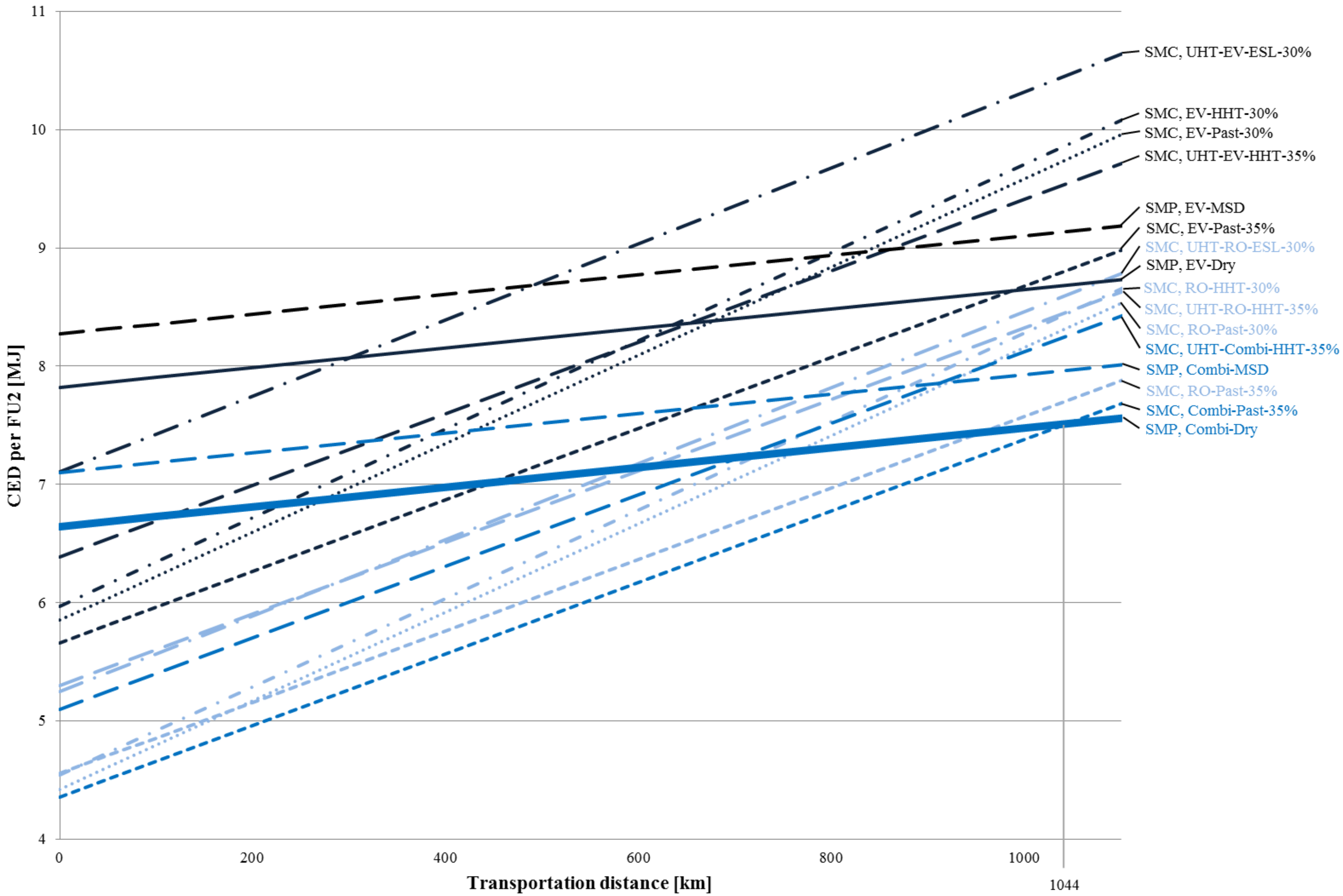

Figure 2.3. Cumulative energy demand (CED) of different skim milk concentrates and powders for FU2 as a function of transportation distance. Results are based on the lower limit of raw-milk impact.

Table 2.2
Break-even transportation distances and break-even cumulated energy demand (CED) of different skim-milk concentrates (SMC) with skim-milk powder.[a]

	Unit	RO Past 20%	RO Past 30%	RO HHT 30%	UHT RO ESL 30%	EV Past 30%	EV HHT 30%	RO Past 35%	UHT RO HHT 35%	EV Past 35%	UHT EV HHT 35%	Combi Past 35%	UHT Combi HHT 35%
FU 12.5%, low-heat, skim-milk reconstitution/dilution													
Lower limit	km	181	672			185		831		333		**919**	
	MJ	*1.826*	*1.893*			*1.827*		*1.915*		*1.847*		*1.927*	
Upper limit	km	216	739			239		894		401		**1007**	
	MJ	*6.159*	*6.230*			*6.162*		*6.251*		*6.184*		*6.267*	
FU 30%, skim milk reconstitution / dilution													
Lower limit	km		765	724	587	273	232	954	613	450	117	**1044**	706
	MJ		*7.280*	*7.246*	*7.133*	*6.873*	*6.839*	*7.438*	*7.154*	*7.019*	*6.743*	*7.512*	*7.231*
Upper limit	km		943	902	800	438	397	1183	842	665	331	**1279**	941
	MJ		*18.268*	*18.234*	*18.149*	*17.849*	*17.815*	*18.467*	*18.184*	*18.037*	*17.761*	*18.547*	*18.266*
FU 35%, skim milk reconstitution / dilution													
Lower limit	km							958	617	453	120	**1048**	709
	MJ							*9.006*	*8.487*	*8.655*	*8.144*	*9.098*	*8.750*
Upper limit	km							1195	853	676	342	**1291**	952
	MJ							*21.955*	*21.604*	*21.421*	*21.078*	*22.053*	*21.705*

[a] Skim-milk powder produced with combined concentration (Combi-Dry) has the least CED and is used for break-even calculations. Considered SMCs are restricted to those with a lower intercept than Combi-Dry. Boldface numbers represent the maximum break-even distance in each case.

Abbreviations: FU—functional unit, RO—reverse osmosis, EV—evaporation, Combi—combined concentration, Past—pasteurization, HHT—high-heat treatment, ESL—extended shelf life, UHT—ultrahigh temperature.

2.4.2 Global warming, acidification, and eutrophication potential

Raw milk required for the different processing variants (comprising necessary volume reduction and product losses) is a major contributor to the GWP, AP, and EP of powders and concentrates. For example for SMC option *Combi-Past-35%*, more than 90% of GWP, 98% of AP, and 85% of EP stem from raw-milk production across all FUs, if transportation is disregarded. Additional impacts from transportation are small.

Table 2.3 summarizes break-even GWPs, APs, EPs, and transportation distances for concentrates with the respective best powder alternative. The results for the indicators GWP and AP show an identical product ranking as with the CED, whereas the product ranking differs for the EP indicator. For this indicator, SMP and SMCs concentrated with evaporation have lesser impacts than those concentrated with reverse osmosis or combined concentration. The best product choices *Combi-Past-35%* and *Combi-Dry* are supplanted by *EV-Past-35%* and *EV-Dry*. The difference is mainly caused by the processing variants' energy profiles. Reverse osmosis demands more electricity and less natural gas than evaporation does. Electricity provision produced with the German average composition contributes substantially to eutrophication. Natural gas provision, by contrast, is a major contributor to acidification.

Overall, the results for GWP, AP, and EP show considerably larger break-even distances for SMCs with the respective best powder options than the results for the CED do. For GWP, the largest break-even distances range between 1027 km (FU1) and 1436 km (FU3), for AP between 1252 km (FU1) and 2792 km (FU3), and for EP between 5318 km (FU1) and 8898 km (FU2). These distances stem from the minor importance of truck transportation for GWP, AP, and EP when compared to CED. CED thus limits the transportation distance up to which SMCs are environmentally advantageous compared to SMP.

Table 2.3
Break-even transportation distances and break-even environmental impacts of different skim-milk concentrates (SMC) with powder.[a]

	Unit	RO Past 20%	RO Past 30%	RO HHT 30%	UHT RO ESL 30%	EV Past 30%	EV HHT 30%	RO Past 35%	UHT RO HHT 35%	EV Past 35%	UHT EV HHT 35%	Combi Past 35%	UHT Combi HHT 35%
FU 12.5%, low-heat, skim-milk reconstitution/dilution													
GWP	km	228	754			283		920		455		**1027**	
	kg CO_2-eq	*0.601*	*0.606*			*0.602*		*0.607*		*0.603*		*0.608*	
AP	km	216	895			378		1146		596		**1252**	
	g SO_2-eq	*7.498*	*7.515*			*7.502*		*7.522*		*7.508*		*7.524*	
EP	km	1227	3503			3851		3231		**5318**		5012	
	g PO_4^{--} -eq	*1.069*	*1.082*			*1.084*		*1.080*		*1.092*		*1.090*	
FU 30%, low-heat, skim-milk reconstitution/dilution													
GWP	km		1049	1008	940	574	533	1311	976	839	513	**1420**	1089
	kg CO_2-eq		*1.686*	*1.683*	*1.680*	*1.661*	*1.659*	*1.699*	*1.682*	*1.675*	*1.658*	*1.705*	*1.688*
AP	km		2004	1975	2150	1481	1452	2618	2417	2061	1864	**2727**	2530
	g SO_2-eq		*19.366*	*19.362*	*19.389*	*19.285*	*19.281*	*19.462*	*19.431*	*19.375*	*19.345*	*19.479*	*19.448*
EP	km		6186	6055	5960	6538	6408	6781	5443	**8898**	7594	8588	7484
	g PO_4^{--} -eq		*3.514*	*3.510*	*3.506*	*3.527*	3.519	*3.535*	*3.488*	*3.609*	*3.564*	*3.598*	*3.560*

[a] For the categories global warming and acidification, skim-milk powder produced with combined concentration (*Combi-Dry*) has the lowest impact, whereas for eutrophication, powder produced with evaporation (*EV-Dry*) is optimal and is used for break-even calculations. SMCs with a lower intercept than the respective best powder option are considered; pre-excluded are SMCs with higher intercepts for the cumulated energy demand. The comparison is restricted to the lower limit of raw-milk impact. Boldface numbers represent the maximum break-even distance in each case.

Abbreviations: FU—functional unit; RO—reverse osmosis; EV—evaporation; Combi—combined concentration; Past—pasteurization; HHT—high-heat treatment; ESL—extended shelf life; UHT—ultrahigh temperature.

Table 2.3 (continued)
Break-even transportation distances and break-even environmental impacts of different skim-milk concentrates (SMC) with powder.

	Unit	RO Past 20%	RO Past 30%	RO HHT 30%	UHT RO ESL 30%	EV Past 30%	EV HHT 30%	RO Past 35%	UHT RO HHT 35%	EV Past 35%	UHT EV HHT 35%	Combi Past 35%	UHT Combi HHT 35%
FU 35%, low-heat, skim-milk reconstitution/dilution													
GWP	km							1327	992	855	528	**1436**	1105
	kg CO_2-eq							*2.011*	*1.989*	*1.981*	*1.960*	*2.018*	*1.997*
AP	km							2685	2483	2126	1929	**2792**	2596
	g SO_2-eq							*22.879*	*22.840*	*22.771*	*22.733*	*22.899*	*22.861*
EP	km							6386	5047	**8506**	7200	8195	7089
	g PO_4^{--} -eq							*4.153*	*4.245*	*4.245*	*4.189*	*4.232*	*4.184*

Abbreviations: FU—functional unit; RO—reverse osmosis; EV—evaporation; Combi—combined concentration; Past—pasteurization; HHT—high-heat treatment; ESL—extended shelf life; UHT—ultrahigh temperature.

2.5 Discussion

The findings confirm that SMCs are a viable substitute for reconstituted SMPs. Across all FUs, their environmental impact is generally lower if they are processed in-house. The best option reduces CED by 19% (FU1) to 35% (FU3). The environmental reduction potential of SMCs decreases with increasing transportation distances due to cooling requirements and greater transportation volumes; a break-even with SMP is first reached in the impact category CED. For the indicators CED, GWP, and AP, the optimal concentrate choice is *Combi-Past-35%*. For the indicator EP, this is the second-best option, while *EV-Past-35%* is optimal. However for EP, both concentrate options are environmentally advantageous compared to SMP over the whole transportation-distance range. These results hold for all FUs. From a comprehensive environmental perspective, therefore, *Combi-Past-35%* should be chosen up to the CED transportation limit.

Results presented in this study are subject to uncertainties regarding input data on raw-milk impact and processing (i.e., types and utilization of processing equipment). Additionally, future technological developments in processing and transportation as well as shelf-life requirements of the customers are uncertain.

Data on the environmental impact of raw-milk production was obtained from the literature. To account for the variability and uncertainty associated with the impacts of raw-milk production, their LL and UL were considered. If the UL of the environmental impacts of the raw milk is used instead of the LL, the ranking of powders and concentrates remains constant. However, the environmental-impact differences between powders and concentrates (without transportation to customers) increase. As the transportation gradients remain constant, break-even distances rise (FU1: 88 km; FU2: 235 km; FU3: 243 km). By considering the LL for raw-milk impacts, a conservative estimate for a maximum transportation distance was obtained, which makes an introduction of concentrates in industrial practice attractive.

Life cycle inventory data related to processing was collected at two mid-sized German dairy plants, which are currently investigating a switch to concentrates, and from their supply chains. Because concentrates are generated by novel combinations of existing processing steps, uncertainty related to processing data was limited. For skim-milk powder produced with evaporation, the results are also backed up by the findings of Müller-Lindenlauf et al. (2014), who analyzed several dairy plants. They determined ranges for environmental impacts in the categories CED, GWP and AP, which include the results of the present study. An exception is the impact category EP. Here, Müller-Lindenlauf et al. (2014) report lesser impacts at the dairy-plant level. An analysis of the underlying reasons, however, was not possible, as the detailed results of the present study could not be matched against the aggregate numbers reported in their study.

To test the results for robustness against the uncertainty in the employed equipment types, different drying equipment (*single-stage spray drying* vs. *multistage drying*) and concentration equipment (*thermal vapor recompression* vs. *mechanical vapor recompression*) were considered. If multistage drying is applied instead of single-stage spray drying, the CED break-even distance for the best concentrate choice, *Combi-Past-35%*, rises by 208 km for FU2. This effect originates mainly from the multistage dryer's greater electricity demand, which outweighs its lower natural gas consumption. The effect of using an evaporator with a more efficient mechanical instead of thermal vapor recompression on the CED break-even distance depends on the chosen processing variants for concentrates and powders. For the best concentrate choice, *Combi-Past-35%*, and the best SMP choice, *Combi-Dry*, the break-even distance remains almost constant with a decrease of 18 km. Both processing variants profit equally from the use of the more efficient evaporation technology, albeit for different reasons. In case of SMC, large concentrate amounts are needed to obtain the respective FU. The amounts are smaller for SMP, but the DMC increase in the evaporator is significantly larger. By contrast, if SMP production is done in a traditional way (without RO equipment) and compared to the corresponding SMC processing variant (*EV-Dry* and *EV-Past-35%),* then the DMC increase in the evaporation stage is great for both variants. Consequently, the break-even distance rises significantly (FU2: 560 km). Overall, this uncertainty analysis shows that with different equipment choices, the break-even distance of concentrates and powders would remain constant or even increase.

Future technological developments might affect the environmental-impact analysis of SMCs and SMP. While the development of more efficient spray dryers for SMP production will reduce the break-even distance of SMCs and SMP, increasingly efficient production equipment (for RO, EV, and heat treatments) and more efficient truck transportation will push the break-even to greater distances. The present study, for instance, considers a truck fleet with an average consumption of 31.75 L of diesel per 100 km (ambient transport). Reducing the fleet's average consumption to 25 L of diesel per 100 km would increase the optimal transportation distance of the concentrate *Combi-Past-35%* by 218 km (lower limit) for FU2 in the CED impact category.

When considering replacing SMP with SMC, the shelf life of concentrates at the customer stage can play an important role. The shelf life of concentrates is influenced mainly by their dry-matter content and the applied heat treatment. The shelf life of SMCs with a DMC of 35%, for instance, can be extended from 19 to 50 days by introducing an additional pre-heat treatment step (i.e., UHT for presterilizing unconcentrated skim milk) before concentrating and allows for the application of a final heat-treatment step with a higher temperature. This additional processing step exacerbates the environmental impact and leads to a reduced optimal break-even distance with the SMP curve. For example, choosing *UHT-Combi-HHT-35%* instead of *Combi-Past-35%* reduces the CED savings relative to *Combi-Dry* from 34% to 23% for FU2 (without transportation to customers). However, this switch accords customers 31 more days of shelf life and still has less environmental impact than powder up to a transportation distance of 709 km. Moreover, an ambient-temperature chain for handling concentrates might be preferred over a low-temperature chain. In this case, *UHT–RO–ESL-30%* would be the preferred option. This choice leads to a reduced break-even distance of 587 km on the SMP curve. Hence, the possibilities of a longer shelf life or of ambient-temperature handling must be traded off against the environmental-impact reduction potential.

2.6 Conclusions

This paper analyzes the environmental-impact reduction potential of the new *milk-concentrate* products relative to that of the benchmark, *milk powder*. The findings highlight the environmental-impact advantage of most milk concentrate products. The best concentrate option saves up to 35% of the cumulative energy demand, depending on the application.

The advantage of concentrates decreases with greater transportation distances to the customer; a break-even with skim-milk powder is first reached for the indicator cumulative energy demand. The processing variant with the lowest cumulative energy demand and the lowest impact on global warming and on acidification is a combined concentration with reverse osmosis and evaporation to a dry-matter content of 35% and preservation via subsequent pasteurization. With regard to eutrophication, this processing variant is the second-best option. The minimum break-even distance for truck transport of this skim-milk concentrate shows that for downstream manufacturers located within a radius of around 1000 km from the dairy plant, a switch to skim milk concentrate is environmentally advantageous.

The main implication of this study is that changing from milk powders to concentrates can contribute to reducing the environmental impact of dairy products. The results show under which circumstances substitution is advantageous and indicate which product alternatives and processing variants should be chosen from an environmental point of view. These findings are particularly interesting for dairy operators and downstream manufacturers, who are interested in switching to milk concentrates. The development and use of milk concentrates instead of powders is at the core of developments in the food sector that aim for environmental sustainability: a shift towards more specific processes targeted to the application at hand. For applications that are currently using reconstituted powders as ingredients, tailor-made products and specific processes were developed that were shown to be environmentally superior. This paper underscores how process engineering can be combined with environmental product assessments. Even before production processes are installed and products are produced, a detailed environmental assessment can be carried out to support processing technology selection and product design.

The adoption of such products and processes in practice also depends on economic aspects. Therefore, a complementary economic performance analysis of milk concentrates deserves further consideration. This analysis should not only address transportation distance but also other major economic aspects such as the economic value of a longer shelf life of milk powders and the investments required for the different products. Determining economic benefits enables to identify the extent to which environmental and economic goals are compatible or incompatible.

Acknowledgments

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3 Impact of shelf life on sustainability objectives

This chapter is based on an article published as:

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3.1 Abstract

Food manufacturers introduce more environmental-friendly processes to account for increasing sustainability concerns. However, these processes often go along with a reduction of product shelf life, limiting the delay of sales to future periods with higher prices. We develop a framework to analyze the impact of shelf life on the trade-off between economic and environmental performance of two types of dairy products. Since the differences in shelf life have their key impact at the tactical planning level, we develop an optimization model for this aggregation level. Its objectives reflect profit and relevant environmental indicators. A rolling horizon scheme is used to deal with price uncertainty, using Eurex futures as price predictors. Our framework uses these tactical planning results for strategic decisions on product and process selection. A real-life case study contrasts traditional milk powders against novel milk concentrates. Concentrates require less energy in processing, but have a shorter shelf life. Results show that powders offer a potential profit benefit of up to 34.5%. However, this economic value of shelf life is subject to *a priori* perfect price knowledge. If futures are used as price predictors, the value of shelf life is reduced to only 1.1%. The economic value of shelf life is therefore not a strong argument against the substitution of powders with more environmental-friendly concentrates. We also show that two objectives, profit and eutrophication potential, are sufficient to capture trade-offs in the case. Several product mixes are determined that omit powders and perform well with regard to profit and environment.

3.2 Introduction

In the food sector, there is a quest to replace highly processed products with more sustainable products (Van der Goot et al., 2016). As a result, manufacturers introduce novel processing technologies or novel combinations of existing technologies that often involve less or alternative processing steps. In addition, less intensive, so-called minimal process conditions can be applied that prevent pre-term spoilage (Fellows, 2017; Sybesma et al., 2017).

The introduction of more environmentally sustainable manufacturing processes often goes along with a reduction of product shelf life. This is, for example, the case when a more moderate heat treatment is applied. In the dairy industry, for instance, milk powders are replaced with concentrates, for which the energy-intensive drying stage required for powders is omitted. However, concentrates have a much lower shelf life (9–50 days) than powders (up to two years) (Depping et al., 2017). Another example for the interrelation of sustainable manufacturing processes and product shelf life is the substitution of heat treatments with the now increasingly applied technology of modified atmosphere packaging. For finished meals the shelf is cut in half (Pardo and Zufía, 2012). Also, novel technology combinations that for example involve less processing steps and thus are more sustainable, generally have a negative impact on shelf life. The omission of freezing used for stabilization of an intermediate (beet leaves) reduces the shelf life from several months to 5–7 days (Tenorio et al., 2017).

While the environmental impacts decrease in manufacturing, the downstream impacts of the more perishable products can offset these gains. Such products may require chilled storage and transportation to ensure an adequate shelf life. New perishable products thus need to be assessed along the whole supply chain to determine the effect on total environmental impacts. Furthermore, the economic performance of the shelf-life reduction is negatively affected by the limit on the storage duration. Storable, long-shelf-life products are beneficial when price fluctuations occur. For example, if demand volumes or prices increase, long-shelf-life products may be stored for later sale. Strategic planning for the selection of new sustainable products and processes thus requires a comprehensive evaluation of the shelf life's impact on the economic as well as the environmental assessment.

Multi-objective optimization is frequently applied to tackle the trade-offs between economic and environmental objectives (Banasik et al., 2018). Whereas the economic dimension is typically represented in a single objective of either cost minimization or profit maximization, the environmental dimension may require a whole range of environmental indicators. A common tool to assess the performance of products or production processes across different environmental indicators is the Life Cycle Assessment (LCA). The LCA under ISO standards (ISO 14040, 2006; ISO 14044, 2006) is based on the analysis of materials and energy flows at each phase of the life cycle. Thereby, a comprehensive assessment of environmental consequences along the value chain is assured. The use of multi-objective optimization avoids the controversial aggregation of different environmental indicators in a single objective. However, a number of difficulties arise when having many objectives, such as increased computational costs and complications in visualizing the objective space (Deb and Saxena, 2005). The δ-error method can be used to reduce the number of objectives while retaining as much of the problem characteristics as possible.

This study is based on a case from the dairy industry that is well suited to exemplify the impact of shelf-life reduction due to more environmentally sustainable manufacturing processes. The study evaluates novel and sustainable dairy products – milk concentrates – in comparison to their more shelf-stable benchmark products – milk powders. Since the production of milk powders includes drying, one of the most energy-intensive processes in the dairy industry, alternative processing variants have been developed in which the drying stage is omitted and milk concentrates are produced instead. The drying stage consumes around 50 % of the total energy demand (Ramirez et al., 2006), although only 10 % of the water is removed in this stage. The new products, milk concentrates, have been proposed as a substitute for milk powders in applications in which the latter is reconstituted, e.g., in the production of yoghurts, ice cream, filled bakery products, or finished meals. Milk concentrates can be produced with shelf lives ranging from 9 to 50 days, depending on the selected processing variant. Most milk concentrates require chilled storage. By contrast, milk powders have up to two years shelf life and can be stored under ambient conditions.

Depping et al. (2017) show that switching to milk concentrates is advantageous, even when taking the downstream impacts into account. This analysis only determined environmental impacts and assumed a short and fixed-storage duration. Our study also includes the economic dimension and focuses on the impact of shelf life on the environmental and economic assessment. Particularly important is the variability of dairy product prices, which have been fluctuating strongly in the past years including price jumps of up to 43% within one year for skim-milk powders traded on the German market (Süddeutsche Butter- und Käse-Börse e.V.).

The paper provides the following contributions:

- We systematically analyze the impact of shelf-life reduction due to sustainable processing on the trade-off between economic and environmental performance for the example of dairy products.
- We develop a framework to allow for a comprehensive sustainability evaluation. Since the differences in shelf life have their key impact at the tactical planning level, we develop an approach that determines the production and storage volumes at this aggregation level. A multi-objective optimization model covers profit and all relevant environmental indicators. We apply the δ-error method to identify trade-offs. Our framework deals with product price uncertainty by updating price information in a rolling horizon scheme. We use the tactical planning results from a rolling horizon application over a historical period to make strategic decisions on product and process selection.
- A real-life case study based on detailed economic and environmental data is used to contrast traditional milk powders against novel milk concentrates that require less energy in processing but have a shorter shelf life. We used historical data on powder prices in the years 2013 up to 2016 and the corresponding prices of futures traded at the Eurex.
- Through objective reduction we show that trade-offs exist between the economic objective and one of the environmental objectives, while other objectives can be reduced without a δ-error.
- We quantify the economic value of the shelf life provided by powders. The results show a potential profit benefit of up to 34.5%. However, this value is subject to *a priori* perfect knowledge of prices. If futures are used as price predictors, the value of shelf life is reduced to only 1.1%. The economic value of the shelf life is therefore not a strong argument against the substitution of powders with more environmental-friendly concentrates.

The remainder of this paper is organized as follows. In section 3.3, the main related literature is outlined. Section 3.4 introduces the problem definition and the supply chains for milk powders and concentrates. In section 3.5, we present the proposed evaluation framework that supports a selection of products and processes. In section 3.6, the developed methodology is applied to a real-life dairy case study and numerical analyses are carried out. Finally, section 3.7 summarizes the main conclusions and presents future research opportunities.

3.3 Literature review

In the following, we first review papers that develop planning approaches under economic objectives considering shelf life and demand variability. We also discuss papers that determine the economic value of storage under uncertain prices. Then, we outline studies that have considered products' environmental impacts in combination with their shelf life. Finally, studies that deal with products' environmental and economic benefit in combination with their shelf life are reviewed.

3.3.1 Economic objectives, shelf life, and demand variability

Several studies have accounted for shelf life and demand variability in planning approaches with economic objectives. Stefansdottir and Grunow (2018) study the selection of product designs and processing technologies under demand uncertainties with regard to volumes and product specifications, such as the shelf-life requirement. They show that shelf life is a key driver in the selection of product designs and technologies. Amorim et al. (2013b) review studies on production and distribution planning for perishable products. They identify seven papers that include demand uncertainties. The finding that demand uncertainty is restricted to uncertainty in demand levels is valid across all papers reviewed by Amorim et al. (2013b). In another study, Amorim et al. (2013a) also consider the risk of spoilage and of revenue loss, which results from uncertainties in the decay rates, demand level, and customer purchasing behavior. Pauls-Worm et al. (2014) moreover consider a practical problem in which a food producer faces non-stationary stochastic demand. The existing work on shelf life in planning approaches under economic objectives thus only deals with demand volume uncertainty, while the impact of variable product prices is not discussed. In addition, none of these studies addresses the economic value of shelf life.

3.3.2 Economic value of storage and price variability

A range of analytical papers from the energy sector has analyzed the economic value of storage capacity under uncertain prices. Lai et al. (2011), for instance, develop a heuristic to determine the value of storing liquefied natural gas at a regasification terminal. Their heuristic accounts for seasonal and volatile natural gas prices, shipping models, and inventory control. Arvesen et al. (2013) analyze the option of using different injection and withdrawal rates in natural gas pipelines as a means for short-term gas storage. They value the storage option of this so-called linepack for power plants by applying a Least Squares Monte Carlo algorithm, incorporating both gas price (i.e., input) and electricity price (i.e., output) volatilities. They find that the linepack storage option has significant value for power plants to better exploit the sometimes extreme electricity price fluctuations. While the available analytical papers determine the economic value of storage capacity, the related issue of a limited storage duration (i.e., shelf life) has not been considered so far. The economic value of shelf life under price variability thus has not been tackled. Furthermore, despite the possibility to optimally determine the economic value of storage, a major drawback of analytical approaches is the lacking inclusion of other criteria and thus, for instance, the neglect of economic and environmental trade-offs.

3.3.3 Environmental impacts and shelf life

Several studies consider the impact of novel techniques on products' shelf life and environmental sustainability. Valsasina et al. (2017) describe the future potential of applying one-stage ultrahigh pressure homogenization (encompassing ultrahigh temperature) instead of conventional homogenization followed by ultrahigh heat treatment for the preservation of milk. In their case, the novel technique results in both a higher product shelf life and an improved environmental sustainability. Hoang et al. (2016) and Claussen et al. (2011) compare the environmental impacts of fish cold chains that use traditional chilling or new superchilling technologies. They point to the higher environmental sustainability of superchilled fish along the supply chain, which, in addition, has the advantage of an extended shelf life at the customer stage. Manfredi et al. (2015) assess the environmental impacts of incorporating antimicrobial agents into a packaging film for fresh milk. Although the antimicrobial coating goes along with additional environmental impacts, the authors argue for an overall lower environmental impact due to food waste reduction at the customer stage. This finding is true for the specific case in which an initially low shelf life can be increased significantly (i.e., shelf life increases from two to nine days). The relation between shelf life and environmental sustainability thus depends on the assumption of whether and to what extent food waste is affected. Pardo and Zufía (2012) compare four different technologies for preserving finished meals. They find that the most environmentally sustainable and novel solution, namely modified atmosphere packaging, reduces shelf life by half compared to traditional but less sustainable heat treatment. Novel techniques thus must be assessed carefully to determine whether environmental sustainability is enhanced in line with shelf life or at its expense. Yet, no study explicitly considered the impact of shelf life on environmental sustainability.

The possibility to improve products' environmental sustainability with novel combinations of existing technologies has also been addressed in several studies (e.g., Cespi et al., 2014; Huntzinger and Eatmon, 2009). However, only Depping et al. (2017) so far have considered the effect of these combinations on the products' shelf life. Combinations including less intensive process conditions thereby lead to a reduced shelf life while increasing environmental sustainability. No study has explicitly looked into the challenges that can arise from a trade-off between environmental sustainability and shelf life.

3.3.4 Multiple sustainability objectives and shelf life

Only few studies consider the environmental and economic benefits of products in combination with their shelf life. In multi-objective approaches, shelf life has been included either explicitly as an objective or within the model constraints. Sazvar et al. (2014) develop a bi-objective stochastic mathematical model that accounts for the deterioration process of products and determines both the optimal inventory policy and the type of transportation vehicles. Both economic (i.e., cost) and environmental (i.e., greenhouse gas emission) criteria are considered under uncertain demand volumes. Their generic, bi-objective tactical-operational model is valid for supply chains of perishable products. The analyzed problem settings therefore exhibit some similarities to our paper, but the developed methodologies are different. In the chemical industry, You et al. (2012) determine the optimal network design of a cellulosic ethanol supply chain with a multi-objective optimization model. Besides the minimization of costs and greenhouse gas emissions, a social objective is considered in terms of the maximization of accrued jobs along the supply chain. They account for the shelf life of biomass used for ethanol production. The shelf life, however, is simply modeled as a percentage of deteriorated biomass.

Although challenges associated with highly perishable products are common within the food industry, corresponding papers investigating shelf-life restrictions in multi-objective optimization are scarce. Soysal et al. (2014) design a generic beef network using a bi-objective model with greenhouse gas emissions as an environmental indicator. They consider product perishability by restricting the maximum number of periods that beef can be stored. Furthermore, shelf-life restrictions are accounted for in two multi-objective vehicle routing papers (Bortolini et al., 2016; Govindan et al., 2014). While Govindan et al. (2014) consider the same objectives as Soysal et al. (2014), Bortolini et al. (2016) additionally minimize delivery time as a third objective.

No study to date captures the influence of shelf life on the combined economic and environmental evaluation of products. Based on a real-life case study, we take a first step in assessing the extent to which the choice of production processes is determined by perishability of the resulting food products. To quantify the effects of shelf-life reduction, we cover product price variability and develop a multi-objective optimization model that includes, besides profit, all relevant environmental indicators.

3.4 Problem definition and dairy supply chain context

The case of substituting milk powders with milk concentrates exemplifies the impact of shelf-life reduction due to sustainable processing. Milk powders are one of the key intermediate products in the dairy sector. They consume large amounts of energy in the drying process. A large proportion of this energy can be saved by producing concentrates instead of using novel processing variants. However, the shelf life of concentrates is significantly lower. We therefore compare the shelf-stable milk powders to novel, shelf-life-reduced milk concentrates. The comparison must capture the impact of price variability. Under fluctuating prices, shelf-stable milk powders allow for the delay of sales until a higher price level is reached. Consequently, higher profits can be realized; however, this requires information on the upcoming prices. The value of shelf life therefore depends on the accuracy of the price information.

While long shelf life can have an economic benefit in the case of fluctuating prices, environmental impacts increase with longer shelf lives and longer storage durations under chilled conditions. Switching to more environmental-friendly milk concentrates thus impacts the trade-off between the economic and the environmental performance. Moreover, the environmental performance must be assessed through a whole range of environmental indicators.

The following additional problem characteristics have to be captured in the comparison of the two types of dairy products. At the processing stage, a multitude of processing variants results in numerous different powder and concentrate products. These processing variants differ in their processing impacts and product losses. Furthermore, the resulting products differ in storage and transportation impacts. They may require ambient or chilled temperatures. They differ in their degree of concentration that determines the product mass needed to fill customer demand. Therefore, all supply chain stages, from farming to customers, have to be considered. Detailed economic and environmental data for all stages must be elicited.

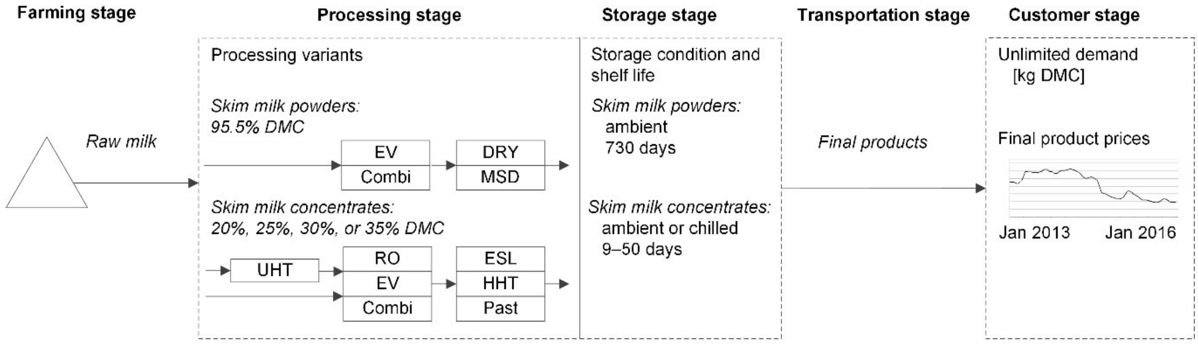

Figure 3.1. Representation of the skim-milk-powder and skim-milk-concentrate supply chain. Abbreviations: Combi–reverse osmosis and subsequent evaporation, DMC–dry-matter content, DRY–spray drying, ESL–extended shelf life, EV–evaporation, HHT–high-heat treatment, MSD–multi-stage drying, Past–pasteurization, RO–reverse osmosis, UHT–ultrahigh temperature.

The supply chain for skim-milk powders and concentrates (see figure 3.1) consists of the following stages: farming, processing, storage, transportation, and customer. The present case considers a dairy plant that has long-term contracts with its supplying dairy farms or a cooperative in which farmers own the plant. Raw milk volumes are therefore delivered to the dairy plant and must be processed into powders or concentrates.

Skim-milk powders are typically processed into a dry-matter content (DMC) of around 95.5%. The industrial skim-milk-powder production process comprises a facultative skim milk pre-concentration step involving reverse osmosis, followed by multiple-effect evaporation, and subsequent immediate drying. Skim-milk concentrates, on the other hand, can be produced to different final dry-matter contents. This study considers four concentrate dry-matter contents: 20%, 25%, 30%, and 35%. Processing variants related to obtaining these four degrees of concentration are selected based on previous research (cf. Depping et al., 2017; Stefansdottir and Grunow, 2018). The production process of concentrates consists of an optional pre-heat treatment, a concentration step involving reverse osmosis, evaporation, or a combination of the two, and, finally, a post-heat treatment. Considered heat treatments include ultrahigh temperature (137 °C, 5 s), extended shelf life (125 °C, 2 s), high-heat treatment (120 °C, 5 s), and pasteurization (72 °C, 25 s).

Powders are stored under ambient conditions. Their shelf life of around two years is limited by caking or other physical changes resulting in decreasing redispersability and flowability in dispensing systems. These effects depend on the processing conditions (e.g., on whether lactose is pre-crystallized) and on the storage conditions (i.e., relative humidity and time).

Table 3.1
Different skim-milk-powder and skim-milk-concentrate products.

Product (Processing variant–DMC)	**Storage condition**	**Shelf life (days)**	**Limiting cause for shelf life**
Skim-milk powders			
EV–DRY–95.5%	ambient	≤ 730	Caking
Combi–DRY–95.5%	ambient	≤ 730	Caking
EV–MSD–95.5%	ambient	≤ 730	Caking
Combi–MSD–95.5%	ambient	≤ 730	Caking
Skim-milk concentrates			
RO–Past–20%	chilled	9	MO – vegetative cells
EV–Past–20%	chilled	9–15	MO – vegetative cells
RO–Past–25%	chilled	9	MO – vegetative cells
EV–Past–25%	chilled	9–15	MO – vegetative cells
UHT–RO–ESL–25%	ambient	40	Age-gelation
UHT–EV–ESL–25%	ambient	40	Age-gelation
RO–Past–30%	chilled	14	MO – vegetative cells
EV–Past–30%	chilled	14–20	MO – vegetative cells
RO–HHT–30%	chilled	20	MO – bacterial spores
EV–HHT–30%	chilled	20	MO – bacterial spores
UHT–RO–ESL–30%	ambient	22	Age-gelation
UHT–EV–ESL–30%	ambient	22	Age-gelation
RO–Past–35%	chilled	19	MO – vegetative cells
EV–Past–35%	chilled	19–30	MO – vegetative cells
Combi–Past–35%	chilled	19–30	MO – vegetative cells
UHT–RO–HHT–35%	chilled	50	Age-gelation
UHT–EV–HHT–35%	chilled	50	Age-gelation
UHT–Combi–HHT–35%	chilled	50	Age-gelation

Abbreviations: Combi–reverse osmosis and subsequent evaporation, DMC–dry-matter content, DRY–spray drying, ESL–extended shelf life, EV–evaporation, HHT–high-heat treatment, MO–microbial growth, MSD–multi-stage drying, Past–pasteurization, RO–reverse osmosis, UHT–ultrahigh temperature.

By contrast, most concentrates must be stored under chilled conditions, while ambient storage conditions are only applicable for certain pre-heated concentrates. The perishability of skim-milk concentrates is determined mainly by the applied thermal pre-heat and post-heat treatments (Dumpler and Kulozik, 2016, 2015; Dumpler et al., 2017b). In case pre-heat treatment is applied in concentrate production, age-gelation becomes the limiting factor for shelf life. Otherwise, shelf life is restricted by microbial growth. Pasteurized concentrates produced with evaporation have a higher shelf life than those produced with reverse osmosis since the heat treatment via evaporation already leads to a reduced initial bacterial count. Table 3.1 summarizes the different skim-milk powder and skim-milk-concentrate products as well as their storage conditions and shelf lives.

In the downstream chain, powders and concentrates are transported to customers under chilled or ambient conditions. A flexible market with variable demand is considered, as fixed demand can already be subtracted from the total demand volumes. Customers require a certain mass of dry-matter content, which can be fulfilled by either powders or concentrates. Whereas concentrates are directly applied in fluid end products, powders must be reconstituted. Final product prices per kilogram dry-matter content are subject to fluctuations.

3.5 Methodology

3.5.1 Evaluation framework

We develop a framework for evaluating the impact of shelf life on the trade-off between the economic and environmental performance of milk powders and concentrates (see figure 3.2). The differences in shelf life have their main impact at the tactical planning level. We therefore perform repeated tactical planning and use the results to draw strategic conclusions on product and process selection.

Part of the data relating to the identified processing variants, such as shelf life, is a direct input to the optimization model. The other part forms the basis for calculating economic and environmental parameters required for the objective functions. The environmental parameters are determined with an attributional LCA. An attributional LCA describes the environmental impact of a product system in steady state, therefore providing insight into the average environmental impact of a product over its life cycle at a certain point in time (Hospido et al., 2010). A detailed approach is applied in which inputs and outputs are assessed for each processing step along the supply chain. This allows for a comparison of different processing variants for skim-milk powders and concentrates. Economic and environmental parameter values are listed in section 3.6.1.

The multi-objective optimization model described in section 3.5.2 is based on one economic objective and several environmental objectives that are first solved separately (single-objective optimization). To deal with uncertainty in final product prices, a rolling horizon scheme is developed. Model solving with the economic objective is implemented within the rolling horizon scheme. At the beginning of the first period, the model is solved based on price predictions of a selected horizon and only the decisions of the current period are fixed. Then, one period later, the price predictions are updated and the model is solved again. This procedure is repeated within the rolling horizon scheme. Due to the perishability of the products, the age of the stored products must be tracked within the rolling horizon scheme.

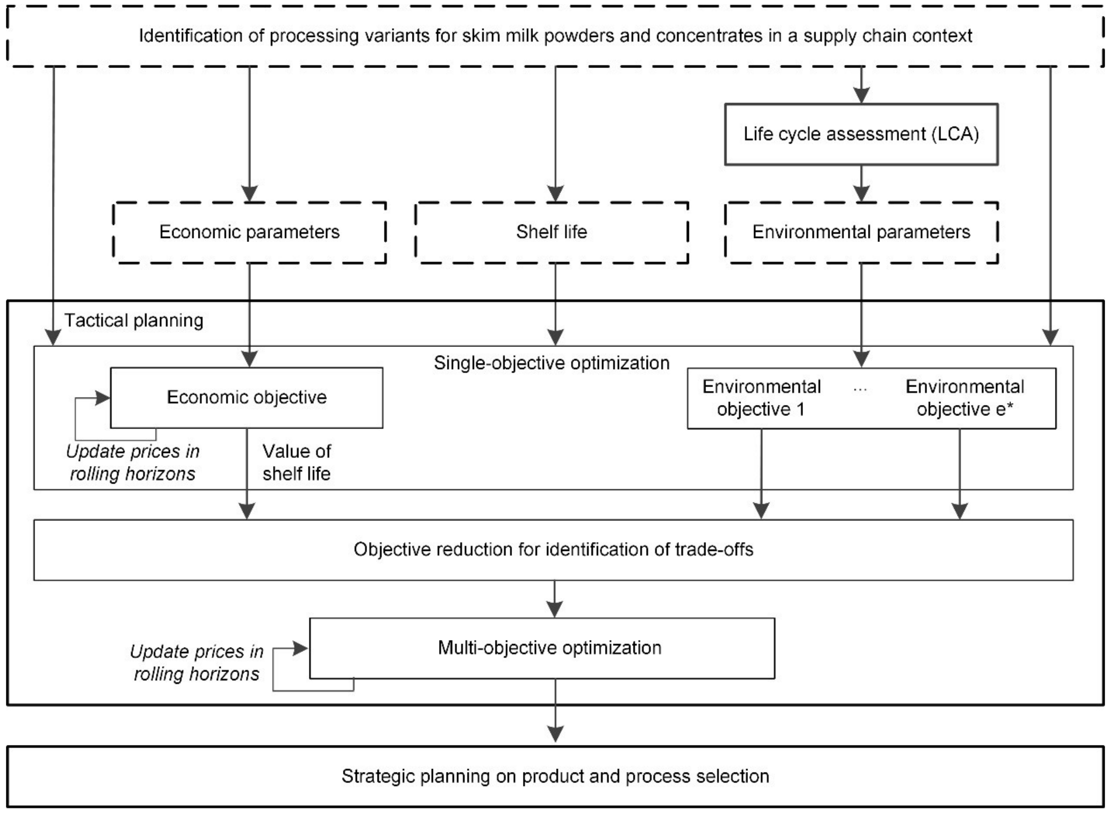

Figure 3.2. Overview of the developed evaluation framework. Standard boxes represent applied methods, dashed boxes represent input parameters.

After solving each objective of the optimization model separately, objective reduction is carried out to limit the difficulties of dealing with several objective functions. The selected approach for reducing objectives is outlined in section 3.5.3. Subsequently, the reduced set of objectives is optimized with the multi-objective optimization model and a range of weighted trade-off solutions is determined, among which decision makers can choose according to their preferences. Finally, the results of the repeated tactical planning are used to select products and processes at the strategic planning level.

3.5.2 Multi-objective optimization model

We develop a multi-objective mixed integer linear programming (MO-MILP) model for the tactical planning of perishable dairy products, accounting both for economic and environmental criteria. The model determines production, storage, and shipment quantities of the different products in each period. The benefit of the storage option, depending on the product's shelf life, is therefore quantified.

The following assumptions are made:

- Depreciation costs are excluded, assuming that equipment units are already in place at a tactical planning level. Since capital goods account for less than 1% of the total environmental impacts at the dairy plant, they are excluded from the environmental parameters.
- Product-dependent production costs and impacts include utility consumption (during production and cleaning) and wastewater generation for all processing stages, as well as required packaging materials.
- Storage capacities for different storage conditions (i.e., ambient or chilled) are limited.
- Transportation capacities are sufficient.
- Products must be shipped within their shelf life. Here, shelf life refers to the time that products may be stored at the dairy plant. This excludes the time needed for transportation as well as the minimum remaining shelf life required by customers.

The following notation is introduced for the model:

Indices and index sets

$p \in P$	product
$j \in J$	product type
$p' \in P(j)$	product belonging to product type *j*
$n \in N$	storage condition
$p'' \in P(n)$	product stored in storage condition *n*
$t \in T$	period
$t' \in T$	production period
$e \in E$	environmental indicator

Parameters

u_t	contracted supply of raw milk in period *t* [kg raw milk]
α	waste in raw milk transportation [%]
f_p	raw factor – amount of raw milk required for 1 kg DMC of product *p* [kg raw milk]

v_p volume of product *p* [m^3/kg DMC]

l_p shelf life of product *p* [periods]

β_j maximum fraction for production of product type *j* per period [%]

b_n storage capacity of storage condition *n* [m^3]

d transportation distance of final products [km]

γ_p waste in reconstitution for product *p* [%]

r_t product price in period *t* [costs/kg DMC]

c_t^{raw} raw milk costs (including transportation) in period *t* [costs/kg raw milk]

c_p^{prod} production costs (including packaging material) of product *p* [costs/kg DMC]

c_p^{inv} inventory costs for product *p* per period [costs/(kg DMC · period)]

c_p^{trans} transportation costs for product *p* [costs/(kg DMC · km)]

i_e^{raw} raw milk impact (including transportation) of environmental indicator *e* [impact/kg raw milk]

i_{pe}^{prod} production impact (including packaging material) of product *p* of environmental indicator *e* [impact/kg DMC]

i_{pe}^{inv} inventory impact of product *p* per period of environmental indicator *e* [impact/(kg DMC · period)]

i_{pe}^{trans} transportation impact of product *p* of environmental indicator *e* [impact/(kg DMC · km)]

Decision variables

$X_{pt'}$ quantity of product *p* produced in period *t'* [kg DMC]

$I_{pt't}$ inventory of product *p* produced in period *t'* at the end of period *t* *(t'≤t)* [kg DMC]

$Z_{pt't}$ quantity of product *p* produced in period *t'* and shipped in period *t* *(t'≤t)* [kg DMC]

D_t demand fulfilled in period *t* [kg DMC]

The multi-objective model is formulated as follows:

$$max\left\{\sum_{t\in T} r_t \cdot D_t - \sum_{t\in T} c_t^{raw} \cdot u_t - \sum_{p\in P}\sum_{t'\in T} c_p^{prod} \cdot X_{pt'} - \sum_{p\in P}\sum_{t'\in T}\sum_{t\in T} c_p^{inv} \cdot I_{pt't} - \sum_{p\in P}\sum_{t'\in T}\sum_{t\in T} c_p^{trans} \cdot d \cdot Z_{pt't}\right\} \quad (1)$$

$$min\left\{\sum_{t\in T} i_e^{raw} \cdot u_t + \sum_{p\in P}\sum_{t'\in T} i_{pe}^{prod} \cdot X_{pt'} + \sum_{p\in P}\sum_{t'\in T}\sum_{t\in T} i_{pe}^{inv} \cdot I_{pt't} + \sum_{p\in P}\sum_{t'\in T}\sum_{t\in T} i_{pe}^{trans} \cdot d \cdot Z_{pt't}\right\} \quad \forall e \in E \quad (2)$$

subject to

$$u_{t'} \cdot (1-\alpha) = \sum_{p\in P} X_{pt'} \cdot f_p \quad \forall t' \in T \quad (3)$$

$$I_{pt't} = X_{pt'} - Z_{pt't} \quad \forall p \in P, t' \in T, t \in T: t' = t \quad (4)$$

$$I_{pt't} = I_{pt',t-1} - Z_{pt't} \quad \forall p \in P, t' \in T, t = 2, \ldots, T: t' < t \quad (5)$$

$$\sum_{t'\in T} X_{pt'} \leq \sum_{t'\in T}\sum_{t\in T} Z_{pt't} \quad \forall p \in P \quad (6)$$

$$\sum_{p'\in P(j)} X_{p't'} \leq \beta_j \cdot \sum_{p\in P} X_{pt'} \quad \forall j \in J, t' \in T \quad (7)$$

$$\sum_{p''\in P(n)}\sum_{t'\in T} I_{p''t't} \cdot v_{p''} \leq b_n \quad \forall n \in N, t \in T \quad (8)$$

$$\sum_{p\in P}\sum_{t'=t-l_p}^{t} Z_{pt't} \cdot \left(1-\gamma_p\right) = D_t \quad \forall t \in T \quad (9)$$

$$X_{pt'} \geq 0 \quad \forall p \in P, t' \in T \quad (10)$$

$$I_{pt't} \geq 0 \quad \forall p \in P, t' \in T, t \in T \quad (11)$$

$$Z_{pt't} \geq 0 \quad \forall p \in P, t' \in T, t \in T \quad (12)$$

$$D_t \geq 0 \quad \forall t \in T \quad (13)$$

In the above formulation, the first objective function aims to maximize the profit (1). The profit comprises the revenues of sold products and the costs along the supply chain, i.e., raw milk costs, production costs, inventory costs, and transportation costs. The second objective function aims to minimize environmental impacts related to the dairy supply chain (2), comprising raw milk impacts, production impacts, inventory impacts, and transportation impacts. The model allows for the consideration of environmental impacts in several environmental impact categories.

Constraints (3) guarantee that total supplies of raw milk are sent from the dairy farms to the dairy plant, also accounting for waste in raw milk transportation. Thereafter, the raw milk is processed into different types of final products. Constraints (4) and (5) represent inventory balances in which the age of the products is tracked. Products in inventory stem either from production in the current period (4) or from inventory at the end of the previous period (5). Constraints (6) ensure that total production quantities of each product are shipped to customers. This restriction is only required for the minimization of environmental impacts, not for profit maximization.

The total production quantities of a specific product type, e.g., powders or concentrates, may be restricted (7). Furthermore, storage capacities for different storage conditions must be respected (8). Constraints (9) ensure that the storage duration of the final products is never longer than the respective shelf life. Products with a long shelf life (like powders) can therefore be stored for more time periods than products with a short shelf life (like concentrates) in order to take advantage of fluctuations in final product prices. Demand fulfillment is also modeled with constraints (9), accounting for waste in reconstitution. Finally, constraints (10–13) are non-negativity constraints.

3.5.3 Objective reduction for identification of trade-offs

Three main methods have been proposed for objective reduction: weighting, including pre-defined weighting schemes like the Eco-Indicator 99, principal component analysis, and the δ-error method. Since weighting omits essential trade-offs between multiple objectives and the principal component analysis lacks to determine the error of combining indicators to principal components, we opt to apply the δ-error method for objective reduction (cf. Brockhoff and Zitzler, 2006). The goal of this method is to identify a subset of objectives so that the error of omitting objectives is at a minimum. The δ-error is thus a measure for the approximation error in objective reduction that quantifies the change in the dominance structure if one solution becomes dominant compared to another. Brockhoff and Zitzler (2006) introduce two different methods for computing the minimum objective subset (MOSS), i.e., the δ-MOSS method, which finds a minimum objective subset for a maximum allowable approximation error and the k-MOSS method, which finds an objective subset of size k with a minimum error. In this study, the δ-MOSS method is applied. The δ-error is defined as in Guillén-Gosálbez (2011):

$$(O_{s'm} - O_{sm}) \cdot Y_m \cdot W_{ss'} = \delta_{ss'm} \quad \forall s \in S, s' \in S, m \in M \tag{14}$$

The parameter O_{sm} is the value of the objective m for solution s. The decision variable Y_m equals 1 if objective m is removed (0 otherwise) and the decision variable $W_{ss'}$ equals 1 if s' dominates s in the reduced space (0 otherwise). The error $\delta_{ss'm}$ is then defined as the difference between the value of objective m in solutions s' and s. This approach allows for the reduction of objectives, while determining and restricting the error of collapsing indicators. Relevant trade-offs can therefore be identified.

3.6 Analyses of skim-milk powders and concentrates

The accessed data on skim-milk powders and skim-milk concentrates is outlined in the following. Results are presented first for the economic objective, since shelf life can provide an additional value for this objective. Subsequently, economic and environmental objectives are considered jointly and trade-offs arising after objective reduction are analyzed.

3.6.1 Parametrization through LCA, cost analysis, and dairy futures

The model is solved with real-life data from two German dairy companies, one producing powders and concentrates, and one using these intermediates to make final products. We collected economic and environmental data at these companies and at equipment manufacturers at all supply chain stages. This industrial data was complemented with experimental data from food engineering (cf. Dumpler and Kulozik, 2015; Dumpler and Kulozik, 2016; Dumpler et al., 2017a; Dumpler at al., 2017b) and literature data.

The planning horizon is one year with a granularity of weeks, leading to 52 periods t. Altogether 22 products p are assessed (see Table 3.1), which are of two product types j, i.e., powders and concentrates. The products are also subdivided according to their required storage condition n into products that can be stored in an ambient environment and products that require a chilled environment. We conducted an LCA that covers four environmental indicators e: cumulative energy demand (CED), global warming potential (GWP), eutrophication potential (EP), and acidification potential (AP). Indicators were selected for their importance to the dairy products' supply chain (De Vries and De Boer, 2010). To ensure compatibility with the literature-based raw-milk production impacts derived from Guerci et al. (2013), the same environmental impact assessment method and characterization factors were used in the LCA of the downstream chain. The methods specified in EPD (2008) were applied for this purpose. For a more detailed description of the conducted LCA, see Depping et al. (2017). The following parameters resulted for each supply chain stage.

Farming stage. The dairy plant is supplied by 200 local farms with an average distance of 100 km from the plant. In raw milk delivery, α = 0.04% of raw milk is wasted. The weekly raw milk supply used for variable demand for powder and concentrate production is on average around $u_t =$ 700,000 kg, which is assumed constant over the year. Raw milk costs (including the delivery costs) are on average over the planning horizon $c_t^{raw} = 0.377$ €/kg, according to long-term contracts with the farms. For the raw milk impacts i_e^{raw}, averages of the environmental impact ranges per kilogram energy-corrected milk from Guerci et al. (2013) were used, namely CED–3.4709 MJ, GWP–1.2691 CO_2-eq, EP–0.0032 PO_4^{--}-eq, and AP–0.0169 SO_2-eq.

Processing stage. At the dairy plant, runtimes, cleaning times, utility consumption, wastewater generation, and product losses were assessed for each processing step. In addition, the required packaging material was determined. Table 3.2 summarizes the resulting costs c_p^{prod} and environmental impacts i_{pe}^{prod} as well as the amount of raw milk required, the so-called raw factor f_p, to produce one ton dry-matter content of different products. The raw factor comprises necessary volume reduction and product losses in processing. Seasonal variations in the composition of raw milk as discussed by Banaszewska et al. (2013) were excluded, since in the present case the changes to the raw factor were minor and did not affect the results. Product shelf lives l_p are shown in table 3.1.

Table 3.2
Economic and environmental data on production, encompassing packaging material.

Product (Processing variant–DMC)	Raw factor[a]	Costs [€/ton DMC]	CED [MJ/ton DMC]	GWP [ton CO_2-eq/ton DMC]	EP [g PO_4^{3-}-eq/ton DMC]	AP [g SO_2-eq/ton DMC]
Skim-milk powders						
EV–DRY–95.5%	7,016	291.81	19,351	1,143.95	2.4495	1.7094
Combi–DRY–95.5%	6,979	224.07	14,617	869.81	1.7477	1.7219
EV–MSD–95.5%	7,000	315.79	21,140	1,278.52	16.9716	3.0247
Combi–MSD–95.5%	6,963	248.21	16,416	1,004.98	16.2714	3.0372
Skim-milk concentrates						
RO–Past–20%	6,950	178.75	7,368	414.09	1.4777	1.3558
EV–Past–20%	6,955	226.65	10,749	607.36	1.9984	1.2134
RO–Past–25%	6,949	151.35	6,448	366.41	1.2353	1.2473
EV–Past–25%	6,963	211.65	10,685	610.36	1.8659	1.1521
UHT–RO–ESL–25%	6,957	191.31	9,273	540.43	1.5392	1.6791
UHT–EV–ESL–25%	6,970	251.67	13,515	784.68	2.1703	1.5847
RO–Past–30%	6,946	135.96	5,947	341.77	1.0864	1.2133
EV–Past–30%	6,973	202.77	10,698	615.94	1.7870	1.1317
RO–HHT–30%	6,946	143.04	6,343	366.57	1.1375	1.2645
EV–HHT–30%	6,974	209.85	11,095	640.76	1.8382	1.1829
UHT–RO–ESL–30%	6,953	174.73	8,683	510.46	1.3809	1.6400
UHT–EV–ESL–30%	6,981	241.67	13,444	785.21	2.0825	1.5599
RO–Past–35%	6,959	150.97	6,687	394.09	1.0991	1.5504
EV–Past–35%	6,981	196.28	10,708	619.98	1.7311	1.1274
Combi–Past–35%	6,950	129.91	6,056	351.19	1.0438	1.1880
UHT–RO–HHT–35%	6,967	188.23	9,321	556.57	1.3816	1.9693
UHT–EV–HHT–35%	6,990	233.65	13,351	782.97	2.0144	1.5475
UHT–Combi–HHT–35%	6,958	167.13	8,686	513.48	1.3260	1.6063

[a] Mass of raw milk required to produce 1 ton of dry-matter content.

Abbreviations: AP–acidification potential, CED–cumulative energy demand, Combi–reverse osmosis and subsequent evaporation, DMC–dry-matter content, DRY–spray drying, EP–eutrophication potential, ESL–extended shelf life, EV–evaporation, GWP–global warming potential, HHT–high-heat treatment, MSD–multi-stage drying, Past–pasteurization, RO–reverse osmosis, UHT–ultrahigh temperature.

Storage and transportation stages. The required storage volume v_p depends on the dry-matter content of the products: 20%–0.0451 m^3/kg DMC, 25%–0.0354 m^3/kg DMC, 30%–0.0289 m^3/kg DMC, 35%–0.0242 m^3/kg DMC, and 95.5%–0.0102 m^3/kg DMC. Unlimited storage capacities b_n are assumed since there is sufficient ambient storage space at the dairy plant and, for chilled storage, there is a natural limit on the stored quantities due to the product's perishability.

Table 3.3.
Economic and environmental data on storage.

	Costs [€/ ton DMC·week]	**CED [MJ/ ton DMC·week]**	**GWP [ton CO_2-eq/ ton DMC·week]**	**EP [g PO_4^{3-}-eq/ ton DMC·week]**	**AP [g SO_2-eq/ ton DMC·week]**
ambient[a]					
25%	3.2346	-	-	-	-
30%	2.6955	-	-	-	-
95.5%	0.8467	-	-	-	-
chilled[a]					
20%	6.4042	199.93	12.5254	0.0157	0.0482
25%	5.1234	159.94	10.0204	0.0125	0.0385
30%	4.2695	133.29	8.3503	0.0104	0.0321
35%	3.6595	114.25	7.1574	0.0090	0.0275

[a] Dry-matter contents are only considered, if at least one corresponding product exists.

Abbreviations: AP–acidification potential, CED–cumulative energy demand, DMC–dry-matter content, EP–eutrophication potential, GWP–global warming potential.

Table 3.4
Economic and environmental data on transportation.

	Costs [€/ ton DMC·km]	**CED [MJ/ ton DMC·km]**	**GWP [ton CO_2-eq/ ton DMC·km]**	**EP [g PO_4^{3-}-eq/ ton DMC·km]**	**AP [g SO_2-eq/ ton DMC·km]**
ambient[a]					
25%	0.2619	12.84	0.8014	0.0024	0.0005
30%	0.2183	10.70	0.6678	0.0020	0.0005
95.5%	0.0686	3.36	0.2098	0.0006	0.0001
chilled[a]					
20%	0.3921	18.67	1.1732	0.0034	0.0008
25%	0.3137	14.94	0.9385	0.0028	0.0006
30%	0.2614	12.45	0.7821	0.0023	0.0005
35%	0.2241	10.67	0.6704	0.0020	0.0004

[a] Dry-matter contents are only considered, if at least one corresponding product exists.

Abbreviations: AP–acidification potential, CED–cumulative energy demand, DMC–dry-matter content, EP–eutrophication potential, GWP–global warming potential.

Table 3.3 shows the inventory costs c_p^{inv} and inventory impacts i_{pe}^{inv} related to storage under both ambient and chilled conditions. Likewise, Table 3.4 shows the transportation costs c_p^{trans} and transportation impacts i_{pe}^{trans} under both ambient and chilled conditions. A typical transportation distance to customers of $d = 500$ km is selected. It is assumed that transportation takes 1 day and that customers require a minimum remaining product shelf life of 5 days.

Customer stage. Skim-milk powder futures that were traded at the Eurex Frankfurt AG from the years 2013 and 2014 are used as predictors for final product prices r_t and contrasted to the realized prices on the German market. The futures have a horizon of up to 12 months, resulting in price predictions from 2013 up to 2016. Currently, the first skim-milk concentrates are on the market and show an identical price per kilogram dry-matter content as powders. Concentrates can be directly applied, while powders must be reconstituted, resulting in an average product loss of $\gamma_p = 4.2\%$ for powders.

3.6.2 Model solving

The price predictions for the next 52 weeks are updated weekly in the rolling horizon scheme and the model with the economic objective is run over 104 datasets (2 years). It is assumed that futures prices from the first period of each dataset equal the realized prices. All test runs are implemented and solved in IBM ILOG CPLEX Optimization Studio 12.6 on a 2.6 GHz Intel Xeon CPU with 32 GB RAM. Each dataset results in a problem size of around 62,000 decision variables and 32,000 constraints, which is solved to optimality in around 50 seconds. The rolling horizon scheme is solved over 104 datasets in approximately 1.5 hours.

3.6.3 Economic analyses of shelf life

3.6.3.1 Impact of price knowledge on production and storage

The economic performance of *a priori* perfect knowledge of prices was compared with using futures as price predictors. Figure 3.3a shows the actual skim-milk powder prices that were realized on the German market in the years 2013 up to 2016. While prices were rising or stable in 2013, prices were mostly falling steeply in 2014, reaching only 57% of their initial state at the end of 2014. The prices remained at a low level throughout 2015.

Profit-maximizing production, inventory, and shipment volumes of skim-milk powders and concentrates were determined based on *a priori* perfect price information. Figure 3.3b illustrates the planning results for the years 2013 and 2014. The figure summarizes the first period of each rolling horizon dataset, which is put into operation. Results showed that powders are preferred over concentrates if prices are expected to rise, as they can be stored over a longer period of time. The skim-milk powder option *Combi–Dry–95.5%* performed best. In the case of stable prices with small variabilities in the near future, the concentrate options *UHT–Combi–HHT–35%* and *Combi–Past–35%* were selected. The concentrate *UHT–Combi–HHT–35%* with a shelf life of 50 days is able to take advantage of near-time price increases, while the less-processed concentrate *Combi–Past–35%* with a shelf life of 19–30 days has a production cost advantage. In a sequence of periods with falling prices, solely the concentrate *Combi–Past–35%* was selected and sold immediately. Together, this shows how shelf life affects the selection of products under fluctuating prices.

Figure 3.4a shows twelve selected skim-milk powder future prices, in order to illustrate price predictions with futures. In March 2013, three futures predicted a slight price increase. The first two futures in April 2013 showed a slightly faster increase, while the third future in April 2013 predicted a slight decrease. In the same time periods, the actual prices for skim-milk powders rose significantly (see figure 3.3a). In September 2014, futures predicted an immediate price decrease with a subsequent increase in March and April 2015. On the other hand, the actual prices for skim-milk powders rose already in January and February 2015 (see figure 3.3a).

Figure 3.4b shows the production, inventory, and shipment volumes of skim-milk powders and concentrates when prices are predicted with futures. The same products are selected for price predictions with futures as for *a priori* perfect price knowledge. However, the decisions on inventory and shipment volumes were substantially different. In the case of price predictions with futures, the storage option was not used as much as with *a priori* perfect price knowledge. The lower inventory and shipment volumes of powders mainly resulted from futures not predicting the large price increase in March and April 2013. In addition, the recorded price fluctuations differed. The price variance, calculated over the 104 datasets of the rolling horizons, is remarkably higher for the actual prices ($\sigma^2 = 0.46$) than the future prices ($\sigma^2 = 0.30$). The possibility of using this higher price variability under *a priori* perfect price knowledge therefore led to an increased short-term storage of the rather shelf-stable concentrate *UHT–Combi–HHT–35%*.

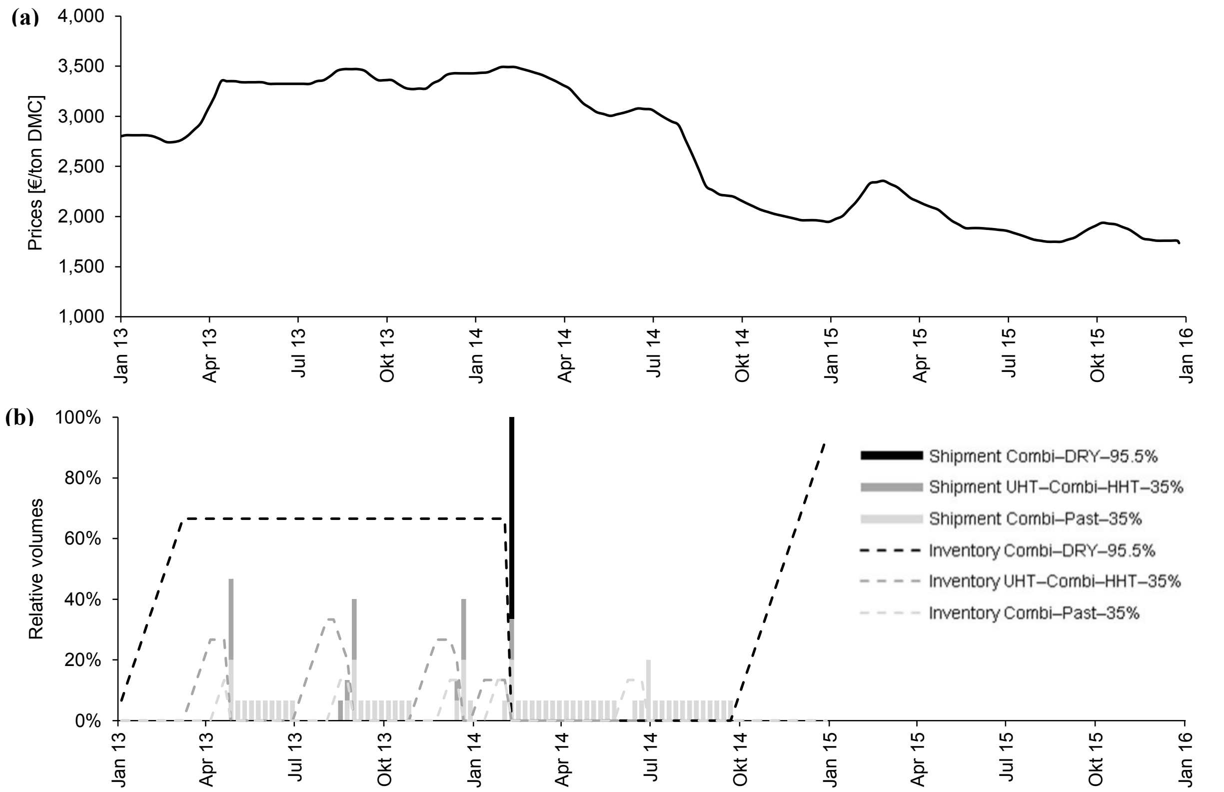

Figure 3.3. (a) Actual German skim-milk powder and concentrate prices for years 2013 up to 2016 (Source: Süddeutsche Butter- und Käse-Börse e.V.); (b) Relative shipment and storage volumes resulting from maximization of profit based on a priori perfect knowledge of prices for the years 2013 and 2014. Volumes are scaled to maximum shipment volumes reached.

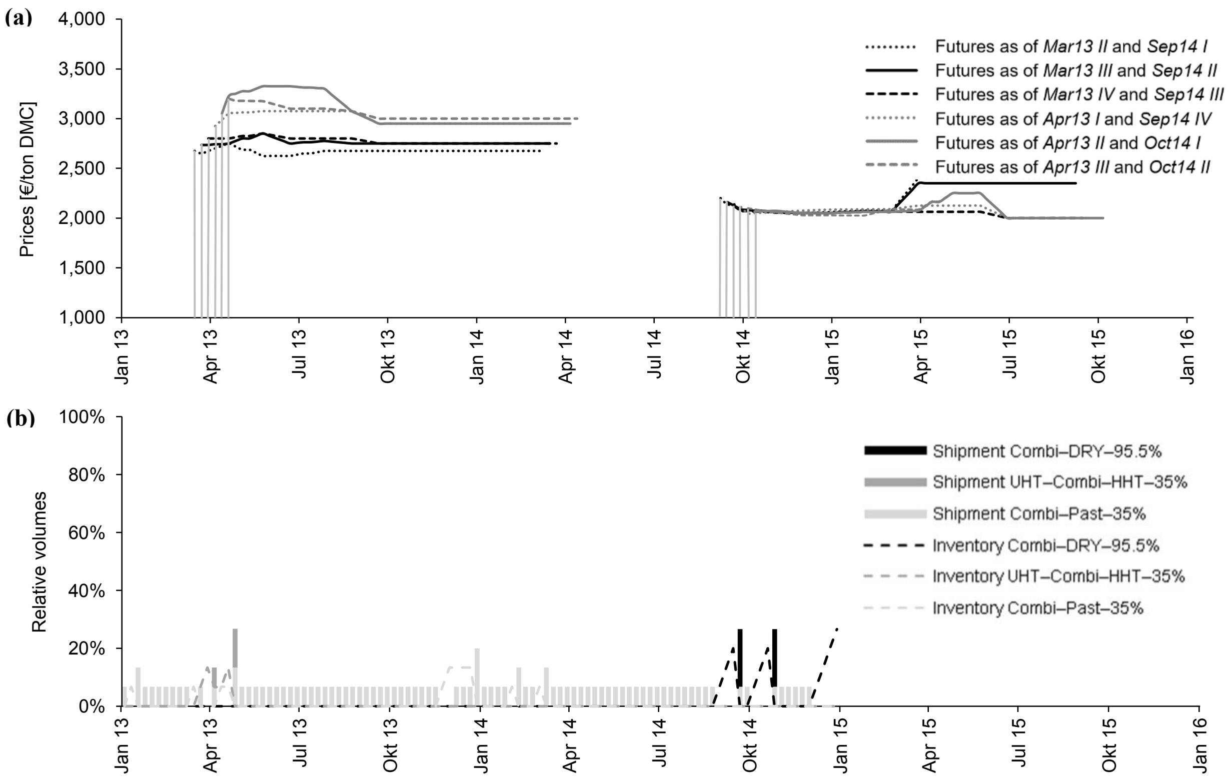

Figure 3.4. (a) Selected skim-milk powder future prices illustrating price predictions for years 2013 up to 2016 (Source: Eurex); (b) Relative shipment and storage volumes resulting from maximization of profit, based on futures as price predictors for years 2013 and 2014. Volumes are scaled to maximum shipment volumes reached based on a priori perfect price knowledge.

3.6.3.2 Value of shelf life

We analyzed the economic value of shelf life provided by powders for both *a priori* perfect price knowledge and price predictions with futures. The aim was to gain managerial insights into whether the long-storage option for powders, which enables the dairy plant to better exploit price variabilities, has a significant economic value. This value of shelf life is lost if producers change from powders to concentrates. In order to determine the value of shelf life, the production of skim-milk powders was restricted to an upper limit (β_j) of the production volume in each period (see constraints (7)), i.e., from 100% to 0% in 25% steps. Note that β_j has only an impact in periods that are attractive for powder production because prices are expected to rise. Figure 3.5 illustrates the resulting relative profits and the product mix (i.e., production volume shares for different powders and concentrates) over all periods of the planning horizon in case of different upper limits on powder production. Relative profits and product mixes were determined both based on *a priori* perfect price knowledge and on price predictions with futures.

The two price scenarios led to significant differences in profit, as upcoming price fluctuations were only captured to a limited extent by price predictions with futures. For unlimited use of powders ($\beta_{powders} = 1$), the difference was the highest. It amounted to 38.5% of the objective value based on *a priori* perfect price knowledge. This value can be interpreted as the expected value of perfect information (EVPI), i.e., the willingness of a decision maker to pay for perfect information on upcoming prices. Even for product mixes without powders ($\beta_{powders} = 0$), there exists a large profit gap.

For *a priori* perfect price knowledge, the optimal share of powder production over all periods of the planning horizon amounted to 23.0%. When restricting the upper limit of powder production to zero, production of the 50-days-storable concentrate *UHT–Combi–HHT–35%* increased from 14.4% to 20.2% with the rest being replaced by the less shelf-stable concentrate *Combi–Past–35%.* Profit decreased significantly. Powders have a potential economic value of shelf life of 34.5% (see figure 3.5). This shows a potentially large impact of shelf life on the economic performance. In contrast, price predictions based on futures resulted in an optimal powder share of only 9.6%. When restricting the powder production to zero, this powder share was replaced exclusively by the production of the less shelf-stable concentrate *Combi-Past–35%.* The economic value of shelf life amounted to merely 1.1% (see figure 3.5).

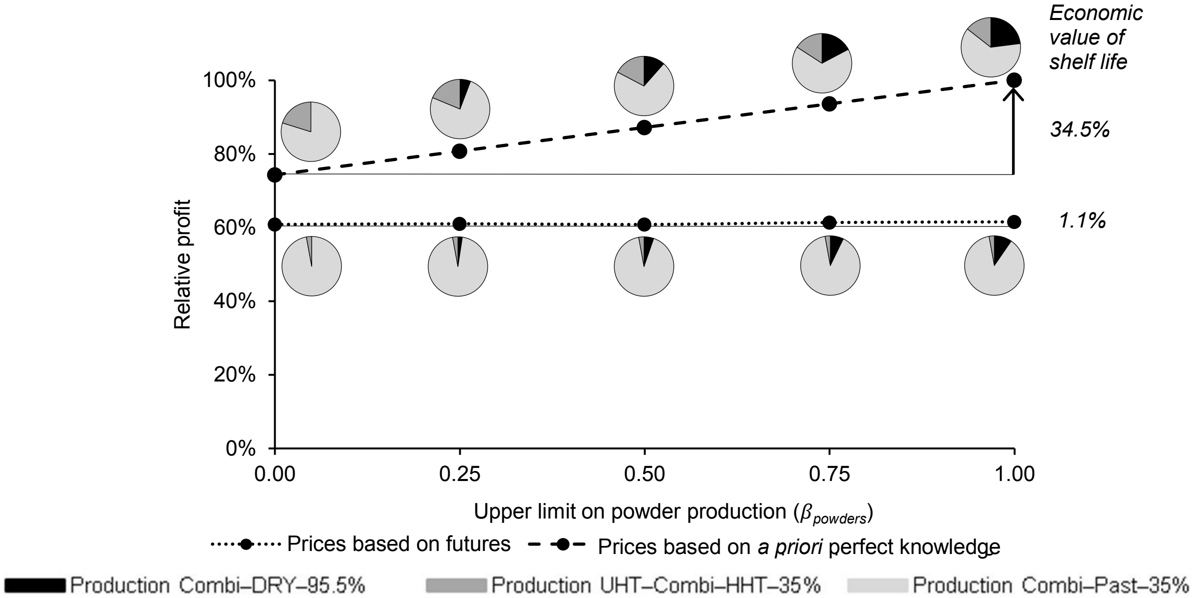

Figure 3.5. Economic value of shelf life. Pie charts indicate share of production volumes over all periods of the planning horizon. Abbreviations: Combi–reverse osmosis and subsequent evaporation, DRY–spray drying, HHT–high-heat treatment, Past–pasteurization, UHT–ultrahigh temperature.

We additionally tested the effect of not allowing any storage, which is equivalent to using a naïve price forecast. We found that an 8.0% lower profit was realized than with futures as price predictors, implying that predictions with futures are nonetheless valuable.

Overall, our results for this case show that the value of shelf life strongly depends on the forecast accuracy. In the realistic case, in which only limited price information is available, concentrates are selected over powders. If price indicators such as futures are used, the economic value of shelf life is not a strong argument against the substitution of powders with more environmental-friendly concentrates.

3.6.4 Trade-off between economic and environmental objectives

Next, we included the environmental objectives in the analyses. In the following tests, futures were used as price predictors and no upper limit on the production of a specific product type was assumed ($\beta_{powders} = 1$). After optimizing each objective separately, the δ-error method was applied to identify trade-offs between the different economic and environmental objectives. Figure 3.6 illustrates a parallel coordinates plot with the set of objectives on the horizontal axis and the normalized value attained by each solution on the vertical axis.

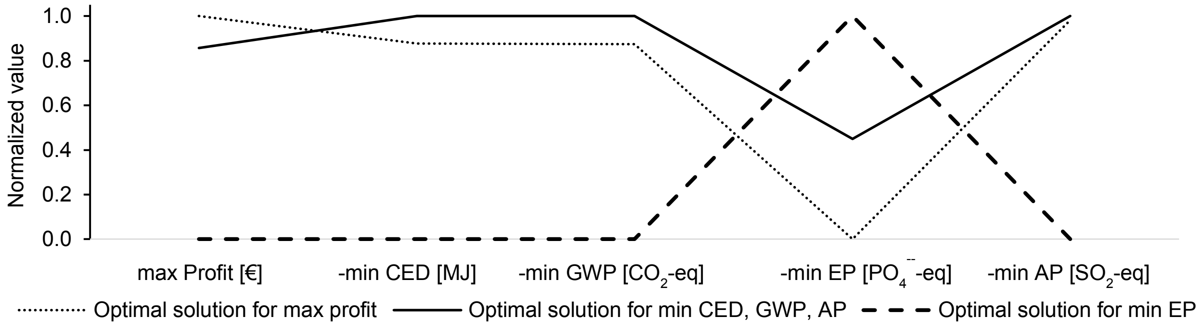

Figure 3.6. Parallel coordinates plot depicting the set of objectives in the horizontal axis and the normalized value of solutions in the vertical axis. Abbreviations: AP–acidification potential, CED–cumulative energy demand, EP–eutrophication potential, GWP–global warming potential.

The Pareto solutions were normalized to values between zero and one, based on Marler and Arora (2004). A value of one indicates the best objective value across the Pareto solutions for both maximization and minimization problems. Each line represents a different Pareto solution. The product mix obtained when maximizing profit in section 3.6.3 results in the normalized objective values represented by the dotted line in figure 3.6. The same Pareto solutions were reached when minimizing cumulative energy demand, global warming potential, and acidification potential (solid line). This solution represents a production of *Combi–Past–35%* in every period with immediate shipments and no storage. When minimizing eutrophication potential, *EV–Past–35%* was selected (dashed line). In both cases, the production of concentrates with a low shelf life is optimal (*Combi/EV–Past–35%)*. This stems from the use of more environmental-friendly processes (i.e., pasteurization) for low-shelf-life products and from omitting storage, which avoids additional environmental impacts.

To perform objective reduction according to the δ-error method, we analyze redundancies between objectives. There is a redundancy between cumulative energy demand, global warming potential, and acidification potential. Thus, the objective set can be reduced to the subset {profit, CED, EP} without losing any problem characteristics. When also removing cumulative energy demand from the subset, a δ-error of zero results, i.e., the dominance structure is not changed. Hence, a bi-criteria problem with the subset {profit, EP} is obtained.

When optimizing the bi-criteria problem, weighting was selected to determine intermediate solutions between the extreme points generated by single objective optimization. For this purpose, both objectives are normalized.

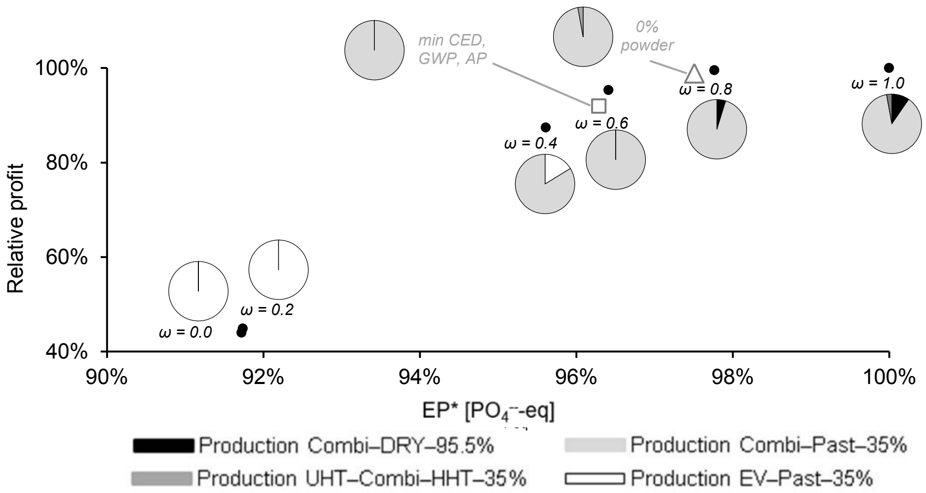

Figure 3.7. Trade-off between profit and eutrophication potential with futures as price predictors. Pie charts indicate share of production volumes over all periods of the planning horizon. The profit objective is assigned weight ω. The square represents the optimal solution for the indicators cumulative energy demand, global warming potential, and acidification potential. The triangle represents the optimal solution with 0% powders and prices based on futures. Abbreviations: Combi–reverse osmosis and subsequent evaporation, DRY–spray drying, EP*–share of eutrophication potential that plant can influence, HHT–high-heat treatment, Past–pasteurization, UHT–ultrahigh temperature.

Figure 3.7 illustrates a clear trade-off between profit and eutrophication potential. Here, EP* is defined as the share of eutrophication potential that the dairy plant can influence. EP* thus excludes the large and fixed eutrophication potential originating from raw milk production, which is the same for all solutions due to the fixed raw milk supply (u_t). The weight of the profit is ω and the weight of the eutrophication potential (EP*) is $1-\omega$.

By decreasing ω from 1.0 to 0.0, the initial product mix of *Combi–Past–35%*, *UHT–Combi–HHT–35%*, and *Combi–DRY–95.5%* at ω = 1.0 was altered. At ω = 0.8, *UHT–Combi–HHT–35%* was eliminated and the production of *Combi–DRY–95.5%* is reduced, since both production and storage of longer shelf-life products cause additional eutrophication potential. At ω = 0.6, all powder production was eliminated. Only *Combi–Past–35%* was produced. The profit only decreased by 4.7% compared to the profit for ω = 1. Even if the shelf life of *Combi–Past–35%* is significantly lower, the profit decline is limited. The reason lies in the low value of shelf life. At ω = 0.4, a part of the *Combi–Past–35%* production was substituted by *EV–Past–35%.* Finally, at ω = 0.2 and ω = 0.0, the entire *Combi–Past–35%* production was substituted by *EV–Past–35%.* Such minimization of the eutrophication potential decreases profits substantially (56.0%) compared to the profit for ω = 1.0. Thereof, 51.3%-points can be attributed to the shift in the concentration technology from a combined concentration, i.e., reverse osmosis and subsequent evaporation, to exclusively evaporation. This shift was caused mainly by the effect of different energy sources on the indicator eutrophication potential. Reverse osmosis demands more electricity and less natural gas than evaporation. However, electricity provision produced with the German average composition, which contains a large share of electricity produced from lignite, contributes substantially to eutrophication.

Choosing evaporation over combined concentration is specific to the indicator eutrophication potential. Model results for the other environmental indicators favored, in line with the profit objective, concentrates produced with combined concentration. The optimal solution for the indicators cumulative energy demand, global warming potential, and acidification potential (see square in figure 3.7) was to produce exclusively the pasteurized concentrate *Combi–Past–35%.* This solution differed from the solution for the bi-criteria problem at $\omega = 0.6$ only by omitting short-term storage of the pasteurized concentrate. The profit decrease compared to the profit for $\omega = 1.0$ amounted to only 8.0%. This represents a dairy plant that switches from powders to concentrates and does not use futures as price predictors, but immediately sells the produced concentrates. In contrast, a dairy that replaces powders by concentrates but still maximizes profits using futures as price predictors only faces a profit decrease of 1.1% (see triangle in figure 3.7 and discussion in section 3.6.3).

Overall, the analyses show that only two objectives (i.e., profit and eutrophication potential) are sufficient to capture the trade-offs in the present case. The minimization of the eutrophication potential leads to a significant profit reduction, mostly due to a shift in the concentration technology from a combined concentration to evaporation. Thus, a shift to solutions that minimize eutrophication potential is unrealistic in practice. However, the profit impact of the other environmental objectives is much less pronounced. In our case, environmental-friendly products have lower shelf lives. Yet, the economic value of the shelf life is low. Hence, we were able to determine a range of solutions that perform well with regard to both profit and the environment.

3.7 Conclusions

This study systematically analyzes the impact of shelf life on the trade-off between economic and environmental performance. We present a real-life case study for two types of dairy products that exemplifies the impact of shelf-life reduction due to sustainable processing. Namely, traditional milk powders are contrasted against novel milk concentrates, based on detailed economic and environmental data. Concentrates require less energy in processing, but have a shorter shelf life. Powders and concentrates can be produced in a multitude of processing variants, resulting in numerous different products.

We develop a sustainability evaluation framework. Part of this framework is a multi-objective optimization model covering profit and all relevant environmental indicators. It determines production, storage, and shipment quantities at the tactical planning level, at which the shelf lives of the considered products have their key impact. Our framework deals with product price uncertainty by updating information on prices in a rolling horizon scheme. Furthermore, we apply the δ-error method to identify trade-offs between objectives. The tactical planning results obtained over a historical period are then used to make strategic decisions on product and process selection.

From an economic perspective, the selection of different powders and concentrates is influenced by upcoming price developments. We use historical data on product prices in the years 2013 up to 2016. However, this price information is not known when the tactical planning is done. For comparison, we therefore use the corresponding prices for futures traded at the Eurex that are known at the time of planning and can thus serve as price predictors. For both price scenarios, powders are selected if prices are expected to rise in the future. Novel, more environmental-friendly concentrates that go along with a reduction of product shelf life are selected if prices are predicted to remain stable or fall. The two price scenarios result in large differences in storage and shipment volumes because upcoming price fluctuations are not fully captured by price predictions with Eurex futures.

We also quantify the value of shelf life to gain managerial insights into whether the long-storage option for powders has significant economic value. The numerical results show that, based on *a priori* perfect price knowledge, profit can be increased by as much as 34.5% when including powders in the product mix. However, this value of shelf life generated by powders depends strongly on the forecast accuracy. In the realistic case in which futures are used as price predictors, the advantage of powders is reduced to only 1.1%. Our analysis therefore shows that the economic value of shelf life is not a strong argument against the substitution of long-shelf-life products with more environmental-friendly low-shelf-life products.

Only two objectives (i.e., profit and eutrophication potential) are sufficient to capture the trade-offs in the presented case. The other three environmental objectives (i.e., cumulative energy demand, global warming potential, and acidification potential) are reduced without a δ-error. Results for the two objectives profit and eutrophication potential differ significantly in their optimal product mix and related indicator performance. While the maximization of profit leads to a selection of powders and concentrates produced with combined concentration (i.e., reverse osmosis and subsequent evaporation), the minimization of eutrophication potential leads to a selection of solely low-shelf-life concentrates produced with evaporation. However, profit decreases substantially if evaporation is used instead of combined concentration. A solution resulting from the minimization of eutrophication potential is therefore unrealistic in practice. However, for the minimization of all other environmental objectives, concentrates produced with combined concentration are selected, resulting in a much smaller profit decrease. Hence, we are able to determine a range of solutions that perform well with regard to both economic and most environmental objectives.

In further research, different methodologies could be developed for evaluating the impact of shelf life on economic performance under price uncertainty. Developing an analytical approach would especially be interesting. This work could build on previous analytical research that investigated economic value of storage capacity. Methods for objective reduction also deserve further consideration. A comparison could be carried out between the results achieved with different objective reduction methods. Further research could also extend the numerical analyses to using different price predictions for final product prices.

Finally, further research could also extend the numerical analyses by investigating other types of products. In particular, it would be interesting to analyze products with even lower shelf lives. Here, the differences in shelf life have their main impact at the short-term, operational planning level. The key challenge then relates to finding ways to draw strategic decisions on product selection based on results obtained at this operational planning level.

Acknowledgment

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4 LCA of fractionated and non-fractionated products

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4.1 Abstract

Fractionation is increasingly applied in the process industries and aids in diversifying the use of biomaterials. However, comparing the environmental impacts of fractionated and non-fractionated products is challenging, since multi-product processes complicate the definition of functional units, and require by-product handling by means of allocation or system expansion. This paper proposes a generic scope-definition framework for multi-product processes in attributional life cycle assessment (ALCA) and in consequential life cycle assessment (CLCA). Considering the potentials and limitations of ALCA and CLCA, this framework addresses the choice of an appropriate functional unit and by-product handling method. Three distinct categories are defined: product systems with *identical products*, with *identical functionalities*, and with exclusively *identical input materials*. The framework is applied to new, fractionated dairy products – micellar-casein concentrate, whey-protein concentrate, and lactose – and their non-fractionated counterpart skim-milk concentrate. The case demonstrates how appropriate functional units can be identified that capture identical specific functionalities. The results for both ALCA and CLCA show that fractionation is environmentally viable. For fractionated products with non-identical functionalities, the methodological choice is reduced to an ALCA yielding a favorable eco-efficiency perspective for fractionation. The framework presented offers a systematic procedure for how to deal with multi-product processes in life cycle assessment that is useful for a wide range of applications.

4.2 Introduction

Fractionation is increasingly applied in the process industries to extract specific product components, upgrade waste streams, or valorize as-yet unused materials. A variety of application possibilities result from fractionation, i.e., from separating products into distinct components or groups of components with different properties. Specific, extracted product components, so-called refined components, often serve as an ingredient in the food industry when final food products are created. They can provide food products with a range of technical or nutritional functionalities, such as thickening properties (Geerts et al., 2018) or a certain nutritional quality (Sonesson et al., 2017). Fractionated waste streams originating from residual biomass can be used in the production of fuels or chemicals (Tuck et al., 2012). For this purpose, carbohydrates and proteins are isolated from biomass residues that are generated in substantial amounts when foods and beverages are produced. Moreover, value can be derived from fractionating as-yet unused materials that, for instance, are marine in origin and might serve as feed stock for food, fuels, or chemicals (Gnansounou and Kenthorai Raman, 2016). Fractionation thus opens a path for further diversifying the use of biomaterials.

The choice to fractionate can be driven by economic or environmental reasons. Economic reasons generally exist when specific product components are extracted from products that can also be used without fractionation. The fractionation of milk, for instance, results in dairy products with enhanced features and a higher economic value than non-fractionated dairy products. By contrast, both environmental and economic reasons may drive the fractionation of current waste streams or unused biomaterials. When considering fractionation, environmental sustainability can therefore be aligned with economic valorization or constitute a trade-off situation. This potential conflict is also characterized by the question of to what extent fractionation should take place in the process industries. Current research suggests using mild fractionation whenever possible and focusing on functionality rather than purity of the different fractions (e.g., Geerts et al., 2018; van der Goot et al., 2016). However, irrespective of the degree of fractionation, fractionation processes are accompanied by a range of environmental impacts that arise when economically valuable streams, waste streams, or as-yet unused materials are converted into products with enhanced features. Consequently, it is essential to focus on the environmental sustainability of fractionated products in comparison to non-fractionated products in order to address the environmental impacts of an increasing use of fractionation technologies.

When applying life cycle assessments (LCA) to comprehensively assess environmental impacts along the value chain, two key issues arise that relate to fractionated products: functional-unit definition and by-product handling. Fractionated products are typically the result of multi-product processes in which several products are created simultaneously. In addition, these processes tend to be joint production processes, implying that the inputs and outputs cannot be independently varied for a specific technology. Addressing functional-unit definition is particularly difficult for the special case of comparing fractionated and non-fractionated products. Since fractionation processes can yield specific functionalities that may be obtained exclusively by the respective process, a trade-off has to be found between functionality and comparability within the functional-unit definition. One example of this trade-off are fractionated dairy proteins. The fractionated proteins can either enhance the existing functionalities of non-fractionated milk concentrate or offer specific, new functionalities, such as the use of microparticulated whey protein as a fat replacement. Challenges related to joint multi-product processes may, moreover, be addressed differently in attributional LCA (ALCA) and consequential LCA (CLCA). While ALCA requires identical products or functionalities, CLCA allows partly differing functionalities to be included in the functional unit. Our methodology encompasses both evaluation possibilities.

Solving challenges related to *multi-product processes*, sometimes also called multi-functionality, is a long-lasting research issue in *LCA*. Most studies, however, have focused on the effects of multi-product processes within the system under study (cf. Pelletier et al., 2015). These studies analyze how to determine the environmental impacts of individual products resulting from a multi-product process. While in ALCA literature, different methods have been proposed and applied for allocating environmental impacts to individual products (e.g., Sandin et al., 2015), CLCA literature restricts the treatment of multiple products to system expansion, including substitution (e.g., Weidema, 2001). By contrast, the question of how to tackle multi-product processes at the system boundary has only been addressed to a limited extent. Nevertheless, the choice of functional units at the system boundary is particularly important when comparing systems that include multi-product processes (Cherubini and Strømman, 2011). Cherubini and Strømman (2011) review the functional-unit definition in ALCA and CLCA studies on multi-product bioenergy systems. The authors find that most studies consider common products (i.e., outputs) as functional units, however, they emphasize that input-based functional units are beneficial for avoiding allocation. Jung et al. (2013) compare multi-product processes with partly differing products from an CLCA perspective. The authors expand on the work by Weidema (2003, 2001) and allow for the inclusion of several determining products in the functional unit with the aid of system expansion. Existing literature on functional-unit definition for multi-product processes thus points to the relevance of choosing both the functional-unit type and the number of functional-unit products. No study to date, however, has systematically analyzed the choice of functional units in both ALCA and CLCA when comparing systems that include multi-product processes. Additionally, the interdependence of functional-unit definition and allocation-method choice is relevant.

Several *LCA* studies have been conducted that consider *fractionation* in the process industries. The studies compare fractionation processes for valuable product streams, waste streams, or as-yet unused biomaterials with the aid of ALCA. In the field of biofuels, Pereira et al. (2015) evaluate different fractionation technologies for the production of butanol from the valuable product-stream sugarcane. In the food industry, Geerts et al. (2018) study the impacts of different fractionation processes for yellow pea flour. Furthermore, Bacenetti et al. (2018) compare environmental impacts related to whey fractionation. While the former two studies apply multiple functional units based on identical products, functionalities, inputs, or economic revenues, Bacenetti et al. (2018) focus solely on identical functionalities. Only one product or functionality is considered in the studies' corresponding functional units. Environmental impacts resulting from waste-stream valorization via fractionation have also recently been addressed. Guerrero and Muñoz (2018) analyzed the impacts of bioethanol production processes derived from lignocellulosic banana waste, while Vauchel et al. (2018) determined impacts related to different extraction processes of polyphenols from chicory grounds. In both cases, functionality-based functional units with one identical functionality are considered. A special case falling into the category of waste-stream valorization is water reuse with the aid of fractionation technologies. In related studies, fractionation leads to only one valuable output in the functional unit: treated water from which pollutants were removed (e.g., Manda et al., 2014). As-yet unused materials were studied by Pérez-López et al. (2014). The authors analyzed the environmental impacts of valorizing invasive macroalgae and applied an input-based functional unit to compare different fractionation processes. The conversion of seawater into fresh potable water is another example in this context that was studied by Raluy et al. (2006). The authors use a functionality-based functional unit, covering only one functionality. In addition, a range of ALCA studies consider fractionation technologies in downstream processing to separate product components altered or generated with the aid of other technologies, such as fermentation or hydrolysis (e.g., González-García et al., 2018). These studies typically also apply different types of functional units with a limited number of products or functionalities. Despite the variety of fractionation studies in the process industries, to date no study has compared the fractionated products to non-fractionated products with regard to environmental impacts, nor has the choice of functional units been systematized for the comparison of multi-product processes.

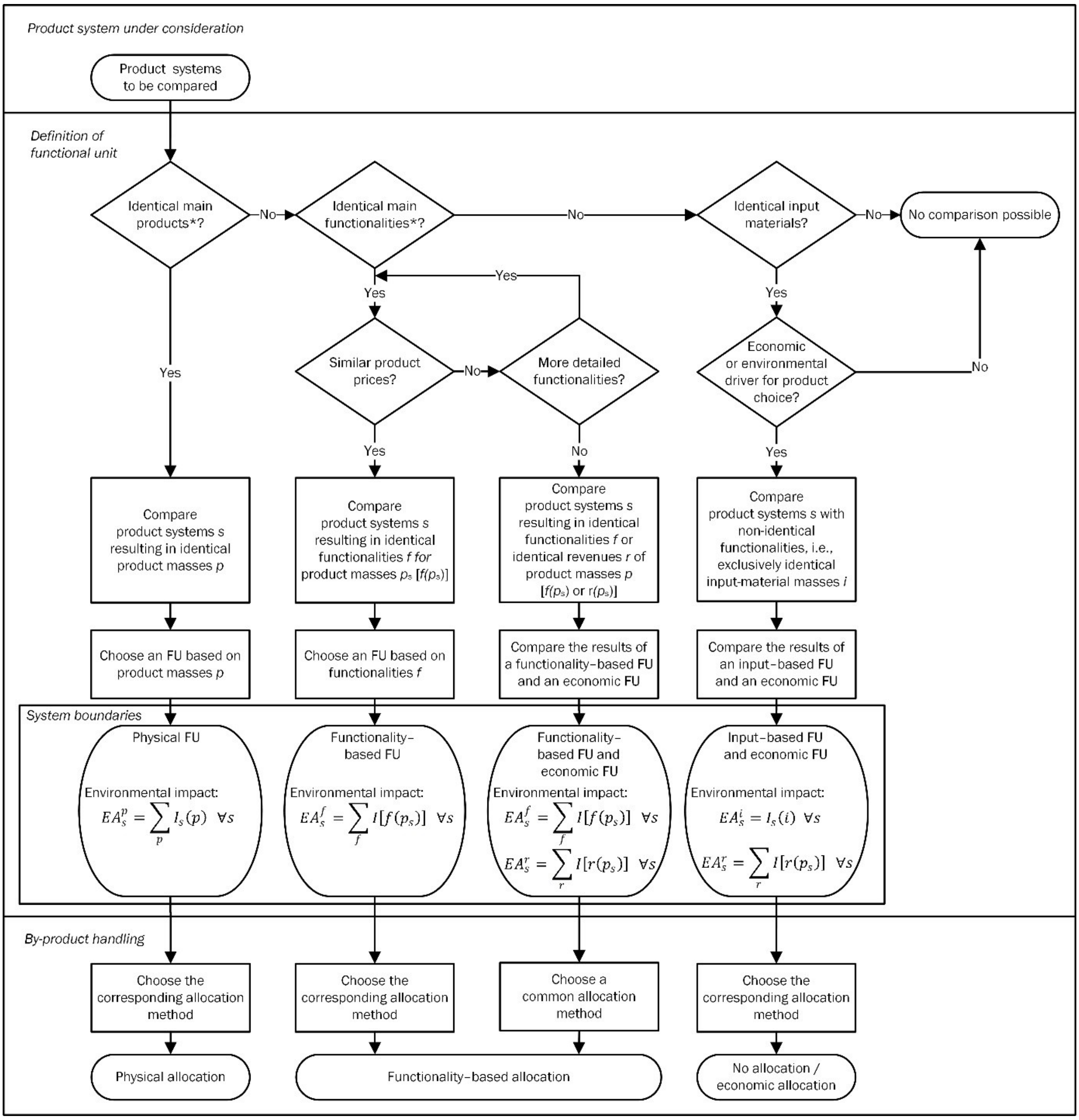
In this study, fractionated and non-fractionated products are compared with the aid of LCA. For this purpose, the authors develop a generic scope-definition framework for multi-product processes. Considering the potentials and limitations of ALCA and CLCA, it addresses the choice of an appropriate functional unit and allocation method. The framework is applied to new, fractionated dairy products – *micellar-casein concentrate*, *whey-protein concentrate*, and *lactose* – and their non-fractionated counterpart *skim-milk concentrate*. The case demonstrates how appropriate functional units can be identified that adequately capture the products' functionalities. For fractionated products with non-identical functionalities, the methodological choice is reduced to an ALCA yielding an eco-efficiency perspective.

4.3 Methods

The methodological framework is separated into ALCA and CLCA, since challenges arising from multi-product processes, such as fractionation processes, have to be approached differently.

4.3.1 Methodological framework for fractionation in ALCA

Figure 4.1 illustrates the methodological framework for ALCA, which addresses comparative assessments. For as-yet unused materials, drawing a comparison between fractionated and non-fractionated streams is not feasible, since these materials constitute no product-system outcome. The same holds true for as-yet unused, harmful materials that may result from human intervention. For comparative ALCAs, different functional units and ways of handling by-products are proposed depending on the product-system category, i.e., product systems with identical main products, identical main functionalities, or identical input materials. The scope-definition (SCODE) framework verifies the existence of these product-system categories on a step-by-step basis.



*Identical main products or identical main functionalities excluding joint products with differing production rates.

Figure 4.1. Scope-definition (SCODE) framework for comparative attributional life cycle assessment.

4.3.1.1 Definition of functional unit

Identical main products. In multi-product systems, an essential outcome may consist of more than one product. In such cases, it may be desirable to include several products in the functional unit. In comparative ALCAs, however, including several main products in the comparative functional unit may lead to a methodological problem. If the production systems compared lead to different main products, or if the production ratios between main products are fixed (i.e., joint production) and differing, then the composition of the functional unit is problematic. The issue could be solved by system expansion, implying the inclusion of external production processes in the functional unit. The use of system expansion has been justified for attributional allocation (Majeau-Bettez et al., 2018) and can thus be considered a potential allocation method for disaggregating multi-product processes with the aid of good technological proxies. However, this does not legitimize the inclusion of non-existent processes within functional units, which would risk comparability and contradicts the basic idea of ALCA.

The SCODE framework therefore supports comparability at the expense of comprehensiveness in comparative ALCAs by accounting only for identical main products and identical joint main product ratios across the product systems s compared. The priority use of a physical functional unit is suggested in line with ISO 14040 (2006). The environmental impact of the physical functional unit EA_s^p can be expressed as the sum of environmental impacts of identical product masses p for each product system s considered. Comparable economic functional units, i.e., those restricted to identical main products and identical joint main product ratios, are related to this physical functional unit through a simple factor $[\frac{kg}{€}]$.

Example. The limitation of accounting only for identical main products in the functional units of comparative ALCA can be seen in the work of Yan and Holden (2018). They compare the environmental impacts of several multi-product dairy plants (EA_s^p) that produce butter, skim-milk powder, or fat-filled powder (p). Since the compared production systems (s) do not only produce identical products and at the same time have different production ratios, the comparison is limited to the environmental impact of single products $[EA_s^p = I_s(p) \; \forall \; s]$.

Product systems with identical main products are present when comparing different fractionation processes. However, a more detailed analysis of the products' properties is required when comparing fractionated with non-fractionated products.

Identical main functionalities. Product systems with differing products can have identical functionalities, such as several food products providing a certain nutritional value (Sonesson et al., 2017). In line with the rationale for allowing only identical main products in the functional unit of comparative ALCAs, the functionalities of product systems should be identical. The focus on identical main functionalities, however, might omit additional functionalities that are essential to a specific product system. One of these additional functionalities is product quality. Quality can provide a range of quantitative (e.g., vitamin content of food products) and qualitative (e.g., taste) functionalities that differ between product systems and that, therefore, cannot be included in a functionality-based functional unit. Van der Werf and Salou (2015), for instance, find that comparing the environmental impacts of different types of meat, i.e., organic versus conventional meat, with a mass-based functional unit does not account for the quality of the meat. For this reason, they incorporate the quality aspect in the analysis by including product prices, leading to an economic functional unit. In general, significantly differing product prices could be an indicator for neglected functionalities of product systems compared. In some cases, the differences in product prices might be eliminated if the main functionalities are considered in more detail, for example by considering the mass of digestible protein content instead of total protein content (cf. Sonesson et al., 2017). In most cases, however, differing functionalities across product systems cannot be set aside and some functionalities might even be unique to certain product systems.

The framework recommends the use of both a functionality-based functional unit as well as an economic functional unit to compare product systems that show significantly differing product prices while offering identical main functionalities. The environmental impact of the functionality-based functional unit EA_s^f is calculated as the sum of environmental impacts of identical functionalities f, resulting from product masses p of each product system s. The environmental impact related to the revenue-based functional unit EA_s^r is calculated analogously to EA_s^f for identical revenues r. The economic functional unit facilitates determining the impact of neglected functionalities. The combined use of functionality-based and economic functional units thus can support the definition of more specific functional properties.

Example. Geerts et al. (2018) study the environmental impacts of different fractionation processes for yellow pea flour (EA_s^f). They find that the choice of functionality-based functional units alters the ranking of fractionation processes. If the environmental impacts of an economic functional unit had also been determined (EA_s^r), results would likely have shown a higher consistency between functionality-based and economic functional units for the specific functional property (i.e., product viscosity) than for the more generic functional property (i.e., provision of starch-rich fraction). Therefore, defining functionalities as specifically as possible is essential. Remaining inconsistencies after the definition of specific functional properties, for instance, point to differing product qualities.

Fractionated and non-fractionated products are categorized as product systems with identical main functionalities when the fractionated products share at least one functionality with the non-fractionated products. This is, for example, the case when fractionation processes concentrate a valuable component.

Identical input materials. Product systems can have an identical input-material stream. For a comparison to be meaningful, however, economic or environmental reasons have to exist. Material streams that are otherwise used for low-value products or treated as waste are valorized. Economic motives can be congruent or incongruent to environmental motives. A comparison of product systems based on identical input-material streams therefore needs to evaluate their eco-efficiencies.

The SCODE framework hence incorporates an economic functional unit alongside an input-based functional unit. The environmental impact of the input-based functional unit EA_s^i equals the environmental impact of each product system s that results from identical input-material masses. The economic functional unit additionally captures the trade-off with the economic perspective by relating the environmental impacts to the economic benefits. For this category of product systems, the environmental impact of the economic functional unit (EA_s^r) does not include additional functionalities.

Example. Environmental impacts of the input-based functional unit may be based on a certain mass of waste valorized (EA_s^i), such as valorized sugar-beet pulp (cf. González-García et al., 2018). For sugar-beet pulp, however, the economic value of products resulting from potential product systems differs significantly. Impacts of the economic functional unit (EA_s^r) here point to the reason for valorization and provide insights into eco-efficiency.

Fractionated and non-fractionated products are never identical main products and often have no identical functionalities. However, they do have identical input-material streams.

4.3.1.1 System boundaries

In ALCA, the system under consideration depends on the type of functional units and on the intended comparison. When considering product system categories with identical main products and with identical main functionalities, the system has to include stages up to the fulfillment of identical outcomes captured in the functional units. By contrast, when addressing the product system category with identical input-material streams, the input-based functional unit defines the upstream boundary of the system, while the economic functional unit defines the downstream boundary. In practice, this may result in only the processing stage being considered.

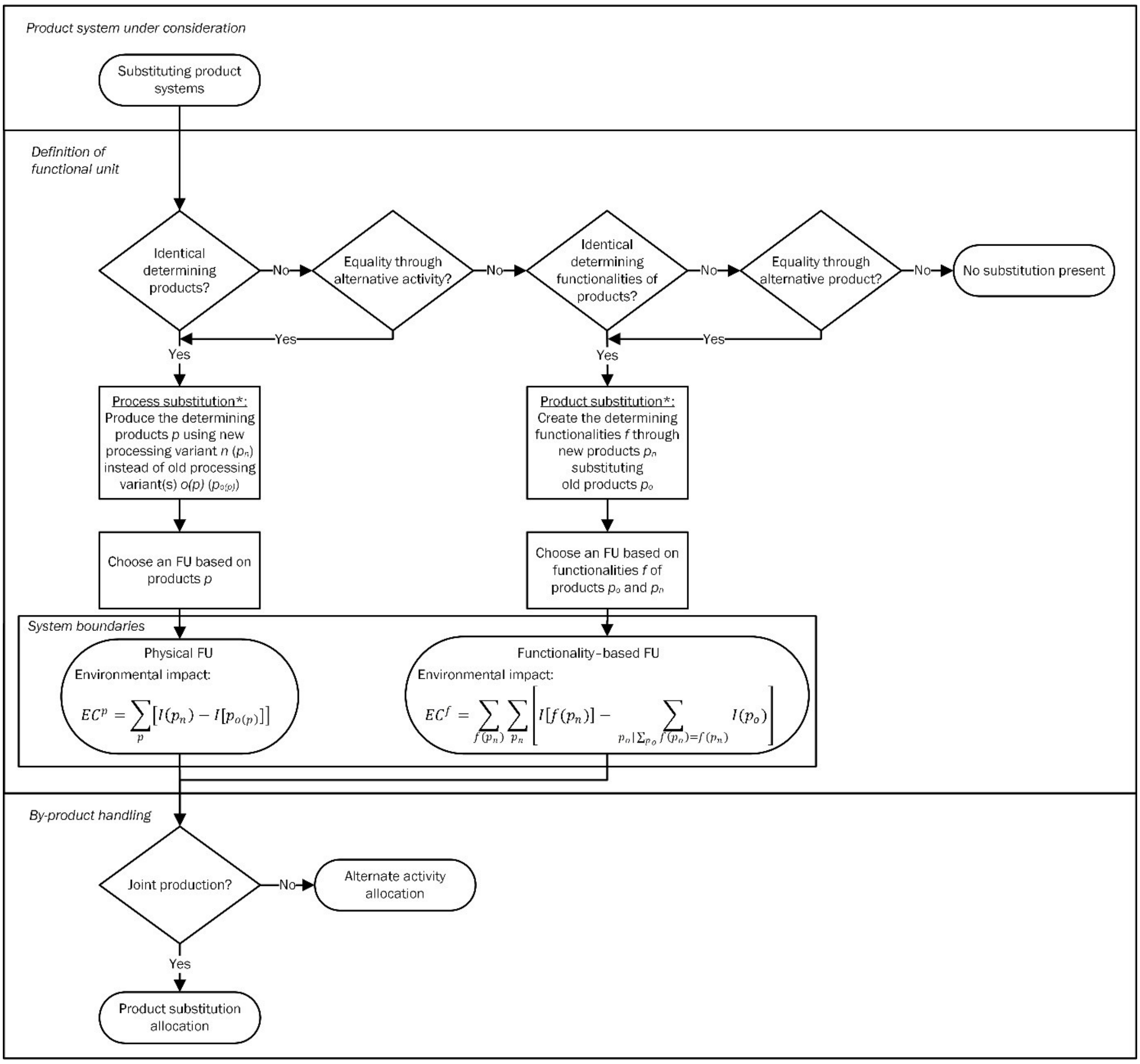
4.3.1.1 By-product handling

By-products are not included in the functional units, but are still attributed environmental impacts with the aid of allocation. For joint multi-product processes, including fractionation processes, the feasibility of physical allocation has been a much-debated issue. In a recent contribution, Pelletier and Tyedmers (2011) emphasized that (bio-)physical variables are much more relevant than economic values for a causal attribution. Pelletier and Tyedmers (2011) use a physical functional unit. For other types of functional units, the allocation method should also be aligned to ensure consistency. The notion of coupling functional unit definition and allocation can also be found in several ALCA case studies (e.g., Cherubini and Strømman, 2011).

In the present framework, therefore, the choice of allocation method is based on the functional unit definition. For product systems with identical main functionalities that require both a functionality-based functional unit and an economic functional unit, a common functionality-based allocation is applied.

4.3.2 Methodological framework for fractionation in CLCA

Figure 4.2 shows the SCODE framework for CLCA, which focuses on substituting product relationships at the consumer stage. Depending on the type of innovation, product relationships may also be non-substituting due to growing or emerging markets. This kind of standalone CLCA is relevant for novel, fractionated products with no current market demand. For substituting CLCAs, two product-system categories, process substitution and product substitution, are subsequently considered.



*Substitution consisting of the most competitive (new) and the least competitive (old) technology or product on the market.

Figure 4.2. Scope-definition (SCODE) framework for substituting consequential life cycle assessment.

4.3.2.1 Definition of functional unit

Identical determining products. The question of how to compare multi-product systems in CLCA was first addressed by Weidema (2003, 2001) and more recently by Jung et al. (2013). Weidema (2001) shaped the term of the determining product as the one product that induces a change in production volume by offering not only high revenues but also the largest market trend. He acknowledges, however, that more than one product can determine multi-product systems (Weidema, 2003). Jung et al. (2013) consider the case of joint multi-product systems with non-common products. They propose including several products in the functional unit and obtaining identical product systems via system expansion. It is noteworthy that they consider a case from the process industries. Since the comprehensive utilization of products resulting from multi-product systems is important in process-industry settings, the existence of several determining products is particularly likely here.

The SCODE framework allows for the consideration of several determining products in functional units. If the determining products differ partly between the substituting processes, system expansion is recommended to allow the differing products to also be captured in the functional unit (cf. Jung et al., 2013). The framework suggests the use of a physical functional unit for process substitutions. The environmental impact of a physical functional unit EC^p is determined by the difference between the sum of environmental impacts of product masses p produced with the new processing variant n and the sum of environmental impacts of identical product masses p produced with one or more old processing variants $o(p)$. The option of using several old processing variants $o(p)$ to produce identical product masses p arises from the feasibility of system expansion within the functional unit.

Example. The number of functional-unit products is relevant when considering process substitution for chlorine electrolysis (cf. Jung et al., 2013). Here, the novel process produces hydrogen in addition to chlorine and caustic acid (p_n). A further processing variant for hydrogen $[o(p)]$ thus must be included in the functional unit to incorporate the impacts related to the determining products of the new processing variant $[I(p_n)]$.

When previous fractionation processes are displaced, the choices for product systems with identical determining products are applicable. Fractionated and non-fractionated products, however, cannot be compared at the product level.

Identical determining functionalities. Products can substitute each other at the consumer due to one or several identical determining functionalities. These identical determining functionalities can also be generated by system expansion within the functional unit in line with the reasoning on multiple determining products. Product substitutions rely on physical substitution relationships, making an economic functional unit not recommendable.

The framework accounts for identical determining functionalities that can be generated by system expansion. The use of a sole functionality-based functional unit is proposed for product substitutions with identical determining functionalities. The environmental impact of a functionality-based functional unit EC^f is calculated as the difference between the sums of environmental impacts of functionalities $f(p_n)$ provided by the new products p_n and environmental impacts related to the old products p_o. Functionalities of the new products

$f(p_n)$ can also be obtained using several old products p_o $[p_o | \sum_{p_o} f(p_o) = f(p_n)]$, i.e., enabling system expansion for functionality-based functional units.

Example. The protein-fraction milk casein is required for the gelation process in cheese production. *Micellar-casein concentrate* $[f(p_n)]$ can be used instead of *skim-milk concentrate* $[f(p_o)]$ to provide milk casein, i.e., the functionality of gelation. The speed of the gelation process, however, depends on the soluble calcium content, which differs between the two products. This additional functionality can be included in the functional unit by expanding the system.

Product systems focused on the substitution of determining functionalities are applicable to the comparison of fractionated and non-fractionated products when fractionation processes provide products with the same determining functionalities as non-fractionated products, for instance, when mainly concentrating one valuable component.

4.3.2.1 System boundaries

In CLCA, product systems are required to be substitutable at the consumer stage in a certain market segment (cf. Weidema, 2003). The system under study thus has to encompass changes along the entire value chain for the substituting product systems. Since substitution at the consumer level is a key prerequisite in CLCA, only fractionated product streams that fulfill the identical determining functionalities as non-fractionated product streams can be addressed using this approach.

4.3.2.1 By-product handling

By-products of multi-product processes are handled with the aid of system expansion encompassing substitution, i.e., the subtraction of single-product processes external to the system under consideration from the original multi-product process (e.g., Pelletier et al., 2015). In a recent publication, Majeau-Bettez et al. (2018) define two approaches for system expansion: alternate-activity allocation and product-substitution allocation. The authors state that alternate-activity allocation is applicable for combined production in which products can typically be obtained using different single-product technologies. By contrast, product-substitution allocation is often used for joint production, since technology replacements are not feasible and, therefore, functionally equivalent products are considered that can substitute the joint products on the market. In the SCODE framework, the choice of by-product handling is based on this distinction by Majeau-Bettez et al. (2018).

4.3.3 Comparison of ALCA and CLCA for fractionation

The most prominent differences between ALCA and CLCA in terms of how they tackle challenges arising from the comparison of multi-product processes, such as fractionation processes, are summarized in the following: (1) Comparative functional units in ALCA may only include identical products with identical production ratios, while in CLCA system expansion within the functional unit is feasible; (2) economic functional units and input-based functional units are possible in ALCA, whereas CLCA is based on physical substitution relationships and requires products to be substitutable at the consumer stage, thereby excluding these options; (3) system boundaries in ALCA depend on the type of functional units and on the intended comparison, while in CLCA, these boundaries are pre-defined; (4) by-product handling in ALCA includes the choice of an allocation method, preferably one aligned with the functional-unit definition, whereas CLCA uses system expansion encompassing substitution.

Overall, ALCA and CLCA differ in their responsibility paradigm (cf. Weidema et al., 2018). Responsibility in CLCA goes beyond the individual substitution decisions of a certain supply-chain actor by accounting for the long-term impacts of all marginal changes resulting from a process or product substitution. CLCA is, therefore, restricted to the analysis of identical products or identical functionalities that enable substitution. Fractionated products, however, may possess new functionalities that cannot be captured with CLCA, thus limiting its applicability to the comparison of fractionated and non-fractionated product streams. By contrast, ALCA allows for a producer-oriented view that paves the way for tackling products with non-identical functionalities.

4.4 Case study

4.4.1 Fractionated and non-fractionated milk concentrates

The case of milk concentrates exemplifies how fractionated products can be contrasted against their non-fractionated counterpart.

Recently, non-fractionated milk concentrates were introduced as substitutes for milk powders wherever powders are reconstituted, such as in the production of yoghurt, ice cream, or finished meals. *Skim-milk concentrates* (SMC), which require no energy-intensive drying, were found to save up to 35% of the cumulative energy demand required for the production of skim-milk powder and to be environmentally advantageous up to a transportation distance of around 1,000 km (Depping et al., 2017). From an economic perspective, the shorter shelf life of SMC (9–50 days) compared to powder (up to two years) also proved not to be a strong argument against the substitution of long-shelf-life products with more environmentally friendly low-shelf-life products (Stefansdottir et al., 2018). This study therefore considers SMC as the non-fractionated counterpart. SMC can be produced from pasteurized skim milk with a variety of processing variants. For this study, one environmentally and economically advantageous concentrate option was selected based on previous research (cf. Depping et al., 2017; Dumpler et al., 2018; Stefansdottir et al., 2018). This concentrate is produced with combined concentration, consisting of reverse osmosis and evaporation, to a dry-matter content of 35% and preserved via subsequent pasteurization (see figure 4.3).

Pasteurized skim milk can, moreover, be fractionated to produce *micellar-casein concentrate* (MCC), *whey-protein concentrate* (WPC), and *lactose* (see figure 4.3). Currently, supplying the fractionated-protein products MCC and WPC in a liquid form is investigated (cf. Marx et al., 2018). For this purpose, the proteins in skim milk need to be separated, concentrated, and stabilized. This study considers the use of membrane technologies, which combine milk separation and concentration. Liquid MCC with a dry-matter content of 20% can be produced by skim-milk microfiltration (pore size: 0.1-0.2 µm) and preserved via high-heat treatment. Liquid WPC with a dry-matter content of 35% results as the retentate of a subsequent ultrafiltration process (pore size: 5-25 kDa) and can be stabilized via pasteurization. The study also includes market-standard pre-concentration of whey, followed by pre-heat treatment to reduce spores in warm ultrafiltration (50 °C). The unstable ultrafiltration permeate containing lactose has to either be dried or processed further. Food-grade, dried lactose can be gained by evaporation and crystallization. Subsequently, lactose crystals and molasses are separated in a two-stage decanter centrifuge and lactose is dried in a fluidized bed. The remaining molasses possesses no economic benefit and is given away directly. The ultrafiltration permeate can alternatively be transformed into lactic acid via fermentation. When considering the production of liquid MCC, liquid WPC, and lactose, challenges related to the joint and additionally coupled fractionation processes microfiltration, ultrafiltration, and decanter centrifugation have to be addressed.

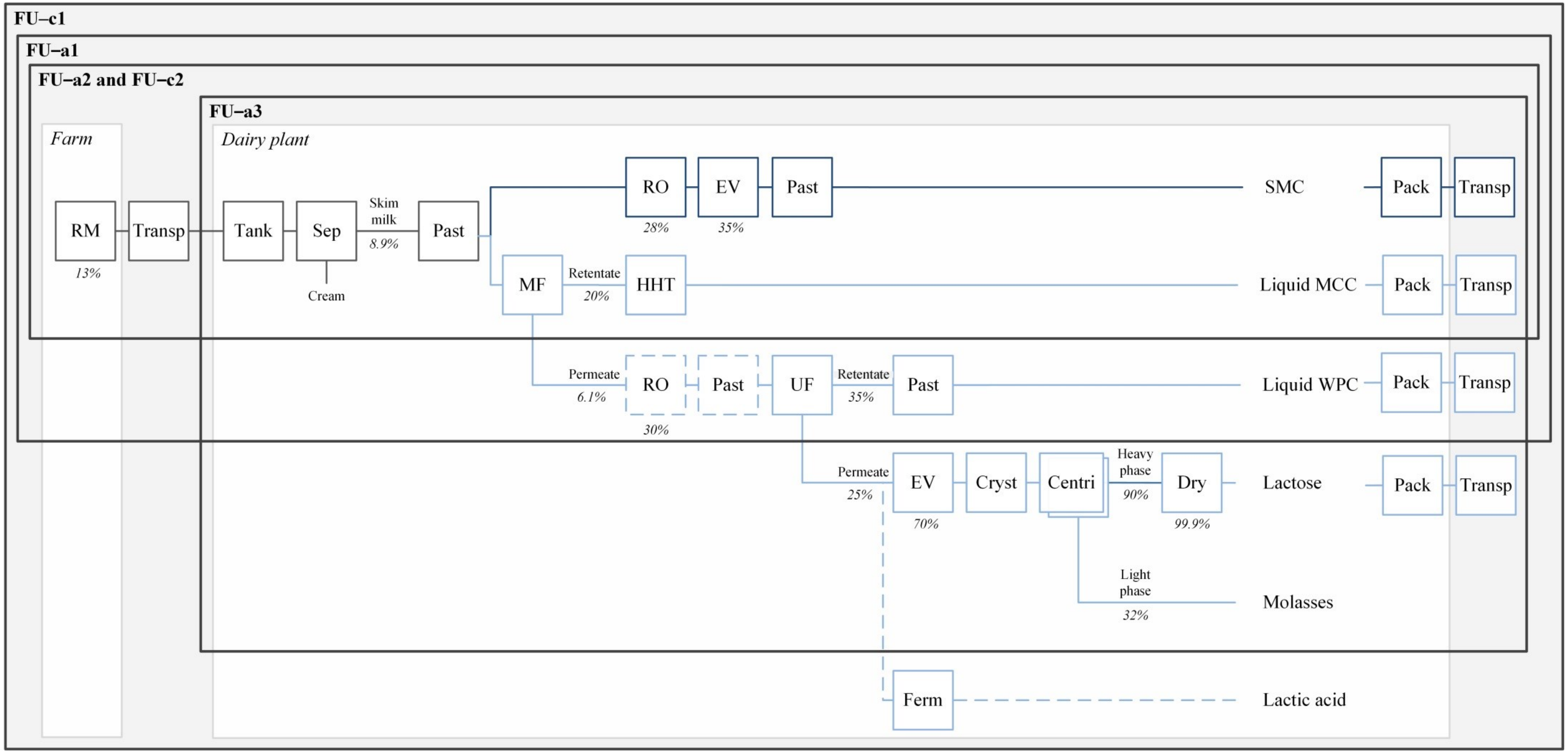


Figure 4.3. Overview of the different attributional and consequential functional units (FU–a and FU–c) that compare the value chains of the non-fractionated dairy product *skim-milk concentrate* (SMC) with its fractionated counterparts liquid *micellar-casein concentrate* (liquid MCC), liquid *whey-protein concentrate* (liquid WPC), *lactose* (or *lactic acid*), and *molasses*. Altered dry-matter contents are stated below the respective processes. Patterned boxes represent optional processes. Abbreviations: RM–raw milk production, Transp–transportation, Tank–tank collection, Sep–separation, Past–pasteurization, MF–microfiltration, RO–reverse osmosis, HHT–high-heat treatment, EV–evaporation, UF–ultrafiltration, Ferm–fermentation, Cryst–crystallization, Centri–two-stage decanter centrifugation, Dry*–fluidized-bed drying, Pack–packaging.

4.4.2 Application of the methodological framework

The SCODE framework proposed in section 2 is applied in order to conduct an ALCA and an CLCA of fractionated and non-fractionated milk concentrates. As in all comparisons between fractionated and non-fractionated products, the main/determining products are non-identical.

4.4.2.1 ALCA and CLCA: Identical main/determining functionalities

One goal driving the fractionation process is to concentrate the protein content. Proteins enhance the nutritional value of food products and possess a range of technical properties. These may be considered the main/determining functionalities of the product systems under comparison. Taking a non-differentiated stance on functionality, total proteins are relevant, since they enable nutritional-value enhancement. When considering functionalities in more detail, however, technical applications of the protein-fraction milk casein emerge as crucial. Milk casein, which is applied in cheese production, can be provided by either SMC or liquid MCC, allowing the protein-fraction liquid WPC to be used for other purposes.

For both identical functionalities, i.e., provision of total proteins or milk casein, product prices are significantly higher for fractionated concentrates than for non-fractionated concentrates. In ALCA, both functionality-based and economic functional units are, therefore, considered. The system being studied also includes the distribution stage, since dry-matter contents of fractionated and non-fractionated concentrates differ and, as a result, require different transportation volumes to fulfill identical functionalities. From the downstream processor to the final consumer, environmental impacts remain the same. The system being studied in CLCA therefore considers the downstream processor as consumer. The downstream system boundaries of ALCA and CLCA are thus identical (see figure 4.3). The following functional units can be defined for ALCA (FU–a) and CLCA (FU–c) of fractionated and non-fractionated milk concentrates:

First identical functionality – provision of total proteins

- FU–a1: 1 kg of protein from SMC or from liquid MCC and liquid WPC delivered to the customers.
  1 € of revenue generated with SMC or liquid MCC and liquid WPC delivered to the customers.
- FU–c1: 1 additionally consumed kg of protein from liquid MCC and WPC instead of SMC.

Second identical functionality – provision of the protein-fraction milk casein

- FU–a2: 1 kg of milk casein from SMC or from liquid MCC delivered to the customers.
  1 € of revenue generated with SMC or liquid MCC delivered to the customers.
- FU–c2: 1 additionally consumed kg of milk casein from liquid MCC instead of SMC.

By-products are handled with functionality-based allocation in ALCA, while product-substitution allocation is used in CLCA. Since no product substitution is available for lactose in the ecoinvent v3.1 (2014) databank, the additional process *fermentation* was included in the system of FU–c1 to obtain the substitutable product lactic acid (see figure 4.3).

4.4.2.1 ALCA: Identical input materials

The separation of milk components also opens up possibilities for developing more specified products, such as lactose-free products. These products possess different functionalities from their non-fractionated counterparts and can be sold to other customer groups, thereby increasing the value of the identical input material – skim milk. Producing these products, therefore, is motivated economically.

To allow a comparison of the input-based and the economic functional unit, the system under study has to be restricted to the processing of collected raw milk up to the producer gate (neglecting the environmental responsibility of the producer for impacts resulting along the downstream value chain). The following functional units can be defined for ALCA (FU–a) of fractionated and non-fractionated milk concentrates:

Non-identical functionality

- FU–a3: 1 kg of raw milk valorized by production of SMC or liquid MCC, liquid WPC, lactose, and molasses delivered to the customers.
  1 € of revenue generated with SMC or with liquid MCC, liquid WPC, lactose, and molasses delivered to the customers.

No by-product handling is required, since all products are considered within the functional units.

4.4.3 Life Cycle Inventory

Detailed life cycle inventory data for the present case study can be found in appendix D and ecoinvent v3.1 (2014) processes utilized are listed in appendix E. The remainder of this section highlights several specifics of the present inventory.

Raw-milk production. The attributional and consequential raw-milk impacts per kilogram of fat-and-protein-corrected milk were determined with the aid of a corresponding ecoinvent v3.1 (2014) process on raw-milk production (see appendix E). The inventory data for raw-milk collection is based on Depping et al. (2017).

Fractionated and non-fractionated concentrate production. The life cycle inventory data on fractionated-protein concentrates and lactose was collected in cooperation with a large German equipment manufacturer and a mid-sized German dairy company, which has been investing in membrane technologies to perform milk fractionation. The data gathered comprised: (1) energy consumption during runtimes and cleaning cycles (i.e., electricity, natural gas, and fuel), (2) fresh water and cleaning-agent consumption, (3) deployed capital goods, and (4) packaging materials (see appendix D). In order to couple this data with environmental impacts, corresponding ALCA and CLCA ecoinvent v3.1 (2014) processes were chosen (see appendix E). Inventory data for the selected non-fractionated skim-milk concentrate and for pre-processing raw milk to pasteurized skim milk originates from Depping et al. (2017).

Fractionated and non-fractionated concentrate distribution. ALCA and CLCA datasets on distribution were adapted to an increased fuel consumption by the engine due to cooling (see appendix E).

4.4.4 Environmental indicator and impact assessment method

The analysis focused on the environmental indicator of global-warming potential (GWP) due to the significant role greenhouse gases play in evaluating dairy products. The characterization factors of the CML-IA 2001 method with a 100-year time horizon were applied for this purpose. Calculations were performed with the LCA software tool SimaPro 8.0.5 (PRé Consultants bv, 2015).

4.5 Results

The results achieved when comparing the GWP of fractionated and non-fractionated milk concentrates are presented in the following. A comprehensive overview can also be found in appendix F (ALCA) and appendix G (CLCA).

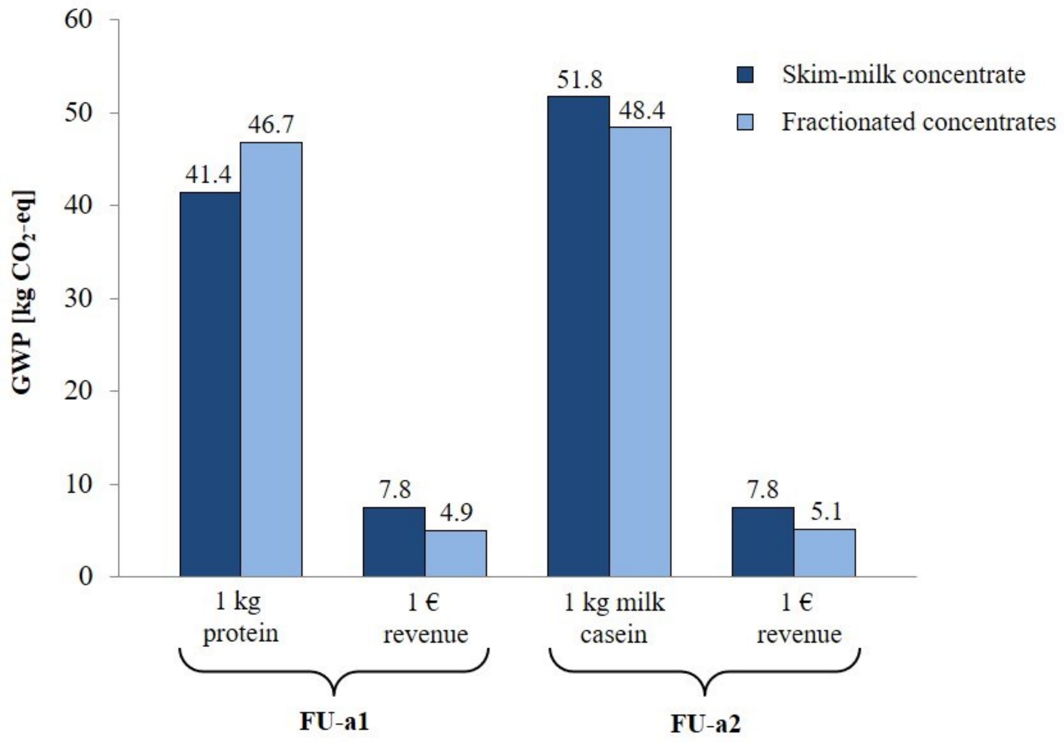


Figure 4.4. Global-warming potential (GWP) of producing fractionated and non-fractionated milk concentrates if transportation impacts are disregarded (FU–a1 and FU–a2).

4.5.1 ALCA

Figure 4.4 illustrates the GWP of fractionated and non-fractionated milk concentrates for the functional units FU–a1 and FU–a2.

These functional units consider product systems with identical main functionalities. Milk concentrates are assumed to be produced at an integrated dairy plant, which does the processing in-house (i.e., without transport from the dairy plant to the customer). Raw-milk production contributes the largest percentage of impacts to the GWP (see appendix F).

Table 4.1

The difference in global-warming potential (GWP) between fractionated and non-fractionated milk concentrates depending on raw-milk impact uncertainty (FU–a1 and FU–a2).

GWP difference for functional units		Unit	Raw-milk impact range from Guerci et al. (2013)		Utilized raw-milk impacts from ecoinvent database
			Lower limit	Upper limit	Cow milk {RoW}
FU–a1	1 kg protein	kg CO_2-eq	2.2	7.7	**4.9**
	1 € revenue	kg CO_2-eq	-1.3	-4.5	**-2.9**
FU–a2	1 kg milk casein	kg CO_2-eq	-1.4	5.0	**-3.2**
	1 € revenue	kg CO_2-eq	-1.2	-4.1	**-2.6**

Table 4.2

Global-warming potential (GWP) of fractionated and non-fractionated milk concentrate production if transportation impacts are disregarded (FU–a3).

Indicator	Unit	1 kg raw milk valorized		1 € revenue	
		SMC	Liquid MCC, liquid WPC, lactose, molasses	SMC	Liquid MCC, liquid WPC, lactose, molasses
GWP	10^{-1} kg CO_2-eq	0.5	1.0	1.8	1.4

Abbreviations: liquid MCC–liquid micellar-casein concentrate, liquid WPC–liquid whey-protein concentrate, SMC–skim-milk concentrate.

Functional unit FU–a1 aims to provide one kilogram of total proteins used as a commodity in food products. The functionality-based definition shows that non-fractionated SMC is environmentally preferable to the protein-fractions liquid MCC and liquid WPC. The corresponding economic functional unit, however, is inconsistent, indicating a high impact of that neglected functionalities have a high impact. This functional unit exemplifies the effect of choosing only a generic functionality related to fractionated milk concentrates. Functional unit FU–a2, by contrast, considers the functionality of fractionated milk concentrates in more detail, and focuses only on the protein-fraction milk casein. For this functional unit, the functionality-based and economic definition consistently show that fractionated concentrates outperform non-fractionated concentrates. Fractionation is thus found to be advantageous for applications that require specific functional ingredients. Table 4.1 shows that this finding remains robust when considering raw-milk impact uncertainty, i.e., when accounting for the environmental-impact range of raw-milk production as determined by Guerci et al. (2013).

Table 4.2 shows the GWP of fractionated and non-fractionated milk concentrates for the functional unit FU–a3. This functional unit addresses product systems with non-identical functionalities that have raw milk as an identical input material. The functional unit therefore excludes raw-milk impacts.

As expected, functional unit FU–a3 shows that per kilogram of raw milk, the environmental impacts of producing SMC are lower than of producing MCC, WPC, lactose, and molasses, due to the additional processing steps. When relating the environmental impacts to economic benefits, however, fractionated concentrates outperform their non-fractionated counterpart. From an eco-efficiency perspective, the benefits of fractionated concentrates thus outweigh their increased environmental impacts (1.4×10^{-1} kg CO_2-eq vs. 1.8×10^{-1} kg CO_2-eq).

One additional consideration was the potential impact of transportation to the customers. To take this into account, a transportation distance of 1,000 kilometers was assumed. This is the maximum distance for which SMC has been found to be environmentally advantageous over powder (cf. Depping et al., 2017). Results show that across all attributional functional units, the product choices remain the same when including transportation (see appendix F).

4.5.2 CLCA

Figure 4.5 shows the effect on GWP when substituting non-fractionated milk concentrates with fractionated concentrates.

A switch from SMC to fractionated concentrates reduces the GWP by 0.7 kg CO_2-eq for FU–c1 and by 4.7 kg CO_2-eq for FU–c2. The minor difference between SMC and fractionated concentrates in case of total proteins (FU–c1) stems from the additional by-product lactic acid when producing liquid MCC and liquid WPC. The possibility to also substitute lactic acid next to cream on the market decreases the GWP of fractionated concentrates by 23.7 kg CO_2-eq compared to a decrease of only 16.2 kg CO_2-eq for SMC. As a result, the larger raw-milk inputs required when producing proteins with fractionated concentrates are compensated. The result for FU–c1 highlights the influence of product-substitution allocation on final results. For FU–c2, fractionated concentrates outperform SMC. Here, substitution of the by-product whey only has a marginal influence on the results.

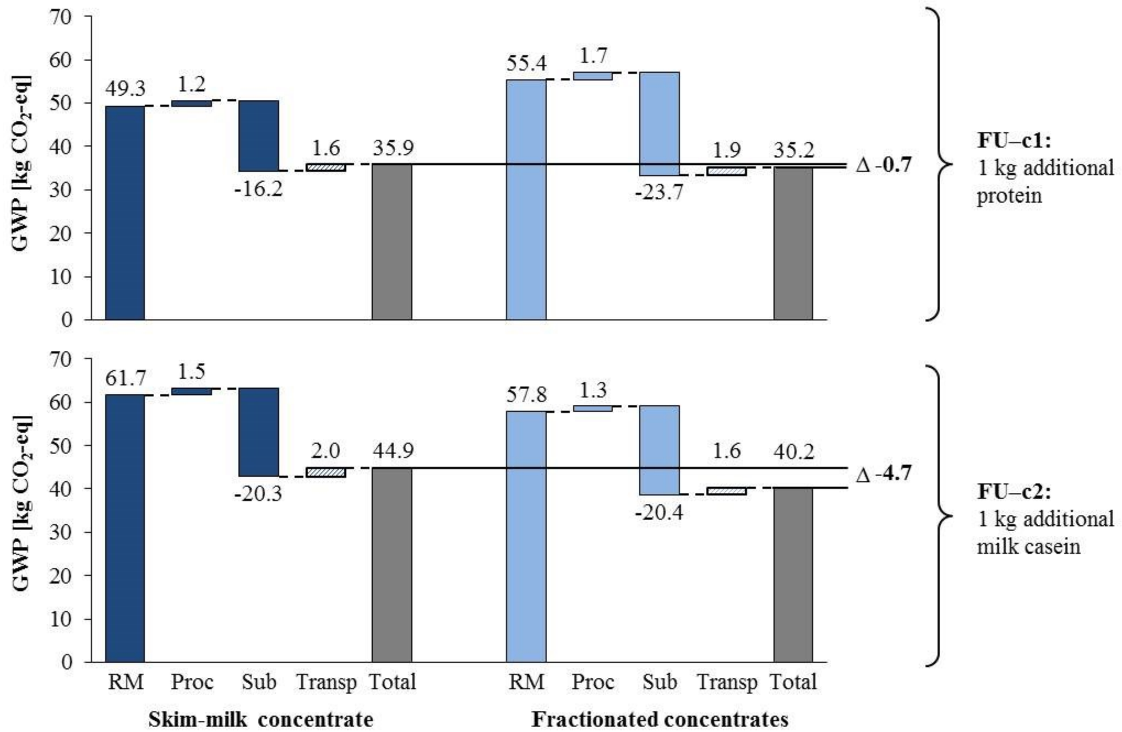


Figure 4.5. Global-warming potential (GWP) of substituting non-fractionated milk concentrates with fractionated concentrates. Abbreviations: RM–raw milk production including transportation, proc–processing, sub–product substitution, transp–transportation.

Table 4.3

The difference in global-warming potential (GWP) between fractionated and non-fractionated milk concentrates depending on raw-milk impact uncertainty (FU–c1 and FU–c2).

GWP difference for functional units		Unit	Raw-milk impact range based on Dalgaard et al. (2014)		Utilized raw-milk impacts from ecoinvent database
			Lower limit	Upper limit	Cow milk {RoW}
FU–c1	1 kg additional protein	kg CO_2-eq	-2.2	0.8	**-0.7**
FU–c2	1 kg additional milk casein	kg CO_2-eq	-3.7	-5.6	**-4.7**

The results for FU–c1 and FU–c2 are also affected by raw-milk impact uncertainty (see table 4.3). Uncertainty here concerns the technology substitutions required when providing one additional kilogram of raw milk. A plausible raw-milk impact range was derived from Dalgaard et al. (2014). Table 4.3 shows that fractionated and non-fractionated milk concentrates should be considered equivalent for FU–c1, since the results depend on raw-milk impacts considered. For FU–c2, the product ranking remains constant, indicating a robust advantage of fractionated concentrates over non-fractionated concentrates.

4.6 Discussion

Fractionated milk concentrates can have functionalities identical to their non-fractionated counterpart. The findings show that for this product-system category, generic functional units (total proteins in FU–a1), lead to inconsistent results from the functionality-based and the economic functional unit in ALCA. An unspecific protein supply does not correspond with the general use and corresponding market evaluation of the fractionated products. In CLCA, the generic functional unit yields equivalent results for SMC and fractionated concentrates (FU–c1). By contrast, fractionated milk concentrates are advantageous whenever their specific functionality is captured in the functional units (the protein-fraction milk casein in FU–a2 and FU–c2). Fractionated milk concentrates with differing functionalities, such as lactose-free products, must moreover be considered under the product-system category *identical input materials* in ALCA. Here, fractionated concentrates show greater environmental impacts per input mass, yet outperform their non-fractionated counterpart from an eco-efficiency perspective (FU–a3). In summary, the environmental assessment of milk fractionation depends on the respective application (milk casein vs. lactose-free).

The results presented in this study are based on life-cycle-inventory data collected at a mid-sized German dairy company as well as at a large equipment manufacturer. These results therefore rely on certain types, ages, and integration extents of processing equipment and are subject to uncertainties regarding the effect of these choices on the environmental impacts of processing. Limited data in the literature prohibited an uncertainty analysis of the determined processing impacts of fractionated milk concentrates. However, results of this study show that for functional units covering *identical functionalities*, processing impacts contribute only 1%–7% to the overall difference in GWP (see appendices F and G). Even for the functional unit covering *identical input materials* (FU–a3), the production process of fractionated concentrates would need to be significantly more energy-intensive to alter the product ranking (e.g., more than a 7-fold electricity consumption for microfiltration would be required). Additionally, the results from the economic functional units (FU–a2 and FU–a3) were tested for robustness against price fluctuations. For this purpose, the product-specific average market prices over 5 years (2014-2018) were also considered separately. The analysis showed that the product ranking remains constant.

The methodology utilized, i.e., ALCA or CLCA, affects the environmental-impact assessment of fractionated and non-fractionated concentrates and is analyzed in more detail. When applied to the product-system category *identical functionalities*, ALCA and CLCA exhibit several differences related to methodological choices and result interpretation. Firstly, the number of products considered in the functional unit differs. While functional units in comparative ALCA may only include identical products with identical production ratios, system expansion is feasible in CLCA. The case study considered the protein-fraction milk casein as a functionality. However, when providing milk casein using liquid MCC instead of SMC for cheese production (FU–a2 and FU–c2), the speed of the gelation process decreases if soluble calcium content is reduced in liquid MCC. Contrary to ALCA, CLCA would allow speed to be included as an additional functionality with the aid of system expansion. The consideration of calcium chloride as gelation-speed enhancer, however, only has a minimal effect on consequential environmental impacts (GWP of MCC: +0.001 kg CO_2-eq). Secondly, by-product handling is different. While the SCODE framework proposes choosing an allocation method aligned with the functional-unit definition in ALCA, system expansion encompassing substitution is used in CLCA. The choice of product substitutions in CLCA, including the determination of the least competitive technology to be replaced, can strongly impact results. The case study, for instance, used lactic-acid production by chemical synthesis as the least competitive technology, which reduced the environmental impact of fractionated concentrates significantly (cf. FU–c1). Thirdly, the interpretation of results differs. Results in ALCA state absolute impacts, while results in CLCA estimate the long-term impacts resulting from a substitution. Considering identical functionalities, milk fractionation can be addressed from both perspectives.

For non-identical functionalities, and thus for exclusively *identical input materials*, the difference between ALCA and CLCA is even more evident. Since CLCA requires substitutability at the consumers of a certain market segment, CLCA cannot be used for this product-system category. By contrast, ALCA allows for a producer-oriented view requiring no substitutability and therefore both an input-based functional unit and an economic functional unit are feasible.

The question arises of how to properly define functional units. Functional units that compare fractionated and non-fractionated products need to capture the advantages of fractionation. The case study showed that when defining the functionalities provided by fractionation too broadly, the resulting evaluation was inconsistent (total proteins in FU–a1). It is, therefore, essential to find more specific functionalities (loop in figure 1) that encompass the market perspective on fractionated products (milk caseins in FU–a2). If the functionalities of fractionated products differ from non-fractionated products, only one approach can be used: an ALCA with a functional unit that considers the input material and the revenue generated. In the case study, this is given when lactose-free products are required and FU–a3 is applied. The case hence demonstrates the significant impact of the product-system category investigated on methodological choices, such as functional-unit definition, in life cycle assessment.

4.7 Conclusions

This paper systematically compares fractionated and non-fractionated products with the aid of LCA. For this purpose, the authors develop a generic scope-definition framework for multi-product processes. The framework is separated into ALCA and CLCA, and addresses the choice of an appropriate functional unit (i.e., functional-unit type and number of functional-unit products) and allocation method. It differentiates three product-system categories for comparative assessments: product systems with identical products, identical functionalities, or identical input materials. The framework verifies the existence of these product-system categories on a step-by-step basis. The framework is applied to new, fractionated dairy products – *micellar-casein concentrate*, *whey-protein concentrate*, and *lactose* – and their non-fractionated counterpart *milk concentrate*.

The findings of the real-life case study highlight the environmental benefits of fractionated milk concentrates across both ALCA and CLCA if they fulfill a specific, identical functionality. Fractionated milk concentrates with functionalities different from their non-fractionated counterpart were moreover considered under the product-system category *identical input materials* in ALCA. Results show a greater environmental impact of fractionated concentrates per input mass, yet a lower impact from an eco-efficiency perspective. Milk fractionation thus proves to be environmentally viable depending on the application of the resulting fractionated concentrates.

The case studied illustrates how the scope-definition framework developed can be applied to evaluate multi-product processes, such as fractionation processes. The comparison of fractionated and non-fractionated products constitutes a special case, for which functional-unit definition and by-product handling is particularly difficult. The framework developed is interesting for researchers who focus on comparative ALCA or substituting CLCA studies, including multi-product processes. Fractionation, a source for multi-product processes, is on the rise in the process industries. Within the dairy sector, milk concentrates fractionated even further milk concentrates may appear on the market. Additional whey-protein fractionation, for instance, offers the potential for hypoallergenic infant formulae and is currently being investigated under pilot scale (Kulozik and Haller, 2014). These developments point to the need to systematically deal with challenges arising from multi-product processes in future LCA studies. This paper offers a methodological framework for choosing appropriate functional units and allocation methods in line with the goals of the respective study.

Future research could focus on a more detailed analysis of how to select system boundaries for comparative input-based and economic functional units in ALCA, such that the functional units both ensure comparability and comprehensiveness of the environmental impacts considered. Additionally, it would be interesting to investigate other types of products with identical functionalities, yet differing product prices. The key questions then relate to how well product prices indicate neglected functionalities and how to evaluate products based on functional units with potentially opposing results. In this context, the derivation of consistency measures may be useful.

Acknowledgments

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5 Conclusions

5.1 Summary of findings

This thesis raises three research questions. The core findings to these questions are summarized below.

> **RQ1:** Are novel milk concentrates environmentally advantageous compared to traditional milk powders along the supply chain? Which product option should be chosen and to what extent does the optimal product choice depend on the transportation distance?

Chapter 2 analyzes the environmental-impact reduction potential of the new milk-concentrate products relative to that of the benchmark, milk powder. For this purpose, a comparative, attributional life cycle assessment was conducted.

The attributional life cycle assessment considered individual processing steps that can be combined and operated in various ways to generate a multitude of different milk concentrates. Functional units were defined at the customer stage; they comprise different reconstituted dry-matter contents based on specific applications of milk powders and milk concentrates. The following four indicators were selected for their importance to the dairy products' supply chain: cumulative energy demand, global warming potential, eutrophication potential, and acidification potential. Detailed life cycle inventory data was collected in cooperation with the partners of the interdisciplinary research project. The data was supplemented and validated with additional data from equipment manufacturers and literature.

The findings highlight the environmental impact advantage of most milk concentrate products. The best concentrate option saves up to 35% of the cumulative energy demand, depending on the application. While environmental impacts are lower in manufacturing, the downstream impacts of milk concentrates can offset these gains. The advantage of concentrates decreases with greater transportation distances to the customer; a break-even with milk powder is first reached for the indicator cumulative energy demand. The processing variant with the lowest cumulative energy demand and the lowest impact on global warming and on acidification is a combined concentration with reverse osmosis and evaporation to a dry-matter content of 35% and preservation via subsequent pasteurization. With regard to eutrophication, this processing variant is the second-best option. The minimum breakeven distance for truck transport of this milk concentrate shows that for downstream manufacturers located within a radius of around 1000 km from the dairy plant, a switch to milk concentrate is environmentally advantageous.

The study identifies the frame within which milk concentrates are an advantageous substitution for milk powder and demonstrates the value of applying environmental assessment to product development and processing-technology selection.

RQ2: From an integrated economic and environmental perspective, should traditional milk powders be substituted with novel milk concentrates? Is the decision impacted by the value of shelf life?

The impact of shelf life on the combined economic and environmental performance of food products is analyzed with the aid of a developed conceptual framework (cf. chapter 3). The framework includes a multi-objective optimization model, a method for objective reduction, and a rolling horizon scheme. Like in company practice, price fluctuations are considered by periodically updating price information. Since the differences in shelf life have their key impact at the tactical planning level, the optimization model was developed at this aggregation level. However, strategic conclusions on the selection of food products are drawn on the basis of the framework. The framework was applied to the comparison of milk powders and milk concentrates and its practicability was tested and verified based on data assessed at the interdisciplinary research partners.

Milk powders and milk concentrates were first evaluated from an economic perspective. The influence of price fluctuations was determined for the time period from 2013 up to 2016. On the one hand, *a priori* perfect price knowledge was assumed. On the other hand, historical price predictions with the aid of Eurex futures for skim-milk powder were used. Results show that powders offer a potential profit benefit of up to 34.5%. This economic value of shelf life, however, is subject to *a priori* perfect price knowledge. If – like in reality –no perfect price information is available in advance, but futures are used as price predictor, the economic value of shelf life is only 1.1%. One reason for this is that futures could not predict the strong price increase of skim-milk powder in spring 2013. For price predictions with futures therefore less skim-milk powder would have been stored for later sale than for *a priori* perfect price knowledge. Moreover, futures overall predicted lower price variabilities over the considered time horizon. As a consequence, the medium shelf life of pre-heated concentrates is sufficient to exploit the price information given by futures. The option of longer storage durations is therefore not a strong argument against the substitution of traditional milk powders by novel milk concentrates.

The two dairy product types were next evaluated from an integrated economic and environmental perspective. Results show that economic and environmental goals are mostly congruent. Two objectives, profit and eutrophication potential, were sufficient to capture the trade-offs in the present case. While a maximization of profit leads to a choice of milk powders and concentrates that are produced by a combined concentration with reverse osmosis and evaporation, the minimization of eutrophication potential leads to a choice of milk powders and concentrates that are produced solely by evaporation. This shift in concentration technology is the main reason for a large profit reduction, which makes a minimization of eutrophication potential unrealistic in practice. For the minimization of all other environmental objectives, however, concentrates produced by combined concentration are selected, resulting in a much less pronounced impact on profit. Environmental objectives favor a selection of solely pasteurized concentrates with a low shelf life. This option equals a dairy company that switches from powders to customers and does not use futures as price predictors, but immediately sells the produced concentrates. The profit decrease amounts to 8% compared to a dairy company that replaces powder, but still maximizes profit with the aid of more shelf-stable concentrates and futures as price predictors. The study determines a range of solutions that omit milk powders and perform well with regard to both profit and environment. To conclude, traditional milk powders should be substituted with novel milk concentrates from an integrated economic and environmental perspective.

RQ3: How can fractionated and non-fractionated products be compared with the aid of life cycle assessment? Are fractionated milk concentrates environmentally viable?

Chapter 4 systematically deals with challenges arising from fractionation, such as multi-product processes. It presents a generic scope-definition framework for multi-product processes, in order to compare fractionated and non-fractionated products with the aid of life cycle assessment (LCA). The developed framework is separated into attributional LCA (ALCA) and consequential LCA (CLCA) and addresses the choice of an appropriate functional unit (i.e., functional-unit type and number of functional-unit products) and allocation method. It distinguishes three product-system categories for comparative assessments: product systems with *identical products*, *identical main/determining functionalities*, or *identical input materials*. The framework verifies the existence of these product-system categories step by step. The framework was applied to new, fractionated dairy products – micellar-casein concentrate, whey-protein concentrate, and lactose – and their non-fractionated counterpart milk concentrate.

The findings show that functional units, which compare fractionated and non-fractionated products, need to capture the advantages of fractionation. The dairy case illustrates that when defining *identical main/determining functionalities* provided by fractionation too broadly, the resulting evaluation is inconsistent. It is therefore essential to find more specific, identical functionalities that encompass the market perspective on fractionated products. Fractionated milk concentrates are advantageous across ALCA and CLCA when the protein-fraction milk casein is specifically considered as functionality in the functional unit. Results in ALCA thereby state absolute impacts, while results in CLCA estimate the long-term impacts resulting from the substitution. The difference between ALCA and CLCA also becomes evident in the number of functionalities considered in the functional unit: While ALCA is restricted to functional units including identical products or functionalities with identical production ratios, CLCA allows for system expansion in the functional unit and thus for the inclusion of additional functionalities, such as cheese-gelation speed of fractionated milk concentrates. Fractionated products with differing functionalities, i.e., with exclusively *identical input materials*, can only be compared to non-fractionated products by one approach: an ALCA with a functional unit that considers the input material and the revenue generated. In the dairy case, differing functionalities are given when lactose-free products are considered. Here, fractionated concentrates show larger environmental impacts per input mass, yet outperform their non-fractionated counterpart from an eco-efficiency perspective (i.e., environmental impacts per Euro revenue generated). The case hence demonstrates that (1) the environmental assessment of milk fractionation depends on the respective application (milk-casein-based products vs. lactose-free products) and (2) the investigated product-system category determines methodological choices in life cycle assessment.

The study investigated how to compare fractionated and non-fractionated products under the criterion of environmental sustainability. The developed scope-definition framework is relevant for researchers and practitioners alike that focus on comparative ALCA or substituting CLCA studies, including multi-product processes. The framework enables the choice of appropriate functional units and allocation methods in line with the goals of the respective study.

5.2 Insights for practitioners

The topics considered in this thesis can be ascribed to applied research. Therefore, it is possible to derive several insights for practitioners within the food industry:

- *Environmental impacts of novel milk concentrates.* Changing from the B-to-B products milk powders to concentrates contributes to reducing the environmental impacts of dairy-containing products. A switch to milk concentrate is environmentally advantageous up to a transportation distance of 1000 km. This finding is particularly interesting for dairy operators and downstream manufacturers, who are interested in switching to milk concentrates. For this purpose, an excerpt of the results from the underlying interdisciplinary research project was published in the monthly released trade journal molkerei-industrie (Marx et al., 2016a, 2016b) that targets decision-makers from the dairy sector. In the meantime, milk concentrates have been introduced to the market by project partners from industry.
- *Process engineering and environmental product assessments.* In the food industry, detailed environmental assessments often can be carried out at an early stage of product development, since new products are frequently generated by combining and operating existing processing steps in novel ways. Therefore, LCA can aid in making processing technology selection and product design more environmentally sustainable, as for the case of novel milk concentrates.
- *Economic value of shelf life.* The forecast accuracy of available price predictors in the food industry has to be considered when storing products for later sale. In case of milk powders, price predictions with futures did not justify the storage of these long-shelf-life products for later sale compared to an earlier sale of novel, more environmentally sustainable milk concentrates.
- *Environmental and economic goals.* A focus on the minimization of environmental impacts related to processes and products can significantly save costs and increase profit for food companies, if environmental and economic goals are congruent. Environmental goals, however, typically consist of various environmental indicators. These indicators each result in objective functions in multi-objective optimization

models and are thus difficult to deal with. Objective reduction, which was feasible in case of milk concentrates, offers a remedy here. It is likely possible in the evaluation of various other food processes and products, particularly of those focusing on energy savings.

- *Environmental impacts of fractionation.* Fractionated milk concentrates proved to be environmentally advantageous compared to non-fractionated milk concentrates, if they are used in milk-casein-based products. Additionally, they possessed a better eco-efficiency when offering novel functionalities (i.e., when providing lactose-free products), while they showed larger environmental impacts per input mass. The analysis of fractionated milk concentrates demonstrates that it is essential to capture the specific advantages of fractionation in the functional-unit definition of ALCA or CLCA, i.e., by considering specific, identical functionalities. Moreover, the developed scope-definition framework shows that product comparisons with non-identical functionalities are restricted to ALCA with a functional unit that considers the input material and the revenue generated.
- *Comparison of multi-product processes with life cycle assessment.* Multi-product processes, in which several products are created simultaneously, are challenging to address with LCA. This thesis proposes a methodology to define functional units and handle by-products in comparative/substituting studies that involve multi-product processes. Practitioners can find guidance on evaluation possibilities for both ALCA and CLCA studies, depending on the considered product-system category, i.e., product systems with identical main products, identical main functionalities, or identical input materials (cf. scope-definition framework in chapter 4).

The research project on novel milk concentrates also motivated the development of a case study used for teaching purposes that already has been tested in three seminars at the Technical University of Munich. The case study called *"How to quantitatively assess the sustainability of supply chains: Learning from the example of novel dairy products"* focuses on the challenges of including environmental sustainability in operations and supply chain management (Depping et al., 2019). By tackling quantitative environmental assessments, the developed case study closes a gap in case-based teaching. The case introduces the Tutzinger Milchwerke (TUMIL) eG as a representative, mid-sized German dairy company that sells in its organic business segment infant formula and skim-milk powder. The case assumes that the product development team of TUMIL recently has developed the new product, skim-milk concentrate, which could replace skim-milk powder, one of the key intermediate products in the dairy sector. It presents Lisa Meier, a young Central Environmental Officer at TUMIL, who has the task of assessing the environmental and economic sustainability of skim-milk concentrate in comparison to skim-milk powder. For this purpose, Lisa talks to several employees at TUMIL, including plant operators, quality managers, and operations managers. At the end of the case, Lisa returns to her office to find answers to the case dilemma. The case study is written in the Harvard-case style and provides readers alongside the case description with supply-chain information on the processing stages of skim-milk concentrate and environmentally as well as economically relevant data. Moreover, the case study considers food-specific characteristics, such as fluctuating agricultural yields and product perishability.

The case requires students to become acquainted with LCA, in order to strengthen their abilities to properly quantify environmental impacts. Moreover, environmental and economic aspects have to be considered jointly in the case study. Besides break-even analyses, this can include the development of a mathematical-programming-based multi-criteria decision making approach to address food-specific challenges in operations management. Depending on the respective target group of students, suitable methodological tools are therefore conveyed that later can be used in industrial practice.

5.3 Research challenges and future directions

Emerging research challenges and possible future directions have already been discussed in chapters 2, 3, and 4. This section outlines some more general challenges and suggestions.

One common challenge when conducting LCAs is the high amount of data required in order to derive meaningful conclusions on the environmental sustainability of products and processes. A generally accepted cut-off criterion is to exclude material, energy, or waste streams that together constitute less than 1% of the overall environmental impact (IDF, 2015; ISO 14046, 2014). This theoretic cut-off criterion, however, can be difficult to assess in practice before conducting an LCA, since some streams may be small in mass, but still large in environmental impacts. Consequently, data collection has to be comprehensive, including detailed data, for instance, on inputs and outputs of production processes. The required data often is not readily available at companies and has to be assessed specifically for this purpose, making data collection for LCAs a time-consuming task. Detailed data collection and the creation of a database, however, improve data availability and data visibility at companies, which in turn can aid in determining levers for cost-reduction. While being challenging in its creation, the database of LCAs therefore enables detailed process analyses under various objectives.

Open source and proprietary databases, such as ecoinvent v3.1 (2014), provide a means to access pre-collected life cycle inventory data for a whole range of products and processes. The data is typically used for the background system of the considered products or processes, such as related supply chains for resource provision and disposal. While available databases are extensive, some environmental impacts scarcely have been addressed so far. Examples are enzymatic cleaning agents or the production of capital goods. Here, further assessments and an integration of lacking impacts into environmental databases are needed.

LCA results must be tested for robustness with regard to input-data uncertainty, such as companies' processing equipment types and sizes or equipment utilization. Additionally, LCA results depend on the extent to which plants in companies are integrated. Large companies typically tend to have a higher degree of integration and therefore reuse, for instance, large shares of water and energy. Producing new or additional products in these companies thus leads to lower environmental impacts than producing the products in hardly integrated companies. When considering different companies and their respective extent of integration, an environmental-impact range can be determined. While this analysis was beyond the scope of the present thesis, it would be interesting to specifically address this source of uncertainty in future research and to assess the effect of integrated production systems on LCA outcomes. In this context, LCA could also be combined with methods that focus on optimizing energy consumption by enhanced process integration, such as the pinch analysis (cf. Kemp, 2011).

The importance of unit-process operations in LCA and the need to consider those in more detail has been pointed out by Jacquemin et al. (2012). In the present case operational parameters related to unit processes (e.g., the equipment utilization rate of different concentration processes) did not alter the product ranking of milk concentrates. However, operations can be significant in the evaluation of other food products. In this case, operational parameters need to be integrated in strategic decision-making. This is particularly relevant when considering the combined environmental and economic performance of products. In multi-criteria approaches, a hierarchical integration of information from different planning levels is required. The key challenge then relates to drawing strategic decisions based on updated environmental information at the operational planning level.

The availability of environmental and economic data is likely to improve in the next years with increasing digitalization in economy. Through modern technologies, amounts of data are growing rapidly. As a result, the next challenge for food planners and LCA practitioners might be how to manage so-called big data stemming from measurement systems, instead of collecting data. Researchers in this field therefore have to investigate how to systematically integrate different data sources into LCA to support data-driven decisions in the future. As production and logistics processes in the food industry are on the verge of becoming digitally and intelligently connected, LCA researchers might be provided with real-time information in the future. In this context, new product developments can be analyzed right away regarding their environmental and economic sustainability. The digital transformation thus offers promising research opportunities for quantitative sustainability analyses.

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Appendix A. Abbreviations.

1) Technological and processing abbreviations

BOD	Biochemical oxygen demand
Centri	Two-stage decanter centrifugation
CIP	Cleaning in place
Combi	Reverse osmosis and subsequent evaporation
Cryst	Crystallization
DMC	Dry-matter content
Dry/DRY	Spray drying
Dry*	Fluidized-bed drying
ESL	Extended shelf life
EV	Evaporation
Ferm	Fermentation
HHT	High-heat treatment
Liquid MCC	Liquid micellar-casein concentrate
Liquid WPC	Liquid whey-protein concentrate
MF	Microfiltration
MO	Microbial growth
MSD	Multistage drying
Past	Pasteurization
Pack	Packaging
Proc	Processing
RM	Raw-milk production
RO	Reverse osmosis
SEC	Specific energy consumption
Sep	Separation

SMC	Skim-milk concentrate
SMP	Skim-milk powder
Tank	Tank collection
Transp	Transportation
UF	Ultrafiltration
UHT	Ultrahigh temperature

2) Methodological abbreviations

ALCA	Attributional life cycle assessment
AP	Acidification potential
CED	Cumulative energy demand
CLCA	Consequential life cycle assessment
EP	Eutrophication potential
EP*	Share of eutrophication potential that the plant can influence
FU	Functional unit
SCODE	Scope definition
GWP	Global-warming potential
LCA	Life cycle assessment
LL	Lower limit of raw-milk impact
MOSS	Minimum objective subset
Sub	Product substitution
UL	Upper limit of raw-milk impact

Appendix B. Life cycle inventory data for milk powders and milk concentrates.

Unit processes	Inflow amount (IA)	Unit consumption per IA									
		During production		During cleaning							
		Electricity	Natural gas	Electricity	Natural gas	Sodium hydroxide [a]	Nitric acid [a]	Phosphoric acid [a]	Tap water	Waste water	Waste water BOD5
	[kg]	[kWh]	[kWh]	[kWh]	[kWh]	[g]	[g]	[g]	[kg]	[kg]	[g/l]
Common processes											
1 Milk reception	**1.0001**	5.79E-05		7.04E-06	1.55E-04	4.43E-03	5.31E-04	2.48E-05	7.32E-04	7.32E-04	1.48E+01
2 Separation	**0.6164**	3.95E-03		2.36E-04	0.00E+00	3.13E-02	2.62E-02	2.45E-03	1.28E-02	1.28E-02	1.70E+01
3 Pasteurization	**1.0000**	7.67E-04	4.42E-03	4.73E-05	4.76E-04						
Powder											
1 EV, 45%	**5.1026**	3.88E-02	7.50E-01	2.63E-03	8.10E-02	7.69E-01	6.44E-01	3.02E-02	3.13E-01	3.13E-01	1.04E+01
2 RO, 28%	**3.1513**	4.19E-02	0.00E+00	8.00E-03	2.21E-03	3.48E-02	5.85E-02	8.08E-02	4.75E-01	4.75E-01	6.03E-01
3 EV, 28% to 45%	**1.6107**	5.77E-03	1.11E-01	3.91E-04	1.20E-02	1.14E-01	9.58E-02	4.48E-03	4.23E-02	4.23E-02	1.15E+01
4 Spray drying	**2.1301**		1.82E+00		1.39E-01	1.39E+00			1.54E+00	1.85E+00	1.75E+00
5 Multi-stage drying	**2.1254**	3.72E-01	1.30E+00	5.90E-04	5.14E-03	4.56E+00	4.56E+00		2.96E-01	2.96E-01	3.70E+00
6 Packaging	**1.0000**	2.15E-01		8.94E-03					3.79E-02	3.79E-02	
7 Redispersion to 12.5% in skim milk	**1.0207**	7.97E-04			1.65E-03			1.59E-04	3.54E-02	2.32E-02	8.50E+01
8 Redispersion to 30% in skim milk	**1.0976**	4.85E-03			4.47E-03			9.67E-04	9.60E-02	2.16E-02	7.59E+02
9 Redispersion to 35% in skim milk	**1.0976**	6.02E-03			5.30E-03			1.20E-03	1.14E-01	2.16E-02	8.86E+02
10 Redispersion to 30% in water	**1.0852**	6.19E-03			5.44E-03			6.56E-04	1.17E-01	2.18E-02	5.20E+02
11 Redispersion to 35% in water	**1.0852**	7.23E-03			6.18E-03			7.66E-04	1.33E-01	2.18E-02	6.07E+02

[a] Sodium hydroxide and nitric acid: 50% in H_2O; phosphoric acid: 85% in H_2O.
Abbreviations: RO – reverse osmosis; EV – evaporation; Past – pasteurization; HHT – high heat treatment; ESL – extended shelf life; UHT – ultra-high-temperature.

Appendix B (continued). Life cycle inventory data for milk powders and milk concentrates.

Unit processes		Inflow amount (IA)	Unit consumption per IA				Capital goods usage per IA [b]		Packaging material per IA [c]	
			During cleaning							
			Waste water Part. P	Waste water Kjeldahl N	Waste water Nitrate N	Waste water Phosphate P	Stainless steel	HDPE	Kraft-paper	LDPE inlay
		[kg]	[g/l]	[g/l]	[mg/l]	[mg/l]	[g]	[g]	[g]	[g]
Common processes										
1	Milk reception	**1.0001**	1.32E-01	8.31E-01	9.12E+00	3.87E+01	2.12E-03			
2	Separation	**0.6164**	1.51E-01	9.52E-01	4.55E-01	5.15E-02	1.30E-03			
3	Pasteurization	**1.0000**					5.03E-03			
Powder										
1	EV, 45%	**5.1026**	1.27E-01	5.54E-01	2.29E+02	2.59E+01	1.59E-01			
2	RO, 28%	**3.1513**	7.72E-03	3.36E-02	1.37E+01	4.57E+01	3.62E-02	5.05E-02		
3	EV, 28% to 45%	**1.6107**	1.95E-01	8.50E-01	2.51E-01	2.84E-02	2.36E-02			
4	Spray drying	**2.1301**	1.32E-02	5.75E-02			1.30E-01			
5	Multi-stage drying	**2.1254**	3.34E-02	1.46E-01	1.71E+00		5.88E-01			
6	Packaging	**1.0000**					3.09E-02		9.20E+00	3.60E+00
7	Redispersion to 12.5% in skim milk	**1.0207**	1.14E+00	4.95E+00		9.79E-04	2.93E-03			
8	Redispersion to 30% in skim milk	**1.0976**	1.29E+01	5.63E+01		6.41E-03	2.73E-03			
9	Redispersion to 35% in skim milk	**1.0976**	1.47E+01	6.43E+01		7.94E-03	2.68E-03			
10	Redispersion to 30% in water	**1.0852**	1.11E+01	4.85E+01		5.02E-03	2.73E-03			
11	Redispersion to 35% in water	**1.0852**	1.27E+01	5.54E+01		5.02E-03	2.68E-03			

[b] End-of-life treatment of stainless steel (8 % inert material landfill, 92% recycling) and HDPE (66 % municipal incineration, 1 % sanitary landfill, 33% recycling).

[c] End-of-life treatment of kraftpaper (12.2% municipal incineration, 0.2% inert material landfill, 87.6% recycling) and plastic inlays (66% municipal incineration, 1% sanitary landfill, 33% recycling).

Appendix B (continued). Life cycle inventory data for milk powders and milk concentrates.

Unit processes	Inflow amount (IA)	Unit consumption per IA									
		During production		During cleaning							
		Electricity	Natural gas	Electricity	Natural gas	Sodium hydroxide [a]	Nitric acid [a]	Phosphoric acid [a]	Tap water	Waste water	Waste water BOD5
	[kg]	[kWh]	[kWh]	[kWh]	[kWh]	[g]	[g]	[g]	[kg]	[kg]	[g/l]
Concentrates											
1 RO, 20%	**2.2521**	2.98E-02		5.31E-03	1.47E-03	2.31E-02	3.88E-02	5.36E-02	3.15E-01	3.15E-01	4.51E-01
2 RO, 30%	**3.3757**	4.54E-02		1.01E-02	2.79E-03	4.39E-02	7.37E-02	1.02E-01	5.99E-01	5.99E-01	6.29E-01
3 RO, 35%	**3.9456**	6.38E-02		3.41E-02	9.41E-03	1.48E-01	2.49E-01	3.44E-01	2.02E+00	2.02E+00	7.24E-01
4 EV, 20%	**2.2540**	1.19E-02	2.29E-01	6.89E-04	2.12E-02	2.01E-01	1.69E-01	7.90E-03	8.21E-02	8.21E-02	5.53E+00
5 EV, 30%	**3.3889**	2.26E-02	4.36E-01	1.41E-03	4.35E-02	4.13E-01	3.46E-01	1.62E-02	1.68E-01	1.68E-01	7.21E+00
6 EV, 35%	**3.9584**	2.80E-02	5.41E-01	1.80E-03	5.54E-02	5.26E-01	4.40E-01	2.06E-02	2.14E-01	2.14E-01	8.11E+00
7 RO, 28%	**3.1491**	4.19E-02		8.00E-03	2.21E-03	3.48E-02	5.85E-02	8.08E-02	4.75E-01	4.75E-01	1.27E+01
8 EV, 28% to 35%	**1.2513**	2.37E-03	4.58E-02	1.61E-04	4.95E-03	4.70E-02	3.94E-02	1.84E-03	1.92E-02	1.92E-02	5.58E+00
9 Downstream Past, 20%	**1.0011**	7.16E-03	3.57E-03	1.02E-04	1.03E-03	6.71E-02	1.12E-01	5.26E-03	1.37E-02	1.37E-02	1.27E+01
10 Downstream Past, 30%	**1.0013**	6.48E-03	3.42E-03	1.47E-04	1.48E-03	9.66E-02	1.61E-01	7.58E-03	1.98E-02	1.98E-02	1.47E+01
11 Downstream Past, 35%	**1.0013**	6.14E-03	3.98E-03	1.68E-04	1.69E-03	1.10E-01	1.85E-01	8.66E-03	2.26E-02	2.26E-02	1.59E+01
12 Upstream UHT	**1.0010**	1.14E-02	0.020724	4.15E-05	1.09E-03	6.06E-02	4.61E-02		5.58E-03	5.58E-03	1.26E+01
13 Downstream ESL, 30%	**1.0014**	1.10E-02	1.95E-02	2.06E-04	5.41E-03	3.25E-01	2.65E-01		2.77E-02	2.77E-02	1.13E+01
14 Downstream HHT, 30%	**1.0014**	1.07E-02	1.79E-02	2.06E-04	5.41E-03	3.25E-01	2.65E-01		2.77E-02	2.77E-02	1.13E+01
15 Downstream HHT, 35%	**1.0015**	1.01E-02	1.69E-02	2.26E-04	5.94E-03	3.57E-01	2.91E-01		3.04E-02	3.04E-02	1.30E+01

[a] Sodium hydroxide and nitric acid: 50% in H_2O; phosphoric acid: 85% in H_2O.

Abbreviations: RO – reverse osmosis; EV – evaporation; Past – pasteurization; HHT – high heat treatment; ESL – extended shelf life; UHT – ultra-high-temperature.

Appendix B (continued). Life cycle inventory data for milk powders and milk concentrates.

Unit processes	Inflow amount (IA)	Unit consumption per IA – During cleaning				Capital goods usage per IA [b]		Packaging material per IA [c]	
	[kg]	Waste water Part. P [g/l]	Waste water Kjeldahl N [g/l]	Waste water Nitrate N [mg/l]	Waste water Phosphate P [mg/l]	Stainless steel [g]	HDPE [g]	Kraft-paper [g]	LDPE inlay [g]
Concentrates									
1 RO, 20%	**2.2521**	5.93E-03	2.58E-02	1.37E+01	4.57E+01	2.55E-02	3.56E-02		
2 RO, 30%	**3.3757**	7.98E-03	3.48E-02	1.37E+01	4.57E+01	4.01E-02	5.60E-02		
3 RO, 35%	**3.9456**	9.00E-03	3.92E-02	1.37E+01	4.57E+01	6.97E-02	9.74E-02		
4 EV, 20%	**2.2540**	7.33E-02	3.19E-01	2.29E+02	2.59E+01	4.79E-02			
5 EV, 30%	**3.3889**	9.27E-02	4.04E-01	2.29E+02	2.59E+01	9.18E-02			
6 EV, 35%	**3.9584**	1.02E-01	4.46E-01	2.29E+02	2.59E+01	1.14E-01			
7 RO, 28%	**3.1491**	7.57E-03	3.30E-02	1.37E-02	4.57E-02	3.62E-02	5.05E-02		
8 EV, 28% to 35%	**1.2513**	6.79E-02	2.96E-01	2.29E-01	2.59E-02	9.70E-03			
9 Downstream Past, 20%	**1.0011**	1.64E-01	7.16E-01	9.06E+02	1.03E+02	5.60E-03			
10 Downstream Past, 30%	**1.0013**	1.82E-01	7.94E-01	9.06E+02	1.03E+02	6.11E-03			
11 Downstream Past, 35%	**1.0013**	1.93E-01	8.42E-01	9.06E+02	1.03E+02	6.35E-03			
12 Upstream UHT	**1.0010**	7.97E-02	3.47E-01	4.27E+02		7.11E-03			
13 Downstream ESL, 30%	**1.0014**	1.41E-01	6.14E-01	1.06E+03		1.00E-02			
14 Downstream HHT, 30%	**1.0014**	1.41E-01	6.14E-01	1.06E+03		1.00E-02			
15 Downstream HHT, 35%	**1.0015**	1.58E-01	6.89E-01	1.17E+03		1.05E-02			

[b] End-of-life treatment of stainless steel (8 % inert material landfill, 92% recycling) and HDPE (66 % municipal incineration, 1 % sanitary landfill, 33% recycling).

[c] End-of-life treatment of kraftpaper (12.2% municipal incineration, 0.2% inert material landfill, 87.6% recycling) and plastic inlays (66% municipal incineration, 1% sanitary landfill, 33% recycling).

Appendix B (continued). Life cycle inventory data for milk powders and milk concentrates.

Unit processes	Inflow amount (IA)	Unit consumption per IA									
		During production		During cleaning							
		Electri-city	Natural gas	Electri-city	Natural gas	Sodium hydro-xide [a]	Nitric acid [a]	Phos-phoric acid [a]	Tap water	Waste water	Waste water BOD5
	[kg]	[kWh]	[kWh]	[kWh]	[kWh]	[g]	[g]	[g]	[kg]	[kg]	[g/l]
Concentrates											
16 Packaging, 20%	**1.0001**	1.63E-03		3.45E-05	0.00E+00	1.33E-02	2.23E-02	1.04E-03	2.99E-03	2.99E-03	4.64E+00
17 Packaging, 30%	**1.0001**	1.56E-03		3.31E-05	0.00E+00	1.28E-02	2.14E-02	1.00E-03	2.87E-03	2.87E-03	7.26E+00
18 Packaging, 35%	**1.0001**	1.53E-03		3.24E-05	0.00E+00	1.25E-02	2.09E-02	9.79E-04	2.81E-03	2.81E-03	8.65E+00
19 Cooled storage (dairy), 20%	**1.0000**	9.60E-05									
20 Cooled storage (dairy), 30%	**1.0000**	9.22E-05									
21 Cooled storage (dairy), 35%	**1.0000**	9.03E-05									
22 Cooled storage (customer), 20%	**1.0000**	1.48E-03									
23 Cooled storage (customer), 30%	**1.0000**	1.42E-03									
24 Cooled storage (customer), 35%	**1.0000**	1.39E-03									
25 Diluting 20% to 12.5% in skim milk	**0.3243**	1.63E-04									
26 Diluting 30% to 12.5% in skim milk	**0.1706**	8.57E-05									
27 Diluting 35% to 12.5% in skim milk	**0.1379**	6.93E-05									
28 Diluting 35% to 30% in skim milk	**0.8084**	4.06E-04									
29 Diluting 35% to 30% in water	**0.8571**	4.31E-04									

[a] Sodium hydroxide and nitric acid: 50% in H_2O; phosphoric acid: 85% in H_2O.

Appendix B (continued). Life cycle inventory data for milk powders and milk concentrates.

Unit processes	Inflow amount (IA)	Unit consumption per IA				Capital goods usage per IA [b]		Packaging material per IA [c]	
		During cleaning							
		Waste water Part. P	Waste water Kjeldahl N	Waste water Nitrate N	Waste water Phosphate P	Stainless steel	HDPE	Kraft-paper	LDPE inlay
	[kg]	[g/l]	[g/l]	[mg/l]	[mg/l]	[g]	[g]	[g]	[g]
Concentrates									
16 Packaging, 20%	**1.0001**	7.98E-03	3.48E-02	1.10E+02	1.24E+01	2.68E-02		2.22E+01	4.23E+00
17 Packaging, 30%	**1.0001**	1.15E-02	5.01E-02	1.05E+02	1.19E+01	2.68E-02			
18 Packaging, 35%	**1.0001**	1.31E-02	5.72E-02	1.03E+02	1.17E+01	2.68E-02			
19 Cooled storage (dairy), 20%	**1.0000**								
20 Cooled storage (dairy), 30%	**1.0000**								
21 Cooled storage (dairy), 35%	**1.0000**								
22 Cooled storage (customer), 20%	**1.0000**								
23 Cooled storage (customer), 30%	**1.0000**								
24 Cooled storage (customer), 35%	**1.0000**								
25 Diluting 20% to 12.5% in skim milk	**0.3243**					1.40E-03			
26 Diluting 30% to 12.5% in skim milk	**0.1706**					1.40E-03			
27 Diluting 35% to 12.5% in skim milk	**0.1379**					1.40E-03			
28 Diluting 35% to 30% in skim milk	**0.8084**					1.31E-03			
29 Diluting 35% to 30% in water	**0.8571**					1.31E-03			

[b] End-of-life treatment of stainless steel (8 % inert material landfill, 92% recycling) and HDPE (66 % municipal incineration, 1 % sanitary landfill, 33% recycling).
[c] End-of-life treatment of kraftpaper (12.2% municipal incineration, 0.2% inert material landfill, 87.6% recycling) and plastic inlays (66% municipal incineration, 1% sanitary landfill, 33% recycling).

Appendix C. Overview on utilized ecoinvent v3.1 processes in chapter 2.

Consumption factors	Ecoinvent v3.1 processes used
Energy	
Electricity	Electricity, low voltage {DE} | market for | Alloc Rec, U
Natural gas	Heat, district or industrial, natural gas {Europe without Switzerland} | market for heat, district or industrial, natural gas | Alloc Rec, U
Cleaning agents	
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO} | market for | Alloc Rec, U
Nitric acid	Nitric acid, without water, in 50% solution state {GLO} | market for | Alloc Rec, U
Phosphoric acid	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO} | market for | Alloc Rec, U
Citric acid	Citric acid {GLO} | market for | Alloc Rec, U
Water	
Tap water	Tap water, {Europe without Switzerland} | market for | Alloc Rec, U
Capital goods	
Stainless steel	Steel, chromium steel 18/8 {GLO} | market for | Alloc Rec, U
HDPE	Polyethylene, high density, granulate {GLO} | market for | Alloc Rec, U
Packaging materials	
Kraft paper	Kraft paper, unbleached {GLO} | market for | Alloc Rec, U
Packaging film (LDPE)	Packaging film, low density polyethylene {GLO} | market for | Alloc Rec, U

Appendix C (continued). Overview on utilized ecoinvent v3.1 processes in chapter 2.

Consumption factors	Ecoinvent v3.1 processes used
Transport	
Lorry	Transport, freight, lorry 16-32 metric ton, EURO5 {RER} | transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U _ milk collection
	Transport, freight, lorry 16-32 metric ton, EURO5 {RER} | transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U _ ambient
	Transport, freight, lorry 16-32 metric ton, EURO5 {RER} | transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Rec, U _ cooled
Disposal	
Kraft paper	Waste paperboard {RoW} | treatment of, municipal incineration | Alloc Rec, U
	Waste paperboard {RoW} | treatment of, inert material landfill | Alloc Rec, U
	Paper waste treatment {GLO} | recycling of paper | Alloc Rec, U
Packaging film (LDPE) & HDPE	Waste polyethylene {RoW} | treatment of, municipal incineration | Alloc Rec, U
	Waste polyethylene {RoW} | treatment of, sanitary landfill | Alloc Rec, U
	PE waste treatment {GLO} | recycling of PE | Alloc Def, U
Stainless steel	Scrap steel {CH} | treatment of, inert material landfill | Alloc Rec, U
	Steel and iron (waste treatment) {GLO} | recycling of steel and iron | Alloc Rec, U

Note: processes related to wastewater treatment are excluded from this overview.

Appendix D. Life cycle inventory data for fractionated concentrates.

Unit processes [a]		Inflow mass(IM)	Outflow mass	Unit consumption per IM							
				During production			During cleaning [b]				
				Electri-city	Natural gas	Tap water	Electri-city	Natural gas	Sodium hydroxide	EDTA	Nitric acid
		[kg]	[kg]	[kWh]	[kWh]	[kg]	[kWh]	[kWh]	[g]	[g]	[g]
Pre-processing											
1	Tank, raw milk	**1.0001**	**1.0000**	5.79E-05			7.04E-06	1.55E-04	4.43E-03		5.31E-04
2a	Sep: skim milk – no alloc	**1.1133**	**1.0000**	4.40E-03			2.63E-04		3.48E-02		5.83E-02
2b	Sep: skim milk – total proteins alloc	**1.1133**	**1.0000**	4.40E-03			2.63E-04		3.48E-02		5.83E-02
2c	Sep: skim milk – milk casein alloc	**1.1133**	**1.0000**	4.40E-03			2.63E-04		3.48E-02		5.83E-02
2d	Sep: skim milk – economic alloc	**0.4936**	**1.0000**	1.95E-03			1.17E-04		1.54E-02		2.59E-02
3	Past, skim milk	**1.0000**	**1.0000**	7.67E-04	4.42E-03		4.73E-05	4.76E-04			
Non-fractionated concentrate production											
1	RO, skim milk, 8.9% to 28%	**3.1491**	**1.0000**	4.19E-02			8.00E-03	2.21E-03	3.48E-02		5.85E-02
2	EV, skim milk, 28% to 35%	**1.2513**	**1.0000**	2.37E-03	4.58E-02		1.61E-04	4.95E-03	4.70E-02		3.94E-02
3	Past, SMC 35%	**1.0013**	**1.0000**	6.14E-03	3.98E-03		1.68E-04	1.69E-03	1.10E-01		1.85E-01
4	Pack, SMC 35%	**1.0001**	**1.0000**	1.53E-03			3.24E-05		1.25E-02		2.09E-02

[a] The utilized technologies for fractionated and non-fractionated products were assumed to be identical across ALCA and CLCA.

[b] For cleaning agents, required production and transport masses of the active substances were taken as a proxy.

Abbreviations: Alloc–allocation, EV–evaporation, Pack–packaging, Past–pasteurization, RO–reverse osmosis, Sep–separation, SMC–skim-milk concentrate, Tank–tank collection.

Appendix D (continued). Life cycle inventory data for fractionated concentrates.

Unit processes [a]		Inflow mass (IM)	Outflow mass	Unit consumption per IM					
				During cleaning [b]					
				Phos-phoric acid	Potas-sium hydroxide	Potas-sium carbonate	Alkyl-benzene sulfonate	Alkyl-amine	Tap water [c]
		[kg]	[kg]	[g]	[g]	[g]	[g]	[g]	[kg]
Pre-processing									
1	Tank, raw milk	**1.0001**	**1.0000**	2.48E-05					7.32E-04
2a	Sep: skim milk – no alloc	**1.1133**	**1.0000**	2.73E-03					1.42E-02
2b	Sep: skim milk – total proteins alloc	**1.1133**	**1.0000**	2.73E-03					1.42E-02
2c	Sep: skim milk – milk casein alloc	**1.1133**	**1.0000**	2.73E-03					1.42E-02
2d	Sep: skim milk – economic alloc	**0.4936**	**1.0000**	1.21E-03					6.31E-03
3	Past, skim milk	**1.0000**	**1.0000**						
Non-fractionated concentrate production									
1	RO, skim milk, 8.9% to 28%	**3.1491**	**1.0000**	8.08E-02				5.82E-02	4.75E-01
2	EV, skim milk, 28% to 35%	**1.2513**	**1.0000**	1.84E-03					1.92E-02
3	Past, SMC 35%	**1.0013**	**1.0000**	8.66E-03					2.26E-02
4	Pack, SMC 35%	**1.0001**	**1.0000**	9.79E-04					2.81E-03

[a] The utilized technologies for fractionated and non-fractionated products were assumed to be identical across ALCA and CLCA.

[b] For cleaning agents, required production and transport masses of the active substances were taken as a proxy.

[c] Since in the fractionated concentrate production only rough estimates on effluents were available for some processing steps, inventory data related to wastewater was excluded from the present analysis. However, wastewater was found to have only a minor impact (<0.8%) on the global-warming potential of non-fractionated skim-milk concentrate (Depping et al., 2017).

Appendix D (continued). Life cycle inventory data for fractionated concentrates.

Unit processes [a]	Inflow mass (IM)	Outflow mass	Capital goods usage per IM [d]					Packaging materials per IM [e]		Transport per IM
			Stainless steel	HDPE	Poly-sulfone	Polyester	Aluminum oxide	Kraft-paper	LDPE	
	[kg]	[kg]	[g]	[g]	[g]	[g]	[g]	[g]	[g]	[tkm]
Pre-processing										
1 Tank, raw milk	**1.0001**	**1.0000**	2.12E-03							
2a Sep: skim milk – no alloc	**1.1133**	**1.0000**	1.45E-03							
2b Sep: skim milk – total proteins alloc	**1.1133**	**1.0000**	1.45E-03							
2c Sep: skim milk – milk casein alloc	**1.1133**	**1.0000**	1.45E-03							
2d Sep: skim milk – economic alloc	**0.4936**	**1.0000**	6.43E-04							
3 Past, skim milk	**1.0000**	**1.0000**	5.03E-03							
Non-fractionated concentrate production										
1 RO, skim milk, 8.9% to 28%	**3.1491**	**1.0000**	3.62E-02	5.05E-02						
2 EV, skim milk, 28% to 35%	**1.2513**	**1.0000**	9.70E-03							
3 Past, SMC 35%	**1.0013**	**1.0000**	6.35E-03							
4 Pack, SMC 35%	**1.0001**	**1.0000**	2.68E-02					2.22E+01	4.23E+00	
Transportation										
1 Milk collection (50 km)	**1.0004**	**1.0000**								5.00E-02

[a] The utilized technologies for fractionated and non-fractionated products were assumed to be identical across ALCA and CLCA.
[d] For the inventory of capital goods, production and transport of the involved raw materials was taken as a proxy. Environmental impacts of capital goods were linearly depreciated over their lifetime according to German depreciation rules (German Federal Ministry of Finance, 2019). End-of-life treatment of capital goods was excluded, due to low environmental-impact contribution (i.e., only up to 1% of capital-goods production impacts).
[e] Both fractionated and non-fractionated concentrates are packaged in bags-in-boxes, consisting of kraftpaper with plastic inlays made of low-density polyethylene that are disposed at the customer stage. End-of-life treatment of kraftpaper (12.2% municipal incineration, 0.2% inert material landfill, 87.6% recycling) and plastic inlays (66% municipal incineration, 1% sanitary landfill, 33% recycling).

Appendix D (continued). Life cycle inventory data for fractionated concentrates.

Unit processes [a]		Inflow mass (IM)	Outflow mass	Unit consumption per IM							
				During production			During cleaning [b]				
				Electricity	Natural gas	Tap water	Electricity	Natural gas	Sodium hydroxide	EDTA	Nitric acid
		[kg]	[kg]	[kWh]	[kWh]	[kg]	[kWh]	[kWh]	[g]	[g]	[g]
Fractionated concentrate production											
1a	MF: retentate – no alloc	**4.6307**	**1.0000**	5.39E-02		2.21E-01	6.84E-03	8.15E-03	1.35E-04	2.92E-02	4.49E-01
1b	MF: retentate – total proteins alloc	**4.3698**	**1.0000**	5.09E-02		2.09E-01	6.46E-03	7.69E-03	1.27E-04	2.75E-02	4.23E-01
	MF: permeate – total proteins alloc	**0.2609**	**3.6307**	3.04E-03		1.25E-02	3.85E-04	4.59E-04	7.58E-06	1.64E-03	2.53E-02
1c	MF: retentate – milk casein alloc	**4.6307**	**1.0000**	5.39E-02		2.21E-01	6.84E-03	8.15E-03	1.35E-04	2.92E-02	4.49E-01
2	HHT, MF retentate (Liquid MCC 20%)	**1.0012**	**1.0000**	8.45E-03	1.89E-02		8.59E-03	2.27E-02	2.28E-04		1.86E-04
3	Pack, Liquid MCC 20%	**1.0001**	**1.0000**	1.64E-03			3.48E-05		1.34E-02	8.95E-04	2.25E-02
4	RO, MF permeate, 6.1% to 30%	**3.6307**	**0.9099**	2.60E-02	2.30E-02		1.09E-02	3.01E-03	4.74E-02		7.96E-02
5	Past, MF permeate 30%	**0.9099**	**0.9087**	6.14E-03	3.98E-03		6.31E-03	5.67E-03	1.10E-01	7.36E-03	1.85E-01
6a	UF: retentate - no alloc	**0.9737**	**0.2086**	3.95E-02		4.29E-01	1.80E-02		1.26E-01		2.31E-01
6b	UF: retentate – total proteins alloc	**0.9737**	**0.2086**	3.95E-02		4.29E-01	1.80E-02		1.26E-01		2.31E-01
7	Past, UF retentate (Liquid WPC 35%)	**0.2086**	**0.2084**	6.14E-03	3.98E-03		6.31E-03	5.67E-03	1.10E-01	7.36E-03	1.85E-01
8	Pack, Liquid WPC 35%	**0.2084**	**0.2083**	1.53E-03			6.82E-06		2.63E-03	1.75E-04	4.40E-03
9	Ferm, UF permeate	**0.7650**	**0.7648**	9.45E-05			5.40E-04	1.19E-02	3.40E-01	2.27E-02	4.07E-02
10	EV, UF permeate, 25% to 70%	**0.7650**	**0.2719**	4.53E-03	8.74E-02		3.35E-04	1.03E-02	9.78E-02	6.52E-03	8.20E-02
11	Cryst, UF permeate 70%	**0.2719**	**0.2717**	1.80E-03			2.03E-05	4.47E-04	1.28E-02	8.52E-04	1.53E-03
12	Centri, UF permeate, 70% to 80%	**0.2717**	**0.2150**	2.85E-03				6.87E-05	1.59E-02		1.59E-02
13	Centri, UF permeate, 80% to 90%	**0.2189**	**0.1609**	2.69E-03				6.48E-05	1.50E-02		1.50E-02
14	Dry*, Lactose, 90% to 99.9%	**0.1609**	**0.1450**	1.79E-03	1.20E-02						
15	Pack, Lactose 99.9%	**0.1450**	**0.1450**	3.11E-02			3.24E-02				

[a] The dairy plant used ceramic membranes for microfiltration and polymer membranes for ultrafiltration. The utilized technologies for fractionated and non-fractionated products were assumed to be identical across ALCA and CLCA.
[b] For cleaning agents, required production and transport masses of the active substances were taken as a proxy.

Abbreviations: Alloc–allocation, Centri–two-stage decanter centrifugation, Cryst–crystallization, Dry*–fluidized-bed drying, EV–evaporation, Ferm–fermentation, HHT–high-heat treatment, MCC–micellar-casein concentrate, MF–microfiltration, Pack–packaging, Past–pasteurization, RO–reverse osmosis, UF–ultrafiltration, WPC–whey-protein concentrate.

Appendix D (continued). Life cycle inventory data for fractionated concentrates.

Unit processes [a]		Inflow mass (IM)	Outflow mass	Unit consumption per IM					
				During cleaning [b]					
				Phos-phoric acid	Potas-sium hydroxide	Potas-sium carbonate	Alkyl-benzene sulfonate	Alkyl-amine	Tap water [c]
		[kg]	[kg]	[g]	[g]	[g]	[g]	[g]	[kg]
Fractionated concentrate production									
1a	MF: retentate – no alloc	**4.6307**	**1.0000**		2.92E-02			8.97E-03	4.49E-01
1b	MF: retentate – total proteins alloc	**4.3698**	**1.0000**		2.75E-02			8.47E-03	4.23E-01
	MF: permeate – total proteins alloc	**0.2609**	**3.6307**		1.64E-03			5.06E-04	2.53E-02
1c	MF: retentate – milk casein alloc	**4.6307**	**1.0000**		2.92E-02			8.97E-03	4.49E-01
2	HHT, MF retentate (Liquid MCC 20%)	**1.0012**	**1.0000**						1.94E-02
3	Pack, Liquid MCC 20%	**1.0001**	**1.0000**	1.05E-03					3.02E-03
4	RO, MF permeate, 6.1% to 30%	**3.6307**	**0.9099**	1.10E-01				7.93E-02	6.47E-01
5	Past, MF permeate 30%	**0.9099**	**0.9087**	8.66E-03					2.26E-02
6a	UF: retentate - no alloc	**0.9737**	**0.2086**	1.11E-01	2.63E-02	1.05E-01	2.31E-02	2.42E-03	1.09E+00
6b	UF: retentate – total proteins alloc	**0.9737**	**0.2086**	1.11E-01	2.63E-02	1.05E-01	2.31E-02	2.42E-03	1.09E+00
7	Past, UF retentate (Liquid WPC 35%)	**0.2086**	**0.2084**	8.66E-03					2.26E-02
8	Pack, Liquid WPC 35%	**0.2084**	**0.2083**	2.06E-04					5.92E-04
9	Ferm, UF permeate	**0.7650**	**0.7648**	1.91E-03					5.62E-02
10	EV, UF permeate, 25% to 70%	**0.7650**	**0.2719**	3.84E-03					3.99E-02
11	Cryst, UF permeate 70%	**0.2719**	**0.2717**	7.16E-05					2.11E-03
12	Centri, UF permeate, 70% to 80%	**0.2717**	**0.2150**						1.45E-02
13	Centri, UF permeate, 80% to 90%	**0.2189**	**0.1609**						1.37E-02
14	Dry*, Lactose, 90% to 99.9%	**0.1609**	**0.1450**						
15	Pack, Lactose 99.9%	**0.1450**	**0.1450**						5.49E-03

[a] The dairy plant used ceramic membranes for microfiltration and polymer membranes for ultrafiltration. The utilized technologies for fractionated and non-fractionated products were assumed to be identical across ALCA and CLCA.
[b] For cleaning agents, required production and transport masses of the active substances were taken as a proxy.
[c] Since for some processing steps only rough estimates on effluents were available, inventory data related to wastewater was excluded from the present analysis.

Appendix D (continued). Life cycle inventory data for fractionated concentrates.

	Unit processes	Inflow mass (IM)	Outflow mass	Capital goods usage per IM [d]					Packaging materials per IM [e]		Transport per IM
				Stainless steel	HDPE	Poly-sulfone	Polyester	Aluminum oxide	Kraft-paper	LDPE	
		[kg]	[kg]	[g]	[g]	[g]	[g]	[g]	[g]	[g]	[tkm]
	Fractionated concentrate production										
1a	MF: retentate – no alloc	**4.6307**	**1.0000**	1.99E-02				3.38E-03			
1b	MF: retentate – total proteins alloc	**4.3698**	**1.0000**	1.88E-02				3.19E-03			
	MF: permeate – total proteins alloc	**0.2609**	**3.6307**	1.12E-03				1.91E-04			
1c	MF: retentate – milk casein alloc	**4.6307**	**1.0000**	1.99E-02				3.38E-03			
2	HHT, MF retentate (Liquid MCC 20%)	**1.0012**	**1.0000**	9.17E-03							
3	Pack, Liquid MCC 20%	**1.0001**	**1.0000**	2.71E-02					2.24E+01	4.27E+00	
4	RO, MF permeate, 6.1% to 30%	**3.6307**	**0.9099**	4.33E-02	1.73E-01						
5	Past, MF permeate 30%	**0.9099**	**0.9087**	5.48E-03							
6a	UF: retentate - no alloc	**0.9737**	**0.2086**	1.24E-02		3.02E-02	7.08E-03				
6b	UF: retentate – total proteins alloc	**0.9737**	**0.2086**	1.24E-02		3.02E-02	7.08E-03				
7	Past, UF retentate (Liquid WPC 35%)	**0.2086**	**0.2084**	1.34E-03							
8	Pack, Liquid WPC 35%	**0.2084**	**0.2083**	5.30E-03					4.39E+00	8.37E-01	
9	Ferm, UF permeate	**0.7650**	**0.7648**	3.60E-03							
10	EV, UF permeate, 25% to 70%	**0.7650**	**0.2719**	1.86E-02							
11	Cryst, UF permeate 70%	**0.2719**	**0.2717**	9.30E-03							
12	Centri, UF permeate, 70% to 80%	**0.2717**	**0.2150**	1.57E-03							
13	Centri, UF permeate, 80% to 90%	**0.2189**	**0.1609**	1.48E-03							
14	Dry*, Lactose, 90% to 99.9%	**0.1609**	**0.1450**	5.79E-03							
15	Pack, Lactose 99.9%	**0.1450**	**0.1450**	4.48E-03					9.20E+00	3.60E+00	
	Transportation										
1	Distribution (1000 km)	**1.0000**	**1.0000**								1.00E+00

[d] For the inventory of capital goods, production and transport of the involved raw materials was taken as a proxy. Environmental impacts of capital goods were linearly depreciated over their lifetime according to German depreciation rules (German Federal Ministry of Finance, 2019). End-of-life treatment of capital goods was excluded, due to low environmental-impact contribution (i.e., only up to 1% of capital-goods production impacts).

[e] Both fractionated and non-fractionated concentrates are packaged in bags-in-boxes, consisting of kraftpaper with plastic inlays made of low-density polyethylene that are disposed at the customer stage. End-of-life treatment of kraftpaper (12.2% municipal incineration, 0.2% inert material landfill, 87.6% recycling) and plastic inlays (66% municipal incineration, 1% sanitary landfill, 33% recycling).

Appendix E. Overview on utilized ecoinvent v3.1 processes in chapter 4.

System inputs and outputs	Ecoinvent v3.1 processes used [a]
Raw material	
Raw cow milk	Cow milk {RoW} | milk production, from cow |
Consumption factors	
Energy	
Electricity	Electricity, low voltage {DE} | market for |
Natural gas	Heat, district or industrial, natural gas {Europe without Switzerland} | market for heat, district or industrial, natural gas |
Cleaning agents	
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO} | market for |
EDTA	EDTA, ethylenediaminetetraacetic acid {GLO}| market for |
Nitric acid	Nitric acid, without water, in 50% solution state {GLO} | market for |
Phosphoric acid	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO} | market for |
Potassium hydroxide	Potassium hydroxide {GLO}| market for |
Potassium carbonate	Potassium carbonate {GLO}| market for |
Alkylbenzene sulfonate	Alkylbenzene sulfonate, linear, petrochemical {GLO}| market for |
Alkylamine	Trimethylamine {GLO}| market for | ; Methylamine {GLO}| market for | ; Ethylamine {GLO}| market for |
Water	
Tap water	Tap water, {Europe without Switzerland} | market for |
Capital goods	
Stainless steel	Steel, chromium steel 18/8 {GLO} | market for |
HDPE	Polyethylene, high density, granulate {GLO} | market for |
Polysulfone	Polysulfone {GLO}| market for |
Polyester resin	Polyester resin, unsaturated {GLO}| market for |
Aluminum oxide	Aluminium oxide {GLO}| market for |

[a] Processes used both as attributional (cut-off by classification) processes and as consequential processes.

Appendix E (continued). Overview on utilized ecoinvent v3.1 processes in chapter 4.

System inputs and outputs	Ecoinvent v3.1 processes used [a]
Packaging materials	
Kraft paper	Kraft paper, unbleached {GLO} | market for |
Packaging film (LDPE)	Packaging film, low density polyethylene {GLO} | market for |
Transport	
Lorry	Transport, freight, lorry 16-32 metric ton, EURO5 {RER} | transport, freight, lorry 16-32 metric ton, EURO5 | ambient
	Transport, freight, lorry 16-32 metric ton, EURO5 {RER} | transport, freight, lorry 16-32 metric ton, EURO5 | cooled[b]
Disposal	
Kraft paper	Waste paperboard {RoW} | treatment of, municipal incineration |
	Waste paperboard {RoW} | treatment of, inert material landfill |
	Paper waste treatment {GLO} | recycling of paper |
Packaging film & HDPE	Waste polyethylene {RoW} | treatment of, municipal incineration |
	Waste polyethylene {RoW} | treatment of, sanitary landfill |
	PE waste treatment {GLO} | recycling of PE |
By-products	
Cream	Cream, from cow milk {GLO} | market for | [c]
Whey	Whey {GLO}| market for | [c]
Lactic acid	Lactic acid {GLO}| market for | [c]

[a] Processes used both as attributional (cut-off by classification) processes and as consequential processes.

[b] Fuel consumption adapted to cooling in line with Tassou et al. (2009).

[d] Utilized only as consequential processes.

Appendix F. Global-warming potential for attributional functional units.

Indicator	Unit	FU–a1				FU–a2				FU–a3			
		1 kg protein		1 € revenue[a]		1 kg MCC		1 € revenue[a]		1 kg RM valorized		1 € revenue[a]	
		SMC	MCC, WPC	SMC	MCC, WPC	SMC	MCC	SMC	MCC	SMC	MCC, WPC, Lactose, Molasses	SMC	MCC, WPC, Lactose, Molasses
Raw milk production and transportation													
GWP	kg CO_2-eq	40.40	45.32	7.63	4.74	50.50	47.32	7.63	4.99				
Production of fractionated and non-fractionated concentrates													
GWP	kg CO_2-eq	0.99	1.41	0.19	0.15	1.25	1.04	0.19	0.11	0.05	0.10	0.18	0.14
Transportation to the customer (1000 km)													
GWP	kg CO_2-eq	1.75	2.02	0.33	0.21	2.19	1.75	0.33	0.18	0.05	0.06	0.33	0.21
Totals													
GWP	kg CO_2-eq	43.15	48.76	8.15	5.10	53.94	50.11	8.15	5.29	0.11	0.16	0.51	0.35

[a] Product-specific average market prices over 5 years (2014-2018) underlie the economic functional units. To test the results for robustness against price fluctuations, averages of each year were also considered separately. The analysis showed that the product ranking remains constant.

Abbreviations: GWP–global-warming potential, MCC–micellar-casein concentrate, RM–raw milk, SMC–skim-milk concentrate, WPC–whey-protein concentrate.

Appendix G. Global-warming potential for consequential functional units.

Indicator	Unit	FU–c1		FU–c2	
		1 additionally consumed kg protein		1 additionally consumed kg MCC	
		SMC	MCC, WPC	SMC	MCC
Raw milk production and transportation					
GWP	kg CO_2-eq	49.34	55.35	61.68	57.79
Production of fractionated and non-fractionated concentrates					
GWP	kg CO_2-eq	1.19	1.71	1.48	1.26
Product substitution allocation [a]					
GWP	kg CO_2-eq	-16.24	-23.73	-20.31	-20.41
Transportation to the customer (1000 km)					
GWP	kg CO_2-eq	1.61	1.86	2.01	1.60
Totals					
GWP	kg CO_2-eq	35.89	35.19	44.87	40.25

[a] FU–c1 (SMC: cream; MCC, WPC: cream and lactic acid), FU–c2 (SMC: cream; MCC: cream and whey).

Abbreviations: GWP–global-warming potential, MCC–micellar-casein concentrate, SMC–skim-milk concentrate, WPC–whey-protein concentrate.