DECISION SUPPORT MODELING FOR MILK VALORIZATION

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This research was conducted under the auspices of Wageningen School of Social Sciences (WASS)

Decision Support Modeling for Milk Valorization

Agata Banaszewska

Thesis

submitted in fulfillment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Thursday 22 May 2014
at 11 a.m. in the Aula.

Agata Banaszewska

Decision Support Modeling for Milk Valorization
184 pages

PhD thesis, Wageningen University, Wageningen, NL (2014)
With references, and summaries in Dutch and English

ISBN 978-90-6173-926-1

Dedicated to my parents

Preface and acknowledgments

A PhD study is a challenge that at the start seems very similar to climbing Mount Everest, but when you look back, was actually more like a pleasant hike. Any challenge we decide to face in our life cannot be overcome without the support of other people. As such, the success of my PhD research is due to a number of people that accompanied me throughout my journey and whom I would like to thank in this chapter.

First of all, I would like to express my gratitude to my supervisors Jack van der Vorst and Frans Cruijssen, as well as to Frits Claassen, for their constant support and guidance during the years of my PhD research at the Operations Research and Logistics group. Each of them played a special role in the overall process.

Jack was my promotor and he always made sure the overall process went in the right direction and with the right speed. Instead of checking my every move, he was always present in the background, thereby giving me enough freedom to formulate my ideas and indicate the research path I wanted to follow. I always had a chance to discuss and, if necessary, defend my choices. Jack, you were not only a great listener and mediator, but you also knew when to intervene. Your 'straight to the point' comments put me back on track whenever I was lost or when I had to restructure my work. Your support in producing my first scientific papers was also of a great value.

Frans, you were my daily supervisor and you certainly lived up to this description. Whenever I needed advice, you were always available and not just on Fridays! ☺ You were the person that made me believe in my abilities and that encouraged me to commence this PhD journey in the first place. It is thus not difficult to imagine how big your impact on my future career and life has been. So thank you for this. Further discussing your involvement and support would, knowing my tendency to write long texts, result in another chapter. Therefore, to keep it short and to the point (the way you taught me!), I would like to thank you for all the advice, discussions, comments, compliments and criticism that I received from you every single week. All that helped me to improve on the quality of my work, on my professionalism and my self-confidence.

Frits, you were another person who directly contributed to the success of this research. You offered me support when I needed it, especially in the development of the mathematical models. And no matter how occupied you were, you always found the time to help me take the next steps, even in the final step of writing this thesis, i.e. the Dutch summary. Your involvement didn't just focus on my work; "how is Agata doing?" was a regular question during our conversations; besides scientific support you also offered me great personal support. But what else could one expect from a person whom students consider 'teacher of the year'? ☺

Whenever I think about Jack, Frans and Frits I am always lost in admiration. They aren't just great scientists with bright minds, but also people with big hearts. This is what

makes them so special and so perfectly suited for the positions they hold. Jack, Frans and Frits, it was a pleasure working with you during these last years!

I would also like to thank Kees-Jan van Wees (the former director of the Milk Valorization & Allocation (MVA) department at FrieslandCampina), without whom this project would not even have started. Kees-Jan believed that a scientific input to the MVA department, in terms of a PhD project, would contribute to a better valorization of milk and he was right. Kees-Jan, I would like to thank you for giving me this opportunity. I would also like to thank you for our first discussions during which the initial topic of "milk valorization" had to be translated into actual goals of this research, which was not that straightforward.

Another person who contributed to my research is Han Kampman, the manager of the Dairy Supply Chain group (part of MVA). Han, I would like to thank you for giving me enough freedom to select research topics that were in line with my research interests. I am happy that we could always find a balance between the world of FrieslandCampina and the world of science, and managed to keep our problems interesting, challenging and value adding for both sides. Furthermore, I would like to thank you for your input during my projects, starting from the collection of data, through the analysis of model outputs and finishing with the interpretation of results. Your critical remarks on decisions made during the development process, numerous questions on the meaning of obtained results and their implications on practice significantly improved the practical relevance of my research.

My sincere appreciation also goes to Jeroen Fey, the current director of MVA, for his support in the second part of my PhD research. Furthermore, I would like to thank Lieuwe Montsma and Jan Drenthen, who were, next to Kees-Jan, my first "teachers" that introduced me to the world of FrieslandCampina and dairy. Special thanks also go to Friso Munnik for his input in my research, especially in the development of the Dairy Valorization Model. I would also like to acknowledge Ovidiu Listes from AIMMS for his support in the implementation of the developed models in AIMMS.

I would also like to express my appreciation to the members of my dissertation committee Prof. Dr H.A. Fleuren, Prof. Dr M. Grunow, Prof. Dr A.G.J.M. Oude Lansink and Prof. Dr A. van der Padt. Thank you for the time spent on the evaluation of my thesis and on the participation in the defense of this dissertation.

I would like to thank my colleagues from the Logistics Decisions and Information Sciences group. It was a pleasure to be the part of this group. I value the scientific discussions we had, the feedback on my work and the interesting ideas related to my research. The casual talks over coffee or by the printer, about daily topics, were a pleasant distraction from the world of scientific challenges. Furthermore, I would also like to thank my colleagues from the MVA department, especially from the Dairy Supply Chain group, for their valuable feedback on my research and critical views on my results. The group discussions we held together significantly improved the quality of the final outcome of this research, thereby making the results more suitable for the improvement of milk valorization at FrieslandCampina.

I would also like to acknowledge Ilona van den Berg, Leonie van Scherrenburg, Thea van den Boom, Claudia Lokers and Margrit van de Braak for their outstanding administrative support throughout the years of my PhD project.

Special thanks go to my office colleagues. Bing, Mehmet and Willem, thank you for all the scientific, formal and informal talks, for the laughs and complaints, frustrations and happiness. It was a pleasure to share all of it with you! Furthermore, I would like to thank my numerous friends from Wageningen, my old group of friends from Poland and all the other individuals I was lucky to meet thanks to this journey. Thank you for your presence and all the experiences we shared together.

Finally, I would like to express my gratitude to my family, my mother and father, my sister and brother. They were an incredible support during the years of my higher education, and especially during the last four years. I could have never gotten this far without their encouragement, patience, advice and love.

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Chapter 1

General introduction

1.1 Introduction

The research presented in this thesis is driven by practical issues that require structured and precise scientific studies to provide strong and reliable answers. An opportunity to contribute to both practical and scientific fields emerged in 2008 when two large Dutch dairy companies (FrieslandFoods and Campina) merged, hereby creating the 4th world largest dairy company at that time: FrieslandCampina (FC). Currently FC has 19,500 member dairy farmers in the Netherlands, Germany and Belgium, who every year deliver around 9 billion kilos of raw milk. The supplied milk is processed into a wide range of end products, for example, milk based drinks, cheeses, yoghurts, milk powders, dairy based ingredients, infant foods, animal feed, etc. The company is divided among four business groups: Consumer Products Europe, Middle East & Africa, Consumer Products International, Cheese Butter and Milk Powders and Ingredients. To process all raw milk FC employs around 20,000 employees in 28 countries. Final products are being delivered to millions of customers in about 100 countries worldwide (FrieslandCampina, 2012).

The dairy processing industry is a specific and challenging field. This is mainly related to the fact that the main raw material (raw milk composed for only 13% of components and for 87% of water) is being transformed via a highly interrelated production processes into thousands of end products. Often a byproduct of a production process of a certain product is an input for production of another product. For instance whey, which is a byproduct of among others cheese production, is an input for the production of various products, e.g. Infant Food and Ingredient products. This high complexity calls for a central and integral planning process that provides plans for the production of all products simultaneously. The process is called **milk valorization** and it aims at the optimal allocation of raw milk to the most profitable dairy products while taking all important constraints and requirements into account. Milk valorization is the main topic of this thesis.

Apart from the large number of products, efficient valorization of milk is, from an organizational point of view, additionally aggravated by the large number (28) of Operating Companies (OpCos) that form the company. Each OpCo is responsible for all or some of the activities related to specific product groups and sometimes specific regions, i.e. production, inventory, distribution, marketing, sales and customer services. Each OpCo also has its own objectives that may not always lead to the best integral valorization of members´ milk, for the company as a whole. As in decoupled supply chains, in which added value can be gained if an integrated planning approach is achieved (Guajardo et al., 2013), an integrated planning approach at FC is required to better valorize members' milk. The approach should incorporate the development of appropriate planning tools that reflect reality well and provide comprehensible solutions to the significant challenge of optimal milk valorization. Furthermore, to assure the successful implementation of solutions, performance should be measured at various levels of the company´s production and logistics system, starting from the accuracy and feasibility of valorization solutions, and finally finishing at the efficient performance of actors involved in the planning process (e.g. employees as demand or supply planners, facilities as factories, warehouses or farms).

To achieve maximum milk valorization, a corporate Milk Valorization & Allocation (MVA) department was created in 2009. The aim of this department is "to ensure getting most value out of members' milk, based on an FC integral valorization point of view"[1]. The main goal of the research presented in this thesis is to, with the use of quantitative methods, provide decision support to MVA in attaining their aim, and thus facilitate better valorization of milk. This creates an opportunity for valuable applied scientific research, especially in the field of decision support modeling and logistics decision making.

1.2 Problem statement

The improvement of milk valorization can be attained in many ways, depending on the angle from which we look at it. For instance, looking from a food science (biotechnology) perspective, milk valorization can be improved through a better decomposition of raw milk into valuable ingredients (Gibson, 1991; Rattray and Jelen, 1996; Steijns, 2001). Looking from a product development or marketing perspective, milk valorization can be improved through new product developments or through the enlargement of market shares and new geographical markets (Biström and Nordström, 2002; Grunert and Valli, 2001). Looking from operations and planning perspective, improvement of logistics in various angles of a supply chain (Claassen and Van Beek, 1993; Current et al., 1990; Vidal and Goetschalckx, 2001) can also contribute to a better valorization of members´ milk. In this thesis, we focus on milk valorization from the perspectives of **Logistics Management** and **Operations Research**. Logistics Management is the part of supply chain management that plans, implements, and controls the efficient, effective flow and storage of goods, services and related information. The activities typically include transportation management, inventory management, supply/demand planning, production planning and scheduling, fleet management, warehousing, materials handling, order fulfillment, logistics network design, and management of third party logistics services providers[2]. Operations Research is a scientific field providing a quantitative basis for operations decisions (Morse and Kimball, 2003; Saaty, 2004). In the presented research, we aim at the development of quantitative decision support models that can be used to improve the overall process of milk valorization from the Logistics Management perspective.

The size of the company and the number of actors and processes involved, defines FC almost as a complete dairy supply chain (see Figure 1.1), in which many logistics management activities take place. The valorization of milk can be performed at any stage of

[1] www.frieslandcampina.com (date visited: October 2013)

[2] Definition provided by the Council of Supply Chain Management Professionals (www.cscmp.org) (date visited: October 2013)

this chain. For instance, a focus can be placed on the improvement of: raw milk collection and delivery, (intra-) transport of (by-) products, inventory management, production planning, etc. Apart from deciding on which stage of the supply chain the main focus should be placed, also a decision on the planning level has to be made. In general, three supply chain planning levels can be distinguished: strategic, tactical, and operational (Chopra and Meindl, 2007). On the strategic level, long-term decisions related, for example, to the supply chain network infrastructure are made. On the tactical level, mid-term decisions related to production capacity, transport capacity, inventory capacity, and sales management are made. On this level the focus is placed on matching supply and demand while minimizing the total cost (maximizing the total profit). On the operational level, short-term decisions related to daily or weekly scheduling are made. An initial study of the FC environments (both internal and external), the investigation of the main responsibilities of the MVA department and an initial literature study indicated that large gains for FC can be obtained by focusing on the improvement of the mid-term planning (tactical level), especially related to the production. In order to improve milk valorization, it was decided to further extend the production planning problem with additional input elements related to supply, demand, and transportation. The part of the supply chain and related to it logistics activities that are the subject of this thesis (the scope) are indicated in Figure 1.1. As can be seen, the core focus of this research is production planning, but necessary input information related to supply (farm data) and demand (customer data) are also incorporated.

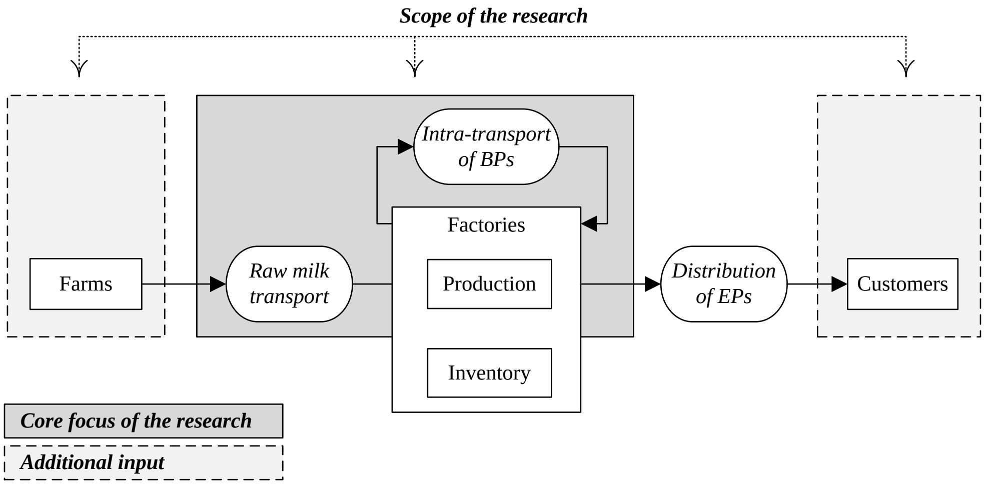

Figure 1.1 Dairy supply chain with indicated research scope. BPs = byproducts; EPs = end products.

The main problem the company was facing at the time this research started was the lack of suitable tools to support mid-term valorization. Therefore, the development of a dairy valorization model at the mid-term planning level was the first step that had to be taken to improve the valorization. The initial model should include all necessary elements to allow for complete and optimal valorization of milk. It should therefore be comprehensive, but also comprehensible; it should provide a good understanding of the underlying complex dairy production processes. In subsequent steps the model will be further developed, so that the most important questions related to milk valorization are answered.

In order to extend the possibilities of improved milk valorization, some important possible extensions of the model were identified during multiple sessions with relevant FC employees. The potential added-value for the company, the availability of data and the contribution to literature were the three main aspects that were taken into account during these discussions. A list of studies that were finally considered is presented in Table 1.1 (see project 2 to 8).

Table 1.1 Initial list of projects defined to improve milk valorization based on expert sessions at FrieslandCampina.

No.	Project name	Project aim
1.	Comprehensive dairy valorization model	Development of a comprehensive mid-term milk allocation and production planning model that incorporates all necessary elements and constraints while providing optimal valorization plans
2.	Byproducts valorization	Evaluation of the effect of byproducts valorization on the valorization of main dairy products and the evaluation of the added value of integral valorization (milk products and byproducts valorized simultaneously)
3.	Robustness of valorization plans	Evaluation of the stability of valorization plans and the identification of critical factors affecting it
4.	Efficiency measurement of processing units	Development of a performance measurement model to evaluate efficiencies of processing units and indicate improvement options
5.	Stochastic dairy valorization model	Development of a stochastic dairy valorization model to mitigate the impact of uncertainties in input data and thus to provide more robust solutions
6.	Input data accuracy	a) Development of mid-term milk supply forecasting model b) Development of a game theory incentive model to stimulate integral valorization way of thinking among Operating Companies while minimizing the interference of a central planning unit
7.	Inventory management	a) Investigation and improvement of current inventory management policies b) Inclusion of inventory management in the dairy valorization model
8.	Transport of raw milk and byproducts	Optimization of collection, transportation and intra-transport through the optimal division of milk supply region and allocation of region-milk combinations to specific factories

By means of a workshop, we made a selection of projects that should receive attention in this PhD project and that all together would provide the largest contribution to the improvement of milk valorization. Next to the development of a comprehensive dairy valorization model (Project 1), also byproduct valorization (Project 2) was seen as a very important topic. Furthermore, two other projects were chosen that aim at performance evaluation; that is, robustness evaluation of valorization plans (Project 3) and efficiency evaluation of processing units (Project 4). In the following section, we provide more background on the investigated problems, as well as the specific research objectives and questions.

1.3 Research objectives and questions

The overall objective of this research is to develop and implement decision support models to improve milk valorization. We will focus on two aspects of milk valorization: valorization model (part I) and performance evaluation (part II). The research should not only provide scientific insights into the design of such models, but also provide practical recommendations to industry on how the valorization of milk can be improved. In this research, valorization is defined as the optimal allocation of input resources to the most profitable products while taking all important constraints and requirements into account. The four selected research topics that are addressed in this work are introduced in the following subsections.

1.3.1 Part I: Valorization model

Investigation of company´s environments and multiple experts' interviews indicated mid-term planning as the activity, where large gains can be achieved with regard to milk valorization. It is important that decision support models used for valorization are complete, comprehensive and comprehensible. Therefore the first part of this research (Chapter 2 and 3) is devoted to the development of the appropriate model for the valorization of milk at dairy processing companies.

Dairy Valorization Model

Milk valorization takes place in a dynamic and complex environment. Every day dairy processing companies face numerous challenges resulting both from unsteady dairy markets and from specific characteristics of dairy supply chains. The volatility of demand and prices of dairy products, the higher competitiveness in the dairy industry, and the increasing regulations that limit access to external markets significantly affect the performance of dairy processing companies. The European dairy sector is under constant changes following, for example, European Union (EU) dairy policies and outcomes of on-going negotiations in the World Trade Organization (WTO). The Luxembourg Reform from 2003 lowered the intervention prices, which made the production of bulk products less profitable. Furthermore, it was decided to gradually increase milk quotas and completely abolish them in 2015 (COM,

1

2009). These changes led and will most likely continue to lead to an increase in milk supply. Moreover, the high fluctuations in milk prices paid to farmers (Figure 1.2) and possible changes in dairy farm management strategies, resulting from the elimination of quota system, may lead to high supply uncertainties after 2015. According to Geary et al. (2010), dairy market fluctuations and price volatility will be a constant challenge to the future dairy industry. Additionally, the enlargement of the EU in 2007 increased the competitiveness on the EU dairy market, thereby making the situation on the market more difficult for dairy processing companies. The high competitiveness on the international dairy market requires the companies to optimize their production and sales to ensure the survival (Guan and Philpott, 2011).

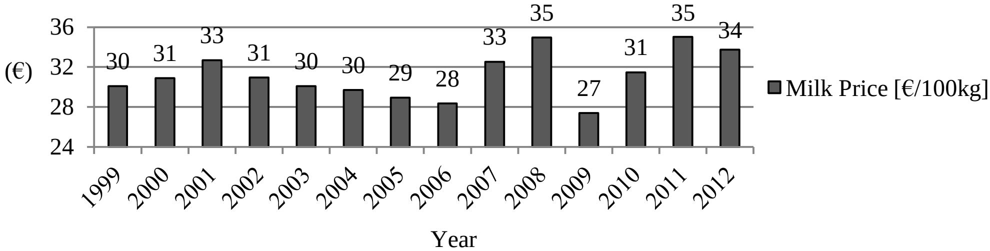

Figure 1.2 Standardized milk's average prices paid to farmers by main dairy processing companies (source: LTO (2013)).

The complexity of dairy supply chains introduces additional difficulties to the process of milk valorization. In a dairy chain, the main raw material (raw milk) is collected from multiple dairy farms scattered all over the supply area and is used for production of all dairy products. The volume of end product obtained from one ton of raw milk and partly the choice of end product to be produced depend on the nutrient content in raw milk, which changes during the year. Furthermore, the production of dairy products is highly inter-related. This considerably complicates the planning process. A byproduct of one production process can be used as an input for another production process, which often takes place at different locations. To profitably manage the incoming milk, decision support models to improve management of transport, milk allocation and production planning are required. It is to be expected that a comprehensive model that captures the dynamics of dairy production and incorporates all relevant constraints related to internal and external environments will considerably improve valorization of milk. The model should create optimal mid-term plans for the allocation of milk, and the production of end products and byproducts while considering all relevant constraints in practice. Additionally, it should also contribute to a better understanding of prevailing production processes.

The results of a literature study indicated a number of studies aiming at the development of an optimization tool for dairy production processes (e.g. Geary et al. (2010), Guan and Philpott (2011), Doganis and Sarimveis (2008), Vaklieva-Bancheva et al. (2007)). A close investigation of the existing models, however, indicated their inadequacy for comprehensive valorization of raw milk. This brought us to the first research objective and related research question:

Research objective 1: *Development of a comprehensive Dairy Valorization Model*
Research question 1: *Which elements should be included in the model to properly represent the complete dairy system and allow for efficient milk valorization?*

The answer to the first research question is provided in Chapter 2, which is based on the journal paper entitled "A comprehensive dairy valorization model" published in the *Journal of Dairy Science* (Vol. 96, No. 2, Year 2013).

Byproducts valorization

Given the complexity of the dairy system, the development of a good valorization model requires a gradual approach. Thus, the initial Dairy Valorization Model focuses on the valorization of milk-based end products (main milk products) to first fully understand the main processes and relations in the system. However, the production of the main milk products results in large volumes of byproducts, which are often not properly valorized and as a result parts of this edible food are wasted. Recent studies of the Food and Agriculture Organization of the United Nations (Gustavsson et al., 2011) estimated that globally 40-50% of fruits and vegetables, 20% of meat and dairy, and 30% of fish are wasted. One of the main stages of the supply chain where food waste takes place is indeed processing (Parfitt et al., 2010). The need to more efficiently utilize food resources and the environmental impact of the disposal of byproducts induce scientists and producers to place more focus on the further processing of byproducts. In the last years, many scientists investigated the valorization potential of byproducts by reducing food wastes obtained during the processing of main products (e.g. Darine et al. (2010); Galanakis (2011); Patel and Murthy (2011); Prazeres et al. (2012); Sun and Tomkinson (2002)). Even though many studies have been conducted, to the best of our knowledge, none of them focuses on the evaluation of the overall economic effect of byproducts valorization on food processing companies i.e. change in the (monetary) value of each ton of valorized food resource. The maximization of food processing company profitability, especially if companies reuse their own byproducts in the production of their end products, is not a key aspect of existing studies, and thus an opportunity to contribute to the literature appears. Furthermore, the outcomes of the study can provide an economic incentive to companies to further reduce waste and contribute to food availability.

There is also a practical case study related reason why this research is relevant. The central MVA department of FC is responsible for the valorization of main milk products, which belong to three out of fours FC´s business groups: Consumer Products Europe, Consume Products International, and Cheese Butter and Milk Powders. The valorization of byproducts of the fourth business group (Ingredients), which are mainly produced out of whey, is conducted separately. Whey is a byproduct of cheese and caseinate production. It is one of the main byproducts of the dairy industry, as it is produced in large volumes, it has a high environmental impact and a high nutritional content (FAPRI, 2012; González-Martínez et al., 2002; Russ and Meyer-Pittroff, 2004; Smithers, 2008). The investigation of the effect of whey valorization on the valorization of main dairy products, as well as the investigation of the added value of integral valorization (simultaneous valorization of both main and byproducts) will provide a valuable insight into the economic effect of byproducts processing, indicate potentials for further decrease of food wastes, and provide recommendations to dairy processing companies on the integration of both valorization processes. Following this, the second research objective and research question were defined:

Research objective 2:	*Evaluation of the effect of byproducts valorization and of integral valorization on the overall valorization of milk*
Research question 2:	*What is the added value of integrating byproducts valorization into the main valorization process and does it affect the production of main milk products?*

The answer to the second research question is provided in Chapter 3, which is based on the journal paper entitled “Effect and key factors of byproducts valorization: the case of dairy industry” published in the *Journal of Dairy Science* (Vol. 97, No. 4, Year 2014).

1.3.2 Part II: Performance evaluation

The completeness and comprehensiveness of the valorization model is one of the most important model characteristics, nonetheless it does not guarantee an overall optimal valorization. This is due to the fact that the quality of solutions is very much dependent on the quality of input data used to create the plans and on the implementation of plans within the company. Milk valorization is affected by various uncertainties related to demand, supply, process, planning and control (Lee, 2002; Stevenson and Spring, 2007; Van der Vorst, 2000; Van Donk, 2001). To assure high level of milk valorization, the second part of this research is devoted to the performance evaluation of valorization plans and of operating units of the supply chains. According to Gibson (1991), monitoring, feedback, learning and re-planning are vital components of the planning process.

Robustness of valorization plans

Information for decision making aiming at high-level milk valorization is subject to many uncertainties related to the external and internal environments of dairy processing companies. Despite the stochastic nature of input data, deterministic programming models are the methods commonly used in practice to support planning processes (Verderame et al., 2010). One of the reasons is the intricacy of production processes that increases the size and the computational time of a programming model, and thus limits the possibility of applying complex modeling techniques. On the one hand, deterministic models are able to describe the core planning issues in complex, real-life environments and provide optimal solutions in a short time. On the other hand, they often fail to incorporate uncertainty ingrained in data of specific model parameters. The first study (Chapter 2) describes a deterministic Dairy Valorization Model to improve the milk valorization process. Even though the model properly represents dairy production processes, the stability of obtained valorization plans is questionable because of uncertainties present in input data related to supply, processing and demand. Stability of plans is often referred as to the 'robustness' of plans: the degree to which the optimal solution might change if realization of certain input parameters turn out to be different than the forecasted values (Vlajic et al., 2012).

Much research is already focused on developing methods to obtain robust solutions in production planning (Aghezzaf et al., 2010; Bredström et al., 2013; Escudero and Kamesam, 1995; Kazemi Zanjani et al., 2010) and some on evaluating robustness at the modeling/design level (Fujita and Takewaki, 2011; Jensen, 2001; Mondal et al., 2013; Zakarian et al., 2007). However, to the best of our knowledge no work has been devoted to the assessment of the robustness degrees of valorization plans obtained with deterministic models. An explicit evaluation of robustness of valorization plans, which is a simple task in theory, may have a large impact on decision making in practice, because it can indicate sources of possible problems and provide recommendations on the necessity of using advanced stochastic techniques in the planning process. In order to further improve milk valorization, a third study was defined with the following research objective and question:

Research objective 3:	*Evaluation and improvement of robustness of valorization plans obtained with deterministic models*
Research question 3:	*How can we assess robustness of valorization plans obtained with deterministic models?*

The answer to the third research question is provided in Chapter 4, which is based on the manuscript entitled "Robustness evaluation of valorization plans. The case study of dairy processing industry" submitted for publication to a scientific journal.

Benchmarking efficiency of processing units

The effectiveness of the valorization model is mainly linked to the optimality, feasibility and robustness of obtained plans. However, even if these three aspects are satisfied, the success of the valorization process is still very much dependent on the performance level of actors and units that are involved in the process and that implement valorization decisions e.g. sales departments, processing units, warehousing facilities. Given the fact that processing units (factories) are the most important units in the supply chain of a processing company, because they can easily affect the value of each ton of raw milk used in the production process, the last topic investigated in this thesis is related to the performance evaluation of processing units.

Fawcett and Cooper (1998) state that performance measurement is critical to the success of almost any organization, as it creates understanding, shapes behavior, and leads to competitive results. Performance and competitiveness of manufacturing companies is very much dependent on the productivity of their production facilities (Fleischer et al., 2006; Madu, 1999). Therefore, additional profits that can be achieved by developing and applying the new valorization model can easily be in vain if processing units converting raw milk into desired products are underperforming. To ensure high performance levels, a performance framework and indicators that are able to measure important elements of production facilities should be developed and implemented (Muchiri et al., 2011). Benchmarking of performance levels of production units allows for the improvement of the overall valorization process, but also for the identification of the worst performing units.

A wide number of methods to measure performance is available in the literature. The methods can be grouped into three categories: ratio analysis, parametric methods, and nonparametric methods (Düzakın and Düzakın, 2007). In order to properly evaluate efficiency of processing units, an appropriate method should be chosen. Furthermore, a selection approach to choose relevant inputs (resources) and outputs should also be developed. Finally, those factors that have the largest impact on the performance should be identified to provide recommendations on efficiency improvements. Therefore, a framework for the evaluation of efficiency of processing units is necessary to provide a structured assessment approach and to further improve the valorization of milk. This brings us to the fourth research objective and question:

Research objective 4: *Development of a framework for efficiency measurement of processing units*

Research question 4: *How can the performance of processing units be measured and improved?*

The answer to this research question is provided in Chapter 5. The original idea was to conduct this study in the case company. However, due to low data availability, the application to the dairy case turned out to be difficult. Fortunately, we had access to data of another business for which we could develop the framework. In Chapter 5, with the use of a case study of a large express service provider (TNT Express), we developed a framework for measuring efficiency levels of processing units. The presented work is based on the journal paper entitled “A framework for measuring efficiency levels – the case of express depots” published in the *International Journal of Production Economics* (Vol. 139, No. 2, Year 2012). The discussion on the applicability of the results of this study to the efficiency measurement of processing units in the dairy industry is discussed in the last chapter of this thesis (General Conclusions and Discussion).

1.4 Research design

The main objective of the research presented in this thesis is the development and application of decision support models to improve milk valorization in the dairy industry. To achieve this objective, we selected four research topics that were introduced in the previous section and defined four research questions. A standardized research approach, composed of five steps, was used to answer each question (see Figure 1.3). In the third study, to conduct the analyses, the model developed in the first study was used. All research steps were supported with explanatory case studies of FrieslandCampina (studies 1-3) and TNT Express (study 4). Numerical data used in these studies were collected at both case companies.

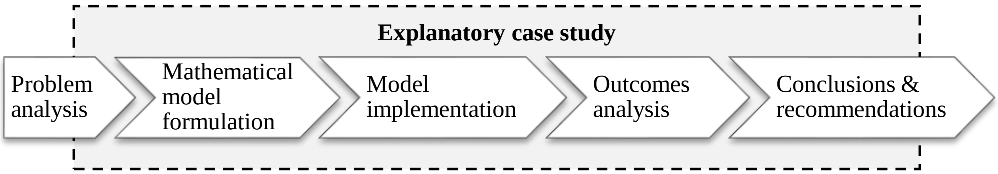

Figure 1.3 Standardized research approach applied to all studies.

To achieve all research objectives, a combination of quantitative and qualitative methodologies was used. In Table 1.2, the methods and the expected deliverables of each conducted research are presented. Literature studies (scientific articles and reports from industries) were carried out to: identify gaps, formulate research questions, investigate the most suitable Operations Research methods for the problems at hand, gather and verify collected data, and define scenarios to test hypotheses. Many open and semi-structured interviews with individual experts as well as with groups of experts were conducted throughout the complete research. In the initial phase of each study, interviews were conducted in order to provide better understating of the investigated problems. In the mid-phase of each study, interviews were used to gather and verify collected data. In the last phase of each study, interviews were conducted in order to verify the outcomes, but also to better understand their managerial implications.

The outcomes of the conducted studies contribute to three scientific fields: Decision Support Modeling, Food Logistics Management and Performance Management. The field of Performance Management creates the context for and the measures of performance that are needed for successful implementation of actions to reach certain objectives and targets (Wang and Fang, 2001). This research proposes and applies Decision Support Models to support dairy production planning including supply and demand characteristics (Food Logistics Management), and evaluates the performance of the planning model and of processing units (Performance Management). The link between each of the studies and the enumerated fields is presented in Figure 1.4.

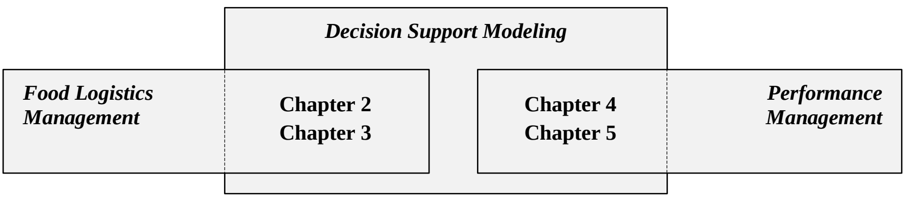

Figure 1.4 Contribution to the scientific fields.

1

Table 1.2 Research objectives, methods and expected deliverables

Chapter and objective	Method	Deliverables
Chapter 2: Development of a comprehensive Dairy Valorization Model	• Literature study, interviews • Operations Research method • Model output analysis, interviews	• List of inputs and outputs important for mid-term milk valorization; Constraints and processes of the dairy system • Linear programing model suitable for mid-term milk valorization • Impact of seasonality of raw milk's composition on valorization decisions
Chapter 3: Evaluation of the effect of byproducts valorization and of integral valorization on the overall valorization of milk	• Literature study, interviews • Operations Research method • Model output analysis, interviews	• Elements important for whey valorization; Constraints of and relations in whey processing • Linear programing model suitable for mid-term milk and whey valorization; Approach to evaluate the effect of byproduct valorization and integral valorization • Added value of whey valorization; Potential gains coming from the integration of valorization processes; Parameters driving the effect of integral valorization
Chapter 4: Evaluation and improvement of the robustness of valorization plans obtained with deterministic models	• Literature study • Literature study, interviews • Model output analysis, interviews	• Definition of robustness of valorization plans • Assessment procedure for robustness evaluation of valorization plans • Robustness degree of valorization plans; Parameters with the highest impact on the robustness degree
Chapter 5: Development of a framework for efficiency evaluation of processing units	• Literature study, interviews • Operations Research method • Model output analysis, statistical tests	• Method most suitable for efficiency evaluation; Parameters most relevant for performance measurement • Model for efficiency measurement • Inefficient processing units; Critical factors contributing to successful performance; Recommendations on possibilities for efficiency improvements

In the following section the outline of this thesis is presented. Afterwards each study is discussed in a separate chapter.

1.5 Outline of the thesis

This thesis is a collection of four papers that all aim at the improvement of milk valorization in the dairy industry. Chapter 2 describes a Dairy Valorization Model for valorization of main milk products and covers the first research questions. The model presented in Chapter 2 is further extended in Chapter 3 to include whey-based products. The second research question is answered in this chapter. In the following Chapter 4, the model developed in Chapter 2 is used to evaluate the robustness of valorization plans. The third research question is answered in this chapter. The last problem related to the efficiency evaluation is addressed in Chapter 5. A framework for evaluating efficiencies of processing units is developed based on a case study of an international express provider. The fourth and last question of this thesis is answered in this chapter. In the last chapter (Chapter 6) the conclusions following from the conducted studies and general discussion of the results are presented. Additionally limitations of the conducted studies and recommendations on further research, as well as managerial implications are provided.

PART I:
Valorization Model

Chapter 2

A comprehensive Dairy Valorization Model

This chapter is based on the following journal paper:

Banaszewska, A., Cruijssen, F., van der Vorst, J.G.A.J., Claassen, G.D.H. and Kampman, J.L., 2013. *A comprehensive dairy valorization model*. Journal of Dairy Science, 96(2): 761-779.

Abstract

Dairy processing companies face numerous challenges resulting from both unsteady dairy markets and some specific characteristics of dairy supply chains. To maintain a competitive position on the market, companies must look beyond standard solutions currently used in practice. This paper presents a comprehensive dairy valorization model that serves as a decision support tool for mid-term allocation of raw milk to end products and production planning. The developed model was used to identify the optimal product portfolio composition. The model allocates raw milk to the most profitable dairy products while accounting for important constraints (i.e., recipes, composition variations, dairy production interdependencies, seasonality, demand, supply, capacities, and transportation flows). The inclusion of all relevant constraints and the ease of understanding dairy production dynamics make the model comprehensive. The developed model was tested at the international dairy processing company FrieslandCampina (Amersfoort, the Netherlands). The structure of the model and its output were discussed in multiple sessions with and approved by relevant FrieslandCampina employees. The elements included in the model were considered necessary to optimally valorize raw milk. To illustrate the comprehensiveness and functionality of the model, we analyzed the effect of seasonality on milk valorization. A large difference in profit and a shift in the allocation of milk showed that seasonality has a considerable impact on the valorization of raw milk.

2.1 Introduction

Dairy processing companies face numerous challenges resulting both from unsteady dairy markets and from specific characteristics of dairy supply chains. The volatility of demand and prices of dairy products, greater competitiveness, and the increasing regulations that limit access to external markets significantly affect the performance of dairy processing companies. The European dairy sector is under constant change following for example the new European Union (EU) dairy policy and the outcomes of ongoing negotiations in the World Trade Organization. In 2003 the intervention prices for butter and skim milk powder (SMP) were decreased by 25 and 15%, respectively. Intervention prices act as floor market prices; that is, every national intervention agency in the EU is obliged to purchase for this price any amount of dairy commodity that is offered to them by dairy companies (Womach, 2005). The substantial decline in the intervention price made the production of bulk products less profitable and more risky. Furthermore, in 2003 it was also decided to gradually increase milk quotas and completely abolish them in 2015. These changes led to, and likely will continue to lead to an increase in milk supply. Furthermore, in the last years, the price of milk fluctuated between €27 and €35 per 100 kg. The yearly percentage change in price in 2000 to 2010 reached 22% (LTO, 2011). According to Geary et al. (2010) dairy market fluctuations and price volatility will be a constant challenge to the future dairy industry. Additionally, the enlargement of the EU in 2007 increased the competitiveness on the EU dairy market, thereby making the market more difficult for dairy processing companies. High competitiveness on the international dairy market requires dairy companies to optimize production and sales to ensure survival (Guan and Philpott, 2011).

The complexity emerging from the uniqueness of dairy supply chains also requires advanced methods for effective dairy supply chain management. In a dairy chain, raw milk (RM), the main raw material, is collected from multiple dairy farms scattered throughout the supply area and used for the production of all dairy products. The volume and, in part, the choice of end product (EP) to be produced depend on the nutrient content of RM, which changes during the year. The production of dairy products is interrelated: a byproduct (BP) of one production process can be used in another production process, which often takes place at a different location. To manage the incoming milk profitably, efficient logistics in many domains are required; for example, transport, allocation, production planning.

A comprehensive model that captures the dynamics of dairy production and incorporates all relevant constraints related to internal and external environments would significantly improve allocation of milk. The results of the literature review provided in the next section clearly indicate the lack of such a model in current use. In this paper, we present a comprehensive Dairy Valorization Model (DVM) that optimizes mid-term plans for the allocation of RM, the production of end products and byproducts while considering all constraints. The model captures all factors that directly or indirectly influence the allocation of milk. Furthermore, the comprehensiveness of the model allows producers to understand the effect of various changing parameters on milk valorization. This is an important advantage, given the constant changes on the dairy market and in RM supply. The model therefore not only improves milk valorization, but also provides a good understanding of prevailing production processes. The developed model was verified at the international dairy processing company FrieslandCampina (FC; Amersfoort, the Netherlands).

We will first present a literature overview, and then present the model in 3 steps. First, the conceptual model will be described, then the model will be verified using information from FC, finally the mathematical model will be formulated. We will discuss the main outcomes of the model and then define and conduct additional scenario that evaluates the impact of RM seasonality.

2.2 Literature review

The literature provides various approaches to maximize profit of dairy processing companies, starting from a general analysis of dairy manufacturing processes (Roupas, 2008), through allocation models that capture parts of the production process (Burke, 2006; Doganis and Sarimveis, 2007; Kerrigan and Norback, 1986; Papadatos et al., 2002), allocation models that aim to allocate milk to all dairy products in a portfolio (Benseman, 1986; Mellalieu and Hall, 1983), and models that represent whole dairy supply chains (Guan and Philpott, 2011; Vaklieva-Bancheva et al., 2007; Wouda et al., 2002). Given the purpose of this paper and the specific characteristics of the dairy supply chain, we have focuses on papers presenting models that aim at the allocation of RM to final dairy products. Readers interested in complete state-of-the-art on production planning models may refer to the following review papers: production-distribution models (Ahumada and Villalobos, 2009; Bilgen and Ozkarahan, 2004; Chen, 2004; Vidal and Goetschalckx, 1997), maintenance and production (Budai et al., 2008), production planning and uncertainty (Mula et al., 2006; Sahinidis, 2004; Wazed et al., 2010), production and transport (Mula et al., 2010), and predictive modeling of manufacturing processes (Roupas, 2008).

Even though the dairy production problem has been treated in many ways, a model that takes into account all factors necessary to create a comprehensive DVM is, to the best of our knowledge, not yet available in the literature. A complete list of important factors affecting the valorization of RM was identified based on a literature study and interviews with experts. Models available in the literature and focusing on the allocation of RM to EPs were investigated with respect to included factors. To verify the list of factors, we studied in detail the environment and processes of one of the world’s largest dairy companies (FC). Additionally, iterative sessions were held with dairy supply chain managers, production planners, technologists, and market analysts at FC. During these sessions intermediate results were discussed. This pragmatic stepwise approach of literature and process analyses resulted in the final list of factors (see Table 2.1).

Table 2.1 Factors relevant for milk valorization

Factor	Relevance for milk valorization
1. Recipes based on raw milk composition 2. Seasonality of raw milk composition and supply	The inclusion of factor 1 and factor 2 allows capturing the changing composition of products, which is influenced by the seasonal composition of raw milk. Since all products are originally produced from raw milk, the composition of input material influences the type or volume of end product that is obtained.
3. Whole product portfolio	Products that cover the whole product portfolio as well as the resulting byproducts should be taken into account during optimization. This guarantees that raw milk is always allocated to the best valorizing dairy products.
4. Byproduct utilization	The production of dairy products is inter-related. Often a byproduct of a certain process can be used as the input for other processes. Consequently, the flow of byproducts between various products and factories might have a significant impact on allocation decisions as well as on the capacity availability.
5. Network of supply regions and production locations 6. Byproducts transportation 7. Raw milk transportation	Large volumes of raw milk and byproducts have to be transported every day. Allocation decisions might be different depending on the distance between a supply region or a source production location, at which an input material is available, and destination production locations, at which that input material is required. Consequently, transport costs might influence valorization of milk.
8. Changes in prices	Market developments should also be incorporated in the model. Especially changes in prices from one planning period to another, and changes during the planning periods resulting from price elasticity (different volumes sold for different prices) should be incorporated.

To investigate the models presented in the literature, we began with the framework developed by Ahumada and Villalobos (2009) and extended it with model features that are especially relevant for the mid-term dairy production planning. Additionally, we looked at the applicability of these models in practice. We analyzed the papers with respect to the following characteristics: modeling technique; modeling approach (deterministic or stochastic); planning horizon (single period, short-term, mid-term or long-term); recipes based on milk composition (yes or no); seasonality of RM composition and RM supply included (yes or no); part of product portfolio covered (whole product portfolio (yes) or a particular product group (no; e.g., cheeses, yoghurts); BPs reutilization (yes or no); BPs transport (yes or no); RM transport (yes or no); network of supply regions and production locations (yes or no); changes in product prices - throughout the whole planning horizon, within planning periods that determine the complete planning horizon, and no changes included (no); model tested on a real-life case – application (yes or no). The results of the analysis are presented in Table 2.2. As can be seen, none of the models available in the literature included all factors relevant to efficient milk valorization. A milk allocation model that included most of the important features was developed more than 25 yrs ago (Benseman, 1986). The seasonality aspect of milk components was partly incorporated in that model; that is, volumes of EPs obtained from 1 t of RM depend on the composition of milk; however, volumes of BPs are fixed. In reality, this is not true because milk composition affects both EP and BP volumes. Furthermore, only a small part of the current set of dairy products and BPs was covered in Benseman (1986), and no explicit relation between EPs and BPs was provided. Additionally, it was not possible to use multiple production recipes. The model did not allow for the possibility of selling and purchasing RM. Finally, only changes in prices throughout the planning horizon (from one planning period to the next) were incorporated. It was assumed, however, that the sale price of an EP remained constant within a planning period. Consequently, no price elasticity reflecting a relationship between prices and volumes was taken into account. Other papers that incorporated a larger number of relevant factors are: Mellalieu and Hall (1983), Vaklieva-Bancheva et al. (2007), and Guan and Philpott (2011).

In the model developed by Mellalieu and Hall (1983), it was not clear which part of the dairy portfolio was included. The relation between EP and BP was not indicated. A network of supply regions and locations was incorporated, but it was used only for the transportation of RM. Byproducts were not reused in the production process. Because the production of dairy products is interrelated, excluding the possibility of using BP as inputs for further production results in suboptimal solutions. The model developed by Vaklieva-Bancheva et al. (2007) aimed at evaluating an existing compromise between actors of the dairy supply chain. It was not a tool designed specifically to optimize production planning, and a very limited number of products was introduced in the model. Therefore, the relation between the current set of EP and BP was missing. The possibility of reusing BP was also limited and no transportation of BP was allowed. Although product recipes depend on the composition of RM, the model failed to fully incorporate the aspect of RM seasonality and price variability. The model recently developed by Guan and Philpott (2011) incorporated uncertainty in milk supply, price–demand relations, and contracting. A large part of the paper was focused on uncertainty in the milk supply, and little attention was given to the representation of the dairy portfolio. Consequently, it is not known which products were incorporated in the model, no BP flows were included, and recipes were not based on RM composition. Thus, the seasonality of milk was included only via volumes supplied throughout the year. Including seasonality, however, would improve the effectiveness of such models, making them a more useful, year-round, decision-support tool (Geary et al., 2010). The results of the literature research conducted in this study and presented in Table 2.2 confirmed the lack of a model that includes all relevant factors affecting milk valorization. Therefore, a comprehensive DVM that incorporates all the important aspects, as developed in this study, would fill this literature gap.

Table 2.2 Literature overview – dairy production planning models

	Method	Factors[1]										
Reference and objective	Model	Approach	Time Scope	Composition based	RM seasonality	Whole portfolio	BPs reutilization	Network of locations	BPs transport	RM transport	Changes in prices	Application
Mellalieu and Hall (1983), Development of a planning model for a large New Zealand dairy company	Network formulation	D	SP	Y	Y	N	N	Y	N	Y	N	Y
Benseman (1986), Development of a model that finds most profitable production schedule of dairy products	Linear Programming	D	M	N	N	N	Y	Y	Y	Y	PH	Y
Kerrigan and Norback (1986), Application of an Operations Research methodology to the problem of milk standardization for cheese making	Linear Programming	D	SP	Y	N	N	N	N	N	N	N	N
Craig et al. (1989), Development of a linear programming model for cheese manufacturing	Linear Programming	D	SP	Y	N	N	N	N	N	N	N	N
Papadatos et al. (2002), Development of a model that maximizes net revenue by identifying the optimal mix of milk resources and types of cheese products and co-products	Non Linear Programming	D	L	Y	Y	N	Y	N	N	N	PH	N
Lutke-Entrup et al. (2005), Development of models that integrate shelf-life issues into production planning and scheduling	Mixed Integer Linear Programming	D	S	N	N	N	N	N	N	N	PH	N
Burke (2006), Development of a model that minimizes net cost of producing a given quantity of cheese	Non Linear Programming	D	SP	Y	N	N	N	N	N	N	N	N

Continued on the next page

[1]*Approach: D = deterministic, S = stochastic; Time scope: S = short-term, M = mid-term, L = long-term, SP = single period; Change in prices: PP = within planning periods that determine the complete planning horizon, PH = throughout the whole planning horizon; Y = yes, N = no; RM = raw milk, BP = byproduct.*

[2]*a) S-graph framework with branch and bound, b) IP with BASIC genetic algorithm.*

2

Reference and objective	Method	Factors[1]										
	Model	Approach	Time Scope	Composition based	RM seasonality	Whole portfolio	BPs reutilization	Network of locations	BPs transport	RM transport	Changes in prices	Application
Doganis and Sarimveis (2007), Development of an optimal production scheduling model in a single yoghurt production line	Mixed Integer Linear Programming	D	S	N	N	N	N	N	N	N	N	N
Johnson et al. (2007), Development of an optimization model to determine the value of the casein genotype and milk composition in cheese and whey production	Linear Programming	D	SP	Y	N	N	Y	N	N	N	N	N
Vaklieva-Bancheva et al. (2007), Evaluation of existing compromise between the dairy supply chain actors, by developing a mathematical model	Multi Objective Optimization Model	D	SP	Y	N	N	Y	Y	N	Y	N	N
Doganis and Sarimveis (2008), Development of a customized model for optimizing yoghurt packaging lines	Mixed Integer Linear Programming	D	S	N	N	N	N	N	N	N	N	Y
Adonyi et al. (2009), Presentation of two independent approaches for obtaining minimal makespan schedule	Two approaches[2]	D	S	Y	N	N	N	N	N	N	N	N
Guan and Philpott (2011) Development of a multistage stochastic programming model	Multistage Stochastic Programming	S	M	N	N	Y	N	Y	N	Y	PH and PP	Y
Geary et al. (2010), Development of a processing-sector model that simulates: (i) milk collection, (ii) standardization, and (iii) product manufacture	Mass Balance Model	D	SP	Y	N	Y	Y	N	N	N	N	Y

[1]Approach: D = deterministic, S = stochastic; Time scope: S = short-term, M = mid-term, L = long-term, SP = single period; Change in prices: PP = within planning periods that determine the complete planning horizon, PH = throughout the whole planning horizon; Y = yes, N = no; RM = raw milk, BP = byproduct.
[2]a) S-graph framework with branch and bound, b) IP with BASIC genetic algorithm

2.3 Materials and methods

To develop the DVM, we used several methods: literature research, interviews, and linear programming. In the first phase of the study, including literature research and interviews, we determined the most important factors that should be included in the model. Furthermore, we described in detail and analyzed all relevant processes to define the constraints of the system. The relevant research papers were analyzed in a structured way with regard to the methodology used, factors included, and application. Additionally, multiple sessions with relevant experts—dairy supply chain managers, production planners, technologists, and market analysts—were held over a year. During these sessions, parameters and constraints that should be included in the model, recipes, and product interrelations were discussed. Finally, the information gathered in the first phase of the research was used to build the model. We used a linear programming method to describe the problem at hand. Following the methodology, we defined the objective and constraints of the problem, and formulated it mathematically. To validate the model we compared 2 scenarios using real data sets supplied by FC. All results were discussed during iterative sessions with experts and their reliability was approved.

2.3.1 Conceptual model description

Model elements

To create an advanced DVM for the mid-term production planning, elements related to external and internal environments should be taken into account. Factors relevant to valorization were presented in the previous section. Based on these factors, we created a scheme of the DVM (Figure 2.1). The scheme of the model was discussed with experts and its completeness was confirmed. The model uses various inputs to create valorization plans. These plans determine the volumes of RM that should be allocated to EP in every period. Every run of the model provides a valorization plan for several consecutive periods, which together form a planning horizon.

The inputs of the model consist of elements related to milk supply, market demand, production, and transport. Elements included in the *milk supply* group ensure that the seasonality and composition of the RM supply are included. Elements of *market demand* group reflect the situation on the dairy market. Price elasticity was captured by means of tranches that indicate volume and price for which a product can be sold. The first tranche represents volumes of products fixed in contracts, together with the average contract sale prices. The residual tranches reflect the situation on the market; that is, the greater the volume of product placed on the market (sold), the lower the selling price. Consequently, the prices assigned to tranches other than the first tranche decrease. The price assigned to the first tranche depends on the contracts that were made in the past. Elements of the *production* group represent parameters related to dairy production. Waste elements represent a loss of components during the production process. More information on waste is provided in the next subsection. Elements included in the *transport* group allow for the optimization of flows of BP required for production. The main output of the model is a production plan resulting from the valorized allocation of RM.

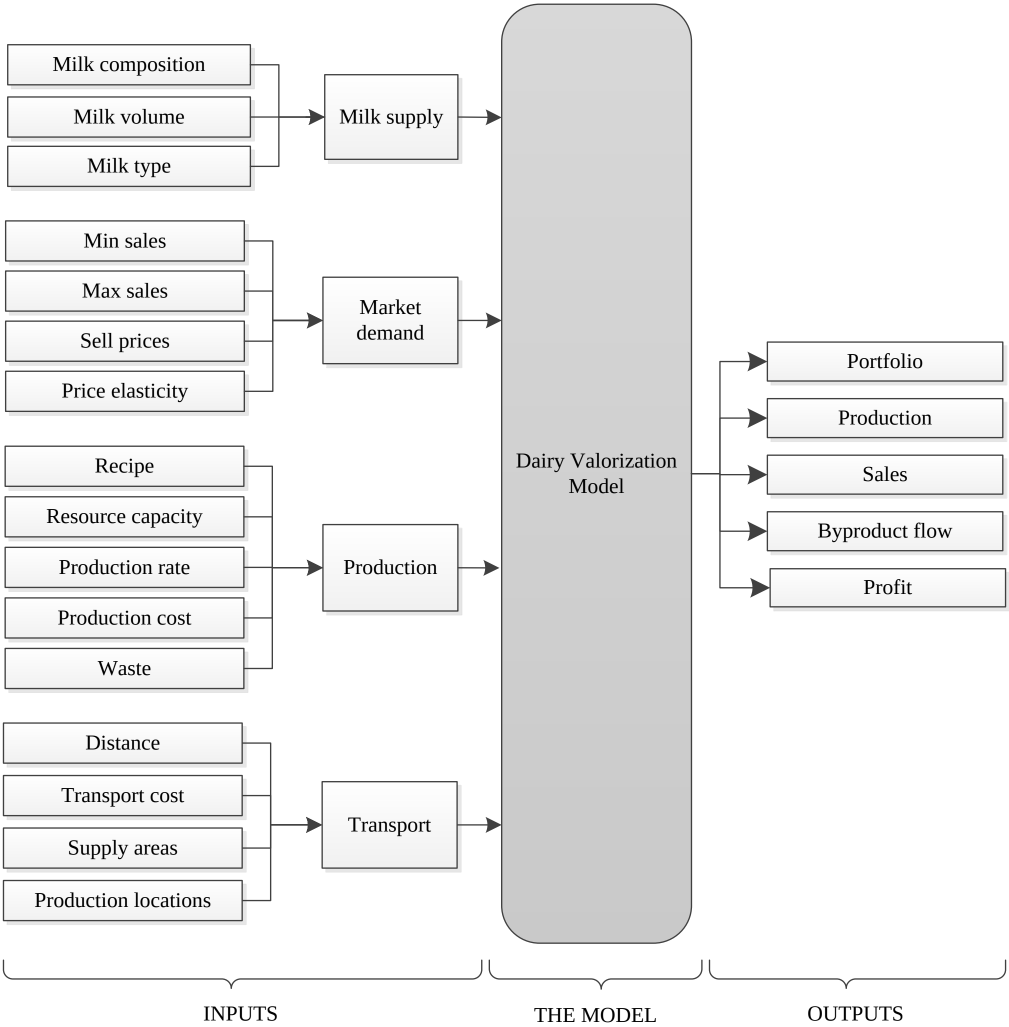

Figure 2.1 Scheme of Dairy Valorization Model.

The optimal production plan is represented by the highest possible profit, and thus the best valorization of milk components. Furthermore, no parameters related to inventory management were included in the DVM. Although inventory is often one of the elements of production planning models, most models developed for the dairy industry do not incorporate the inventory management problem (Adonyi et al., 2009; Burke, 2006; Doganis and Sarimveis, 2007; Geary et al., 2010; Johnson et al., 2007; Papadatos et al., 2002; Vaklieva-Bancheva et al., 2007). The reason behind this, from the perspective of a mid-term model, could be the relatively short shelf life of dairy products. Therefore, we decided not to include inventory management options in the model developed in this study, but instead to focus on a detailed investigation of production planning processes. For the same reason, we decided to use a deterministic approach. A stochastic approach would perhaps allow better capturing of the volatility of variable parameters, but the complexity of such a model would be much higher than that of a deterministic model. Nevertheless, inclusion of stochastic elements in the comprehensive DVM is an interesting and challenging topic for the further research

Production of dairy products

The DVM was designed to optimize the production at dairy processing companies by allocating all incoming RM to the most profitable EPs. All products were clustered into 4 categories: RM, BP, half products (HPs), and EPs. Byproducts are the products additionally obtained while producing main products; that is, HP and EP. Furthermore, cream and skim milk can be also obtained from a decomposition of RM. Half products are the intermediate products necessary for the production of EPs. The EPs are produced by means of a production process, which is divided into 3 stages: decomposition, half production, and end production (Figure 2.2).

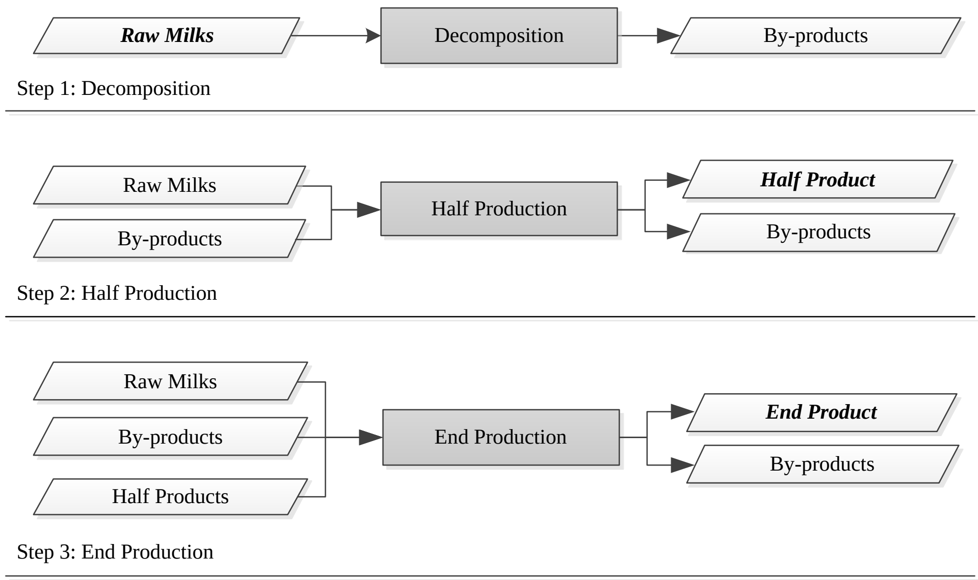

Figure 2.2 Production stages.

The main reason for decoupling the production process into 3 stages is the availability of capacities at various locations. For instance, production of butter requires cream as an input. If a butter location does not have separation equipment, cream could be obtained from another location. Therefore, the introduction of production stages in the optimization model contributes to a reduction in total transportation costs and to optimal use of production capacities.

Every product can be produced with the use of multiple recipes. A recipe includes the information on the type, volume, and composition of inputs used in and outputs obtained from the production. The composition of EP is mostly fixed; that is, a certain level of dry matter (DM), fat, and protein. In certain situations, only selected components must match a specified level, whereas others must fulfill a minimum level. The desired component levels are obtained by means of a standardization technique that calculates fractions; that is, volumes of input materials required to obtain 1 t of product with a desired composition level. Because the composition of RM changes throughout the year (see Figure 2.3), volumes required and obtained from production also change. A crucial part of the production process is to ensure that the volume of a component in all inputs equals the volume of that component in all outputs. The value of RM lies in its components; hence, every kilogram of inefficiently used component is a loss for a manufacturer. Waste products are introduced in the model to track inefficiently used volumes of components.

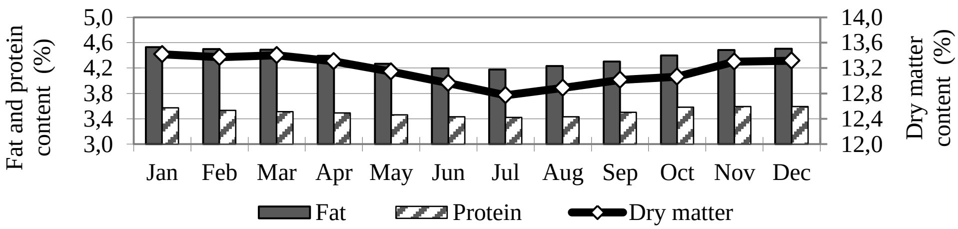

Figure 2.3 Composition of raw milk throughout the year (source: FrieslandCampina).

2.3.2 Case study: FrieslandCampina

FrieslandCampina (FC) is one of the largest dairy companies in the world (2011 sales amounted to around €9.5 billion). The company has approximately 14,500 member dairy farms that deliver almost 9 billion kilograms of RM yearly. This milk is transformed into a wide range of EPs; for example, milk-based drinks, cheese, yogurts, milk powders, dairy-based ingredients, infant food, and animal feed. To process all RM and to market EPs, the company employs 19,000 people in 25 countries. Final products are delivered to more than 100 countries worldwide; key regions are Europe, Asia, and Africa (FrieslandCampina, 2011). The aim of FC is to become the world's most professional, successful and attractive global dairy company by "getting more out of milk." Because milk is the main raw material used for the production of all FC's products, the focus is on complete RM valorization; that is, 3-level valorization. The highest level of valorization takes place on a strategic level. Here, general plans for high-level dairy production are defined. The DVM is used to prepare plans for the

Table 2.3 Dairy products in the Dairy Valorization Model

Product (abbreviation)	Group
Butter Milk Powder (BMP)	End Product
Butter	End Product
Butter Oil	End Product
Caseinate Roller	End Product
Caseinate Spray	End Product
Cheese Foil	End Product
Cheese Nature	End Product
Cream Product (CreamProd)	End Product
Evaporated Milk (EVAP)	End Product
Infant Food & Growing Up Milk Powder (IF/GUM)	End Product
Instant Full Cream Milk Powder (IFCMP)	End Product
Sweet Condensed Milk (SCM)	End Product
Serum Powder	End Product
Skim Milk Concentrate Product (SkimMilkConcProd)	End Product
Skim Milk Product (SkimMilkProd)	End Product
Skim Milk Powder (SMP)	End Product
Standardized Milk (StdMilk)	End Product
Whole Milk Powder (WMP)	End Product
Raw Milk	Raw Milk
Butter Milk	Byproduct
Cream	Byproduct
Cream Serum	Byproduct
Lactose	Byproduct
Retentate	Byproduct
Skim Milk	Byproduct
Whey Casein	Byproduct
Whey Cheese	Byproduct
Cheese Milk Foil (ChMFoil)	Half Product
Cheese Milk Nature (ChMNature)	Half Product
Protein Standardized Skim Milk (ProStdSM)	Half Product
Skim Milk Concentrate (SkimMilkConc)	Half Product

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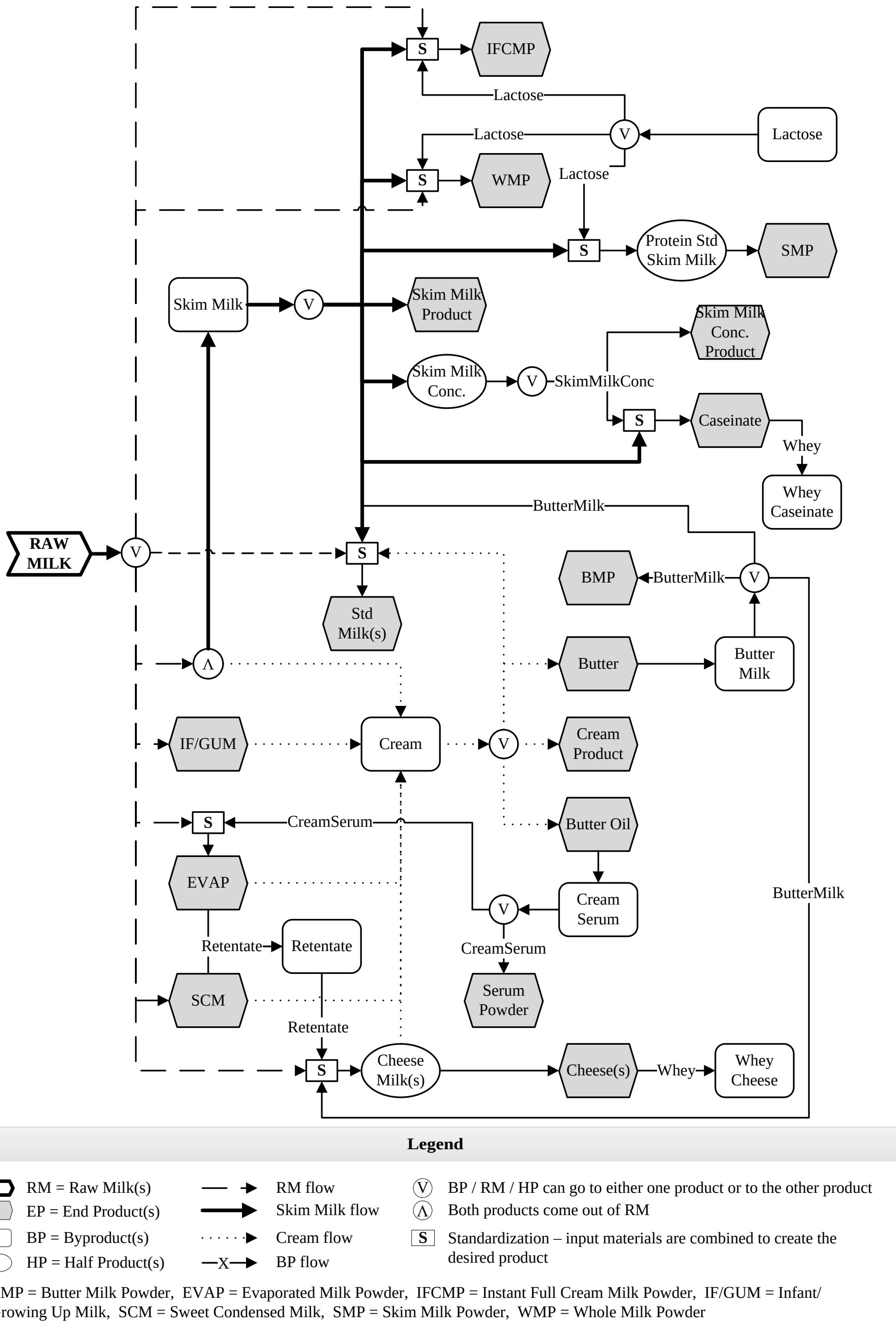

Figure 2.4 Dairy flows (based on Zimmermann (2001) and experts' discussions).

next level (the tactical level). Finally, the output of the DVM can then be used to create the operational production plans.

To create optimal mid-term production plans, original products are aggregated to 82 representative products (hereafter referred to as products). The input data of all original products related to demand and production are aggregated accordingly. All main dairy products are listed in Table 2.3. Although the table lists only 31 products, the product portfolio included in the model distinguishes between multiple Foil Cheeses (6), Nature Cheeses (11), Foil Cheese Milks (11), Nature Cheese Milks (12), and Standardized Skim Milks (16). Furthermore, a large group of whey-based products is represented in this study by cheese whey and casein whey products.

As mentioned previously, production processes of various products are inter-related, mainly because of BPs reuse. Interrelations between dairy products are depicted in Figure 2.4. The figure shows only the internal flow of dairy products, but all products can additionally be purchased or sold on the market. Dairy products can be produced at all 37 FC production locations situated in Belgium, Germany, and the Netherlands. The RM supply area is divided geographically—3 regions corresponding to 3 countries. To convert RM into EPs, 22 resources (production equipment) are used. The produced products can be sold in 4 tranches, the first of which represents the contracted volumes (i.e., minimum sales). Maximum sales volume and selling price are assigned.

2.3.3 Mathematical model description

The parameters in the DVM represent market and supply limitations, composition of products, production characteristics (e.g., recipes, production rates, and costs), and transport. The values of parameters are updated either once a year or every time the model is run (i.e., every month). Decision variables in the DVM represent volumes (tonnes), for example, used, produced, and transported. Indices used to create parameters and variables, decision variables, and enumerated parameters, as used in the equations below, are defined and presented in Table 2.4, Table 2.5 and Table 2.6, respectively. Indices with single and double primes belong to the same index set as the index without the prime symbols. For example, *d*, *d’*, and *d’’* represent 3 dairy products belonging to the same dairy set *D*.

To create a reliable valorization model that correctly describes the reality of dairy manufacturing several constraints were formulated. These constraints are related to market limitations, production limitations, recipes, and product flows. All constraints were formulated for each period *t* and are presented below:

a) Capacities

Capacity of a resource *r* used to decompose RM or to produce products at a location *l* should not exceed the maximum available capacity at that location.

$$\sum_{i \in I}\left(\sum_{m \in M}\frac{Xuse_{(t,m,m,i,l)}}{ProdRate_{(m,i,r)}} + \sum_{d \in H \cup E}\frac{Xprod_{(t,d,d,i,l)}}{ProdRate_{(d,i,r)}}\right) \le ResourceCap_{(t,r,l)} \qquad \forall r, \forall l, \forall t \quad (2.1)$$

Table 2.4 Indexes used in the Dairy Valorization Model

Index and set	Description
$d, d', d'' \in D$	D - dairy set that include all products (raw milk, byproducts, half products, end products)
$e \in E$	E – set of end products, subset of dairy set ($E \subset D$)
$b \in B$	B – set of byproducts, subset of dairy set ($B \subset D$)
$h \in H$	H – set of half products, subset of dairy set ($H \subset D$)
$m \in M$	M – set of raw milks, subset of dairy set ($M \subset D$)
$i \in I$	I – set of recipes
$a \in I$	A – set of supply areas (regions)
$l, l', l'' \in L$	L – set of locations
$r \in R$	R – set of resources
$tr \in TR$	TR – set of tranches
$t \in T$	T – set of time periods (all set elements define the planning horizon)

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b) Supply volume of RM

The volume of RM m sold or delivered to production locations should equal the volume of RM supplied from area a.

$$\sum_{l\in L}\sum_{d\in D\setminus B} RMflow_{(t,m,a,d,l)} + \sum_{tr\in TR} RMsale_{(t,m,a,tr)} = Supply_{(t,m,a)} \qquad \forall m, \forall a, \forall t \qquad (2.2)$$

c) Total sales volume

Total sold volume of a dairy product d should not exceed the maximum sales volume.

$$\sum_{tr\in TR}\left(\sum_{a\in A} RMsale_{(t,d,a,tr)} + \sum_{d\in D\setminus B}\sum_{l'\in L} Xsale_{(t,d,d',l',tr)}\right) \le min\left(\sum_{tr\in TR} MaxSale_{(t,d,tr)}, Demand_{(t,d)} + MaxAddSale_{(t,d)}\right) \qquad \forall d, \forall t \qquad (2.3)$$

d) Sales and purchase volumes per tranche

The volume of a dairy product d sold in the first tranche (tr) should equal the volume fixed in contracts (maximum sales volume of tranche 1).

$$\sum_{a\in A} RMsale_{(t,d,a,tr)} + \sum_{d'\in D\setminus B}\sum_{l'\in L} Xsale_{(t,d,d',l',tr)} = MaxSale_{(t,d,tr)} \qquad tr = 1, \forall d, \forall t \qquad (2.4)$$

Table 2.5 Decision variables used in the Dairy Valorization Model

Variables	Description
$Xbuy_{(t,d,d',l',tr)}$, $d \in D\backslash E, d' \in D\backslash B$	Volume of product *d* bought in tranche *tr* to produce product *d'* at location *l'*, in time period *t*
$Xuse_{(t,d,d',i,l')}$, $d \in D\backslash E, d' \in D\backslash B$	Volume of product *d* used to produce product *d'* with the use of recipe *i* at location *l'*, in time period *t*
$Xprod_{(t,d,d',i,l')}$, $d \in D\backslash M, d' \in D\backslash B$	Volume of product *d* obtained while producing product *d'* with the use of recipe *i* at location *l'*, in time period *t*
$Xsale_{(t,d,d',l',tr)}$, $d \in D\backslash M, d' \in D\backslash B$	Volume of product *d* obtained from the production of product *d'* at location *l'* and sold in tranche *tr*, in time period *t* NB: these variables represent sales of all products apart from raw milk
$RMsale_{(t,d,a,tr)}$, $d \in M$	Volume of raw milk *d* supplied from area *a* and sold in tranche *tr*, in time period *t*
$Xflow_{(t,d,d',l',d'',l'')}$, $d \in B \cup H, d' \in D\backslash B, d'' \in H \cup E$	Volume of product *d* obtained from the production of product *d'* at location *l'* and transported to the production of product *d''* at location *l''*, in time period *t* NB: these variables represent the flow of all products apart from raw milk
$RMflow_{(t,d,a,d',l')}$, $d \in M, d' \in D\backslash B$	Volume of raw milk *d* transported from supply area *a* to a production location *l'* to produce product *d'*, in time period *t*
$Wdry_{(t,d,i,l)}$, $d \in D\backslash B$	Volume of "dry matter-waste" resulting from the production of product *d* with the recipe *i* at location *l*, in time period *t*
$Wfat_{(t,d,i,l)}$, $d \in D\backslash B$	Volume of "fat-waste" resulting from the production of product *d* with the recipe *i* at location *l*, in time period *t*
$Wpro_{(t,d,i,l)}$, $d \in D\backslash B$	Volume of "protein-waste" resulting from the production of product *d* with the recipe *i* at location *l*, in time period *t*
$Profit_{(t)}$	Profit realized in time period *t*
$Revenue_{(t)}$	Revenue from sales realized in time period *t*
$ProdCostTotal_{(t)}$	Total production costs incurred in time period *t*
$TransCostTotal_{(t)}$	Total transport costs incurred in time period *t*
$BuyCostTotal_{(t)}$	Total purchase costs incurred in time period *t*

Table 2.6 Parameters used in the Dairy Valorization Model

Parameter	Unit	Description	Update frequency
$Supply_{(t,m,a)}$	Tonne (t)	Supply level of raw milk *m* coming from supply area *a* in time period *t*	Monthly
$Demand_{(t,d)}$	t	Demand for product *d* in time period *t*	Monthly
$MaxAddSale_{(t,d)}$	T	Maximum market capacity for product *d* in time period *t*	Monthly
$MaxSale_{(t,d,tr)}$	T	Maximum sale volume of product *d* that can be sold in tranche *tr* in time period *t*	Monthly
$SalePrice_{(t,d,tr)}$	€/t	Sale price of product *d* that can be sold in tranche *tr* in time period *t*	Monthly
$MaxBuy_{(t,d,tr)}$	t	Maximum purchase volume of product *d* that can be bought in tranche *tr* in time period *t*	Monthly
$BuyPrice_{(t,d,tr)}$	€/t	Purchase price of product *d* that can be bought in tranche *tr* in time period *t*	Monthly
$ResourceCap_{(t,r,l)}$	h	Capacity of resource *r* in time period *t* available at location *l*	Monthly
$Dry_{(t,d)}$	%	Dry matter content in product *d* in time period *t*	Monthly
$Fat_{(t,d)}$	%	Fat content in product *d* in time period *t*	Monthly
$Pro_{(t,d)}$	%	Protein content in product *d* in time period *t*	Monthly
$FractionIn_{(t,d,d',i)}$, $d \in D \backslash E, d' \in H \cup E$	Unit less	Fraction of product *d* necessary to produce one ton of product *d'* with recipe *i*	Monthly
$FractionOut_{(t,d,d',i)}$, $d \in B, d' \in M \cup E$	Unit less	Fraction of product *d* obtained from a production of one ton of product *d'* with recipe *i*	Monthly
$Distance_{(l,l')}$	km	Distance between production locations *l* and *l'*	Yearly
$TransCost_{(d)}$	€/t·km	Unit transport cost of product *d*	Yearly
$ProdRate_{(d,i,r)}$	t/h	Production rate of product *d* produced with recipe *i* at resource *r*	Yearly
$ProdCost_{(d)}$	€/t	Unit production cost of product *d*	Yearly

The volume of a dairy product *d* sold in every residual tranche (*tr*) should not exceed the maximum sales volume of that tranche.

$$\sum_{a \in A} \mathrm{RMsale}_{(t,d,a,tr)} + \sum_{d' \in D \backslash B} \sum_{l' \in L} \mathrm{Xsale}_{(t,d,d',l',tr)} \leq \mathrm{MaxSale}_{(t,d,tr)} \qquad tr > 1, \forall tr, \forall d, \forall t \qquad (2.5)$$

The volume of a dairy product *d* bought in the first tranche (*tr*) should equal the volume fixed in contracts.

$$\sum_{d\in D\backslash B}\sum_{l'\in L} \mathrm{Xbuy}_{(t,d,d',l',tr)} = \mathrm{MaxBuy}_{(t,d,tr)} \qquad tr = 1, d \in D\backslash E, \forall d, \forall t \quad (2.6)$$

The volume of a dairy product *d* bought in every residual tranche (*tr*) should not exceed the maximum purchase volume of that tranche.

$$\sum_{d\in D\backslash B}\sum_{l'\in L} \mathrm{Xbuy}_{(t,d,d',l',tr)} \le \mathrm{MaxBuy}_{(t,d,tr)} \qquad tr > 1, \forall tr, d \in D\backslash E, \forall d, \forall t \quad (2.7)$$

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e) Recipes

The volume of a BP *b* obtained from the production of EP *e* at a location *l* with a recipe *i* should equal the multiplication between the volume of the EP *e* produced and the fraction of that BP *b* obtained while producing 1 t of the desired product.

$$Xprod_{(t,b,e,i,l)} = FractionOut_{(t,b,e,i)} \cdot Xprod_{(t,e,e,i,l)} \qquad \forall b, \forall e, \forall i, \forall l, \forall t \quad (2.8)$$

The volume of a BP *b* obtained from the decomposition of RM *m* at a location *l* with a recipe *i* should equal the volume of RM *m* decomposed times the fraction of that BP *b* obtained while decomposing 1 t of RM.

$$Xprod_{(t,b,m,i,l)} = FractionOut_{(t,b,m,i)} \cdot Xuse_{(t,m,m,i,l)} \qquad \forall b, \forall m, \forall i, \forall l, \forall t \quad (2.9)$$

The volume of an input material *d* required for the production of a product *d'* at a location *l'* with a recipe *i* should equal the volume of the product *d'* produced times the fraction of the input material required to produce 1 t of desired product.

$$Xuse_{(t,d,d',i,l')} = FractionIn_{(t,d,d',i)} \cdot Xprod_{(t,d',d',i,l')}$$
$$d \in D\backslash E, \forall d, d' \in E \cup H, \forall d', \forall i, \forall l', \forall t \quad (2.10)$$

f) Composition balance

The total content of dry matter (*Dry*), fat (*Fat*), or protein (*Pro*) in inputs materials used in the production of a dairy product *d'* at a location *l'* with the use of a recipe *i* should equal the total content of that component in resulting products.

$$\sum_{d\in D\backslash E} Dry_{(t,d)} \cdot Xuse_{(t,d,d',i,l')} = \sum_{d\in D\backslash E} Dry_{(t,d)} \cdot Xprod_{(t,d,d',i,l')} + Wdry_{(t,d',i,l')}$$
$$d' \in D\backslash B, \forall d', \forall i, \forall l', \forall t \quad (2.11)$$

$$\sum_{d\in D\backslash E} Fat_{(t,d)} \cdot Xuse_{(t,d,d',i,l')} = \sum_{d\in D\backslash E} Fat_{(t,d)} \cdot Xprod_{(t,d,d',i,l')} + Wfat_{(t,d',i,l')}$$
$$d' \in D\backslash B, \forall d', \forall i, \forall l', \forall t \quad (2.12)$$

$$\sum_{d\in D\setminus E} Pro_{(t,d)} \cdot Xuse_{(t,d,d',i,l')} = \sum_{d\in D\setminus E} Pro_{(t,d)} \cdot Xprod_{(t,d,d',i,l')} + Wpro_{(t,d',i,l')}$$

$$d' \in D\setminus B, \forall d', \forall i, \forall l', \forall t \quad (2.13)$$

g) Inflow volumes

The volume of an input material *d* used for the production of a dairy product *d''* at a location *l''* should equal the volume of that input material delivered to that location plus the volume of that input material bought.

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$$\sum_{i\in I} Xuse_{(t,d,d'',i,l'')} = \sum_{l'\in L}\sum_{d'\in D\setminus B} Xflow_{(t,d,d',l',d'',l'')} + \sum_{a} RMflow_{(t,d,a,d'',l'')} + \sum_{tr\in TR} Xbuy_{(t,d,d'',l'',tr)}$$

$$d \in D\setminus E, \forall d, d'' \in D\setminus B, \forall d'', \forall l'', \forall t \quad (2.14)$$

h) Outflow volumes

The volume of a dairy product *d* obtained while producing a product *d'* at a location *l'* should equal the volume of the dairy product *d* send to the production of other products *d''* at locations *l''* plus the volume sold on the market.

$$\sum_{i\in I} Xprod_{(t,d,d',i,l')} = \sum_{l''\in L}\sum_{d''\in E\cup H} Xflow_{(t,d,d',l',d'',l'')} + \sum_{tr\in TR} Xsale_{(t,d,d',l',tr)}$$

$$d \in D\setminus M, \forall d, d' \in D\setminus B, \forall d', \forall l', \forall t \quad (2.15)$$

The DVM maximizes the profit of a dairy processing company. Consequently the objective function incorporates sales revenues, production costs, transport costs and purchase costs. The mathematical formulation is presented below:

$$Profit_{(t)} = Revenue_{(t)} - ProdCostTotal_{(t)} - TransCostTotal_{(t)} - BuyCostTotal_{(t)}$$

$$\forall t \quad (2.16)$$

where

$$Revenue_{(t)} = \sum_{d\in D}\sum_{tr\in TR} SalePrice_{(t,d,tr)} \cdot \left(\sum_{a\in A} RMsale_{(t,d,a,tr)} + \sum_{l'\in L}\sum_{d'\in D\setminus B} Xsale_{(t,d,d',l',tr)}\right)$$

$$\forall t \quad (2.17)$$

$$ProdCostTotal_{(t)} = \sum_{d\in D\setminus M} ProdCost_{(d)} \cdot \sum_{d'\in D\setminus B}\sum_{i\in I}\sum_{l'\in L} Xprod_{(t,d,d',i,l')} + \sum_{m\in M} ProdCost_{(m)} \cdot \sum_{i\in I}\sum_{l'\in L} Xuse_{(t,m,m,i,l')}$$

$$\forall t \quad (2.18)$$

$$TransCostTotal_{(t)} = \sum_{d \in D \setminus E} TransCost_{(d)} \cdot \sum_{d'' \in D \setminus B} \sum_{l'' \in L} \left(\sum_{d' \in D \setminus B} \sum_{l' \in L} Xflow_{(t,d,d',l',d'',l'')} + \sum_{a \in A} RMflow_{(t,d,a,d'',l'')} \right) \quad \forall t \quad (2.19)$$

$$BuyCostTotal_{(t)} = \sum_{d \in D \setminus E} \sum_{tr \in TR} \left(BuyPrice_{(t,d,tr)} \cdot \sum_{d' \in D \setminus B} \sum_{l' \in L} Xbuy_{(t,d,d',l',tr)} \right) \quad \forall t \quad (2.20)$$

The formulated model was implemented in optimization software package called AIMMS 3.11 (Paragon Decision Technology B.V., Haarlem, the Netherlands). The model enables us to optimize production decisions for all 82 products. The outcome of the model provides good insight into various fields of attention; for example, produced volumes, capacity use, BPs use, and components use. The DVM can also be used for milk valorization at other dairy companies because the dairy product portfolio is standardized throughout the world. Moreover, the developed model is flexible in terms of inputs used; thus, it can be adjusted easily to suit dairy production at other dairy companies.

2.4 Results and discussion

In this section numerical results of the study are presented. Detailed results however cannot be provided due to confidentiality. First, main results of a valorization plan are discussed. Next, the impact of raw milk's seasonality, i.e. the impact of yearly variations in raw milk's dry matter, fat and protein content on the milk valorization is illustrated. Both steps are carried out in order to show the comprehensiveness and correctness of the model, and the type of information that can be extracted from the results. At the end of the section managerial implications are described.

2.4.1 Main outcome

The main valorization plan is created with the use of the original data supplied by FrieslandCampina (FC). The planning horizon consists of 12 months (time periods). The model is solved in 9 seconds on a computer with a 3GHz processor and 2GB memory. The number of variables and constraints amounts to 61'645 and 32'635 respectively. The output of the model provides the valorization plan for every month in the planning horizon. It delivers a good overview of the production, use, purchase, sales, and transportation volumes on different levels. For instance, looking at the production of end products, information can be decomposed into: production per months, production per recipes, and production per locations. Looking at byproducts use, the information on total use can be decomposed into the same information as in the case of end products, and additionally into purchase volume, delivered volume, production locations and source products. Therefore, the model gives the possibility to indicate among others:

- volume of byproducts obtained from and used for the production of an end product with the use of a certain recipe, at a certain location;
- the part of the produced (used) byproduct volume that was shipped (delivered) to another location and the part that was sold (purchased) on the market;
- volume of end products sold per tranche;
- volume of input materials purchased per tranche;
- capacity use at production locations.

The results of the model were presented to and discussed with both planners and managers of FC. The valorization plan has been acknowledged not only as a realistic plan, but also as an optimal plan. This assessment was based on the experience of the FC employees and on outputs of current planning tools. It has been concluded that the DVM tool is a promising planning tool for the valorization of raw milk at FC.

2.4.2 Impact of raw milk seasonality

The comprehensiveness and functionality of the DVM can be presented by assessing the consequences of changes in various input parameters. One can conduct different analyses that would evaluate: the profitability of additional available capacities versus investment costs, consequences of possibly inaccurate sales forecasts (impact of changes in prices), and the impact of a higher or lower milk supply. We have, however, decided to investigate the impact of raw milk's seasonality, i.e. the impact of yearly variations in raw milk's dry matter, fat and protein content on the milk valorization. The project team has found this aspect as the most interesting due to following reasons: (i) production recipes are dynamic because they depend on variable milk composition, (ii) most of models available in literature do not base recipes on milk components (see Table 2.2), (iii) composition of milk changes during the year, (iv) the abolition of quota system may result in even higher variation in milk composition. The analysis presented in this section does not only illustrate the functionality of the DVM, but it also emphasizes the importance of basing production recipes on milk components.

In models that do not base recipes on the seasonal composition of milk, ratios between milk, end products, and byproducts are fixed. In reality this is not true. Therefore, construction of a scenario with fixed composition of milk results in fixed ratios. Thus, it imitates models that do not base recipes on components. The differences between a scenario with fixed composition and a scenario with seasonal composition indicates the consequences of not accounting for seasonal milk components. Consequently, to evaluate the impact of raw milk's seasonality on valorization plans, two scenarios are prepared: one scenario that incorporates seasonality of raw milk's components (S) and one scenario that excludes the seasonality of raw milk's components (NS). In the scenario S the composition of milk varies throughout the year. Here the actual percentages of raw milk components are used. In contrast, in the NS scenario the percentages of components are assumed to be constant throughout the year. These constant values are equal to the level of the yearly average of every component. Consequently the content of dry matter, fat and protein in the NS scenario is equal 13.16 %, 4.37 % and 3.51 % respectively. Furthermore, in both scenarios the possibility of selling additional volumes of commodity end products is given. Commodities are products that can be sold on an unlimited world market. The relative percentage difference is used to compare the results of both scenarios; it is calculated as (NS-S)/S. The relative percentage differences in the composition of raw milk are depicted in Figure 2.5. As we can see, in the first and last months of the year the level of components is lower in the scenario NS. This means that in these months the dry matter, fat and protein content in raw milk is higher than the yearly average.

Differences between scenarios' profit levels, byproducts' use and production, and end products' volumes are used to illustrate the impact of milk's seasonality on valorization plans. The analyses of the differences also show the large potential of the model with regard to the extraction of various information that is important for performance improvement. To allow a legible overview of results, raw milk and end products are grouped into a number of clusters. Aggregation is made based on the similarities in input materials used for the production of products. The following clusters are created:

- Caseinate(s): Caseinate Roller and Caseinate Spray;
- Cheese(s): all Foil and Nature Cheeses;
- Condensed(s): EVAP and SCM;
- CreamPowder(s): BMP and SerumPowder;
- CreamProduct(s): Butter, ButterOil and CreamProd;
- InfantPowder: IF/GUM;
- MilkPowder(s): SMP and WMP;
- Decomposition: RawMilk;
- StdMilk(s): all Standardized Milks.

As can be seen from the foregoing list, byproducts and half products are not directly assigned to clusters. The production and use volumes of byproducts per cluster are calculated based on the end product–cluster allocation. Furthermore, volumes of input materials used for the production of half products are assigned to end products, and thus to clusters, based on recipes. For instance, volume of raw milk used for the production of cheese milk, which is required to produce a certain cheese, is included in the cluster *Cheese(s)*. Moreover, the cluster *Decomposition* represents decomposed raw milk volumes as well as the resulting cream and skim milk volumes.

Relative percentage profit changes between two scenarios are depicted in Figure 2.6. One can notice that changes in profit and revenue follow a pattern that is very similar to the pattern of relative percentage changes in raw milk composition (see Figure 2.5). The profit of the scenario NS is lower in the first and last months of the year. This can be explained by the differences in raw milk composition that influence composition-based recipes. The volume of

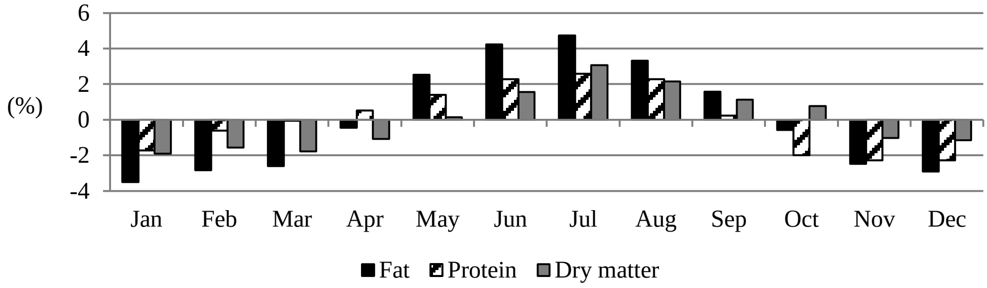

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Figure 2.5 Relative percentage changes in the content of fat, protein and dry matter in raw milk.

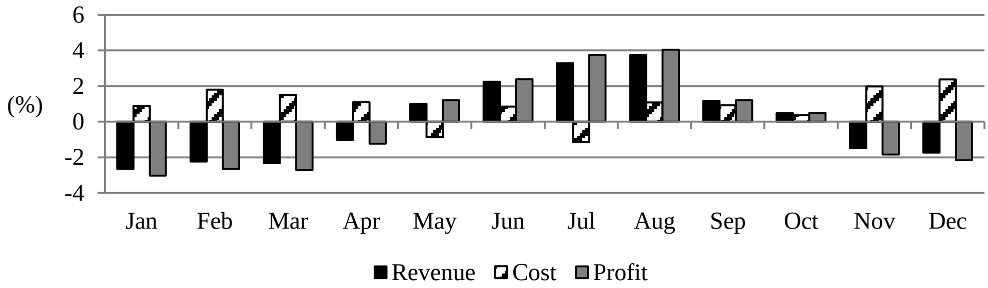


Figure 2.6 Relative percentage changes in the revenue, costs and profit between the scenario with variable composition and the scenario with fixed composition.

input material required for the production of a certain product depends on the content of dry matter, fat or protein in that end product and in all input materials. Therefore, depending on the components level in raw milk, different volumes of end products can be obtained from one ton of raw milk. For instance, the percentage difference between scenarios in the volume of milk required to produce one ton of IF/GUM product (cluster *InfantPowder*) varies between -3.0% and +1.9%. In a situation when more milk is required to produce one ton of IF/GUM, less milk is available for the production of other products, and consequently profit in this month is lower. In the first and last months of the year, components' levels in raw milk are higher than the yearly average. In these months it is possible to produce larger quantities of profitable products and therefore reach higher profits (scenario S).

The impact of seasonality is well reflected in decisions regarding the allocation of raw milk to clusters, and thus in the production of end products per cluster. In Figure 2.7 and Figure 2.8 percentage changes in raw milk allocation and end products production are presented per cluster. The shift in raw milk is reflected in the shift of end products only into two clusters, i.e. *MilkPowder(s)* and *Cheese(s)*. This means that the allocation of larger or smaller volumes of raw milk to clusters *StdMilk(s)*, *InfantPowder* and *Condensed(s)* is driven only by the change in raw milk composition and not by the profitability of products. Different raw milk compositions affect the choice of recipe that is used to produce a certain product as well as the volume of raw milk required to produce one ton of end product. The change in the allocation of raw milk to the cluster *Decomposition* is driven mainly by the end production requirement for skim milk and cream.

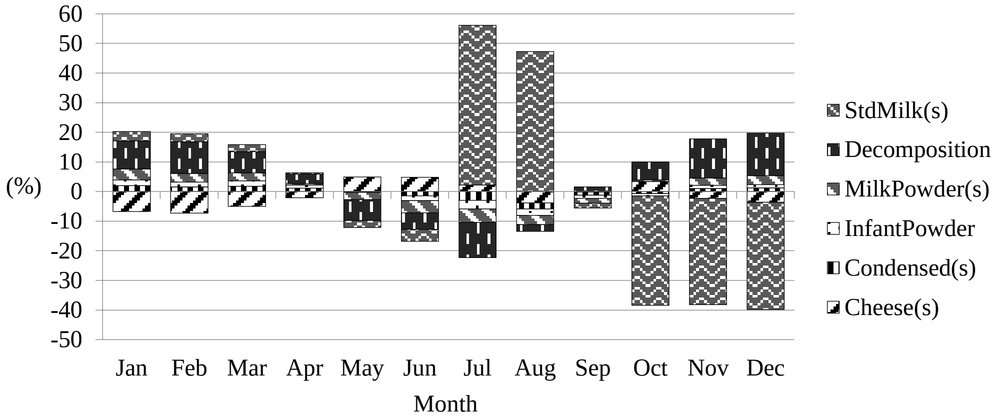


Figure 2.7 Relative percentage changes in the allocation of raw milk to clusters.

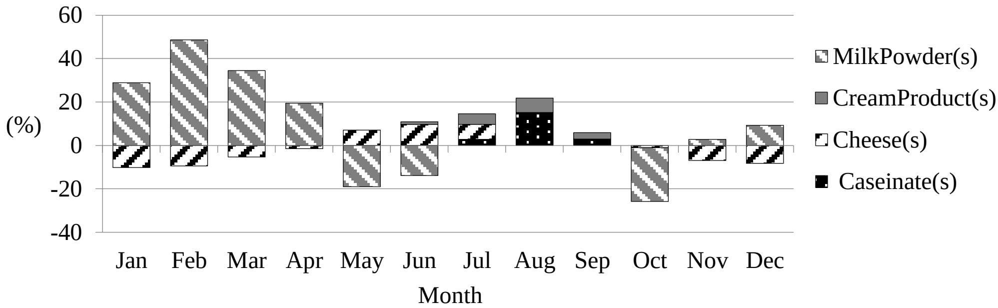


Figure 2.8 Relative percentage changes in the volume of end products produced per cluster in both analyzed scenarios.

In Figure 2.9 and Figure 2.10 relative percentage changes in skim milk and cream use and production are depicted. The differences in raw milk use in the cluster *Decomposition* (see Figure 2.7) are reflected in the production of cream and skim milk in that cluster (see Figure 2.9 and Figure 2.10). Furthermore, there is a very large percentage change in skim milk and cream use in the cluster *StdMilk(s)*, following a change in the recipe that is used to produce these end products. For instance, looking at July, much higher volumes of raw milk, and much lower volumes of cream and skim milk are used in the scenario NS to produce products in the cluster *StdMilk(s)*. In this month a recipe that uses raw milk and buttermilk is favored over a recipe that uses cream and skim milk.

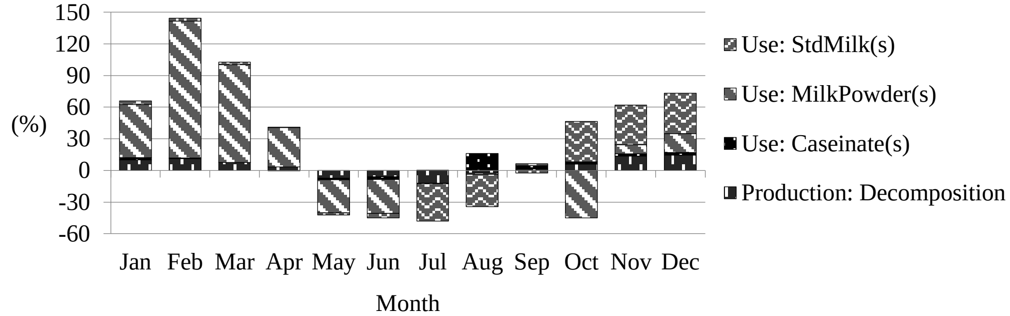


Figure 2.9 Relative percentage changes in the skim milk use and production in analyzed scenarios.

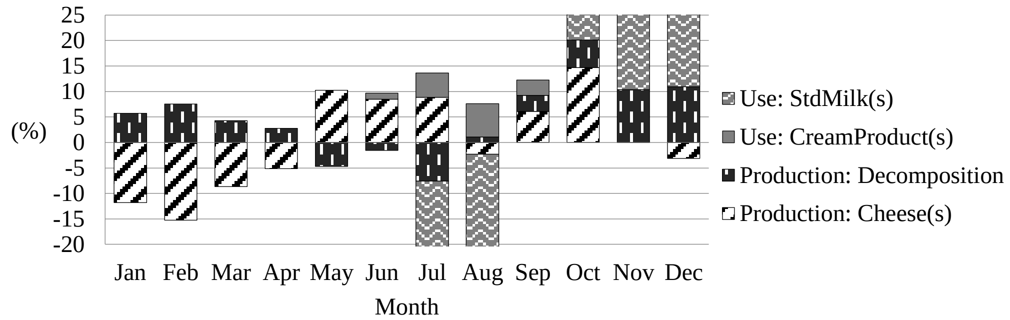


Figure 2.10 Relative percentage changes in cream use and production in analyzed scenarios.

Figure 2.8 shows that differences in end production volumes exist between clusters *Caseinate(s)*, *Cheese(s)*, *CreamProduct(s)* and *MilkPowder(s)*. Changes in these particular clusters can be explained by: the necessity to fulfill various constraints, change in products' profitability and assignment of specialties to clusters. Specialties are the products, which can be sold only as demand driven products. Consequently, from the end products perspective there is no change in produced volumes of specialties. Looking from the raw milk perspective, the change in composition has an impact only on the volume of input materials required to produce these specialties. Figure 2.8 shows that almost in all months raw milk is reallocated between the production of various cheeses (cluster *Cheese(s))* and the production of SMP (cluster *MilkPowder(s))*. A relatively small decrease in cheese production leads to a significantly large increase in SMP production. For instance looking at February, 10% lower production of cheese in the scenario NS leads to a steep 50% higher production of SMP. Given the fact that in the current data set cheese products are more profitable than milk powder products, such reallocation of raw milk has a negative impact on the overall profit of the company (see Figure 2.6). Analyses showed that, the shift in the production of cheese products and SMP is driven by the cream volume required to fulfill constraints, i.e. minimum sales of cream based end products. In other words, the volume of cream that can be obtained from one ton of raw milk allocated to the production of cheese is on average lower than the volume of cream that can be obtained from the decomposition of one ton of raw milk. Therefore, in months when production of cheese products is lower, smaller volumes of raw milk are used to produce cheeses, and thus larger volumes of raw milk are available for the decomposition. In such a way a sufficient volume of cream is obtained to produce contracted cream based products. The second residual byproduct of decomposition, i.e. skim milk is allocated to the SMP production. In months, in which the sufficient volume of cream is available in the milk system, i.e. from May to September, additional volumes of products are produced in clusters *Cheese(s)*, *CreamProduct(s)* and *Caseinate(s)*. The shift in the production of end products presented in Figure 2.8 is also reflected in the change in the raw milk composition previously presented in Figure 2.5. In months, in which the fat content of raw milk is higher than the yearly average, more cheese and cream based products are produced.

2.4.3 Managerial implications

The use of the DVM model within the company has quite some advantages. It is, however, difficult to express the added-value in monetary terms. Nevertheless, one can enumerate a number of benefits from using the model. The following managerial implications are the result of final sessions held with experts, during which outcomes of the DVM were discussed and different ways of using them to support the decision making processes within the company were indicated. First, in large companies like FC a wide range of end products is produced. Products are produced by specialized Operating Companies (OpCo) that belong to the company. One of the OpCos can for instance be responsible for cheeses production, another for powders production. Every OpCo has a certain demand for raw milk. Fulfilling demands of all OpCos might not be the most optimal solution, because no attention is paid to the resulting byproducts. Without an appropriate model it is very difficult to assess what would be the impact of fulfilling the demand of one OpCo on the production of another OpCo. A mid-term allocation and production planning model as the DVM allows to simultaneously optimizing the whole system. The inclusion of all relevant elements in the model provides necessary links between different OpCos. Second, the large amount of information explains well the dynamics and inter-relations between OpCos. This information can be used to improve the communication within the company. The central department responsible for integrated milk allocation and valorization can use the model to support their allocation decisions. Third, the information on limited production of profitable products can indicate scarce input materials or limited capacity. This can trigger changes for instance in purchase and sale strategies or in capacity investment plans. Fourth, the flexibility of the model, in terms of parameters, allows various analyses. This means that the model can be used to explore ideas or plans related to sales strategies, capacity and technology investments, and facility locations. To summarize, proper valorization plans provide managers with information necessary not only for a professional production planning, but also for an effective dairy supply chain management. The developed model is therefore a promising decision support tool.

2.5 Conclusions

In this study we have presented a comprehensive Dairy Valorization Model (DVM). The model was developed in order to improve mid-term milk valorization, which was defined as the optimal allocation of raw milk and production planning of byproducts and end products. The necessity for such a model was mainly driven by the inter-related dairy production processes that complicate the decision making related to the allocation of milk. The volatile market conditions and specific characteristics of dairy supply chains add on complexity. A comprehensive model should include all relevant elements that affect milk valorization; additionally, it should facilitate the understanding of the dynamics of dairy production thereby assisting management. A literature review showed that the following aspects should be taken into account in such a model to account for all factors affecting valorization decisions: production recipes based on raw milk composition, seasonality of raw milk supply and composition, inter-relations in production due to byproducts utilization, complete product portfolio, network of supply regions and production locations.

The model was tested at one of the world largest dairy processing companies FrieslandCampina (FC). The structure and outputs of the model were discussed during iterative sessions with relevant FC employees (dairy supply chain managers, production planners, technologists, market analysts). A number of possible benefits from using the model has been indicated at FC: (i) optimal allocation of milk, (ii) improvement of communication between central planning department and various operational units, (iii) ‘early warning’ system of upcoming developments impacting production, (iv) possibility to prepare for changing market conditions, (v) and possibility to explore ideas and plans related to investment strategies.

Although many aspects allowing for successful valorization of milk have been included in the DVM, further improvements are still possible. In the presented case study the inventory policies were already included in the input data. This could be one of the limitations of the model if one would like to directly incorporate inventory policies. Therefore, one of the possible model extensions would be the inclusion of inventory management options. Further, all parameters in our model are treated as deterministic. Given the fluctuations in a supply and demand, especially for more than 6 months in the future, one might consider using stochastic methods to model related input parameters. Moreover, in this study we incorporated only two types of whey (cheese whey and casein whey). Given the fact that cheeses constitute a large part of every dairy processing company product portfolio, and thus large volumes of the whey byproduct are obtained, a detailed investigation of whey post-processing might further contribute to a better valorization of raw milk. Finally, the presented work does not incorporate analyses on the robustness of valorization plans. Outcomes of such a study would indicate elements with the highest impact on valorization plans.

Chapter 3

Effect and key factors of byproducts valorization: the case of dairy industry

This chapter is based on the following journal paper:

Banaszewska, A., Cruijssen, F., Claassen, G.D.H. and van der Vorst, J.G.A.J., 2014. *Effect and key factors of byproducts valorization*: *The case of dairy industry*. Journal of Dairy Science, 97(4): 1893-1908.

Abstract

Production of many consumer products results in byproducts that often contain a considerably large part of nutrients originating from input materials. High production volumes, environmental impact, and nutritional content of byproducts make them an important subject for careful valorization. Valorization allows exploring the possibility of reusing nutrients in the production of main products, and thus highlights the potential gains that can be achieved. The main aim of this study was to evaluate the added-value of cheese whey valorization, and to determine the effect of integral valorization of main products and byproducts on the profit of a dairy processing company. A number of scenarios and cases were implemented and analyzed using a decision support tool, the Integral Dairy Valorization Model. Data originated from the international dairy processing company FrieslandCampina. The outcomes of scenarios were analyzed with regard to profit and shifts in the production of non-whey end products, and were validated by company experts. Modeling results showed that the valorization of byproducts is very profitable (24.3% more profit). Furthermore, additional profit can be achieved when two valorization processes (main products and byproducts) are integrated. This impact is however considerably affected by current capacity and market demand limitations. Significant benefits can be created if demand of whey-based products is increased by 25%.

3.1 Introduction

As the global population is growing, significantly more food is needed to feed the world. This can partially be realized by increasing farm production levels. It might be however more effective to reduce food waste in supply chains. Recent studies of the Food and Agriculture Organization of the United Nations (Gustavsson et al., 2011) estimate that globally 40-50% of fruits and vegetables, 20% of meat and dairy, and 30% of fish are wasted. This creates an enormous waste of resources and calls for research to reduce the problem.

Food waste is food that is discarded or lost uneaten. Food wastes take place at production, post-harvest and processing stages in the food supply chain (Parfitt et al., 2010). While in most European legislations production residues are defined as wastes, scientists who investigate potentials of reusing food wastes define them as food byproducts (Galanakis, 2012). In this paper we investigate byproducts valorization in the milk processing industry. Valorization is defined as the optimal post-processing of byproducts incorporated in the production of main milk products. Different ways of byproducts valorization have been investigated in various industries, e.g.: citruses, fish, meat, cereals, roots and tubers, oil crops, and dairy (see Table 3.1 for references). Most of these studies are focused on biotechnological developments, and investigate the possibility of extracting various nutrients from byproducts and the possibility of using (parts of) byproducts in the production of end products. The main objective is usually to decrease the environmental impact and to reduce costs related to byproducts processing technology (Galanakis, 2012; Mollea et al., 2013). While biology and technology aspects are better studied, to the best of our knowledge there are no studies that evaluate the overall economic effect of post-processing of byproducts on a food processing company (see Table 3.1). The maximization of food processing company profitability, especially if companies reuse their own byproducts in the production of their end products, is not a key aspect of these studies. Furthermore, the effect of biotechnological developments in extracting and re-using nutrients contained in byproducts on the valorization of main products was also not investigated.

In this paper, we focused on the dairy industry and analyzed the effect of byproducts valorization on the overall valorization of raw milk. We investigate how different levels of valorization of byproducts affect production planning decisions related to main end products and the resulting profit of a processing company. To evaluate the effect of byproducts valorization we use the biggest byproduct of the dairy industry - whey (Koutinas et al., 2009) - as a case study. The dairy industry is focused on maximizing the value of all nutrients contained in the main raw material; that is, raw milk. Byproducts contain various valuable nutrients; thus, their re-use in the production process allows efficient exploitation of all nutrients available in raw milk. Constant developments in science and technology enable the production of sophisticated dairy products (FAO, 2009). However, this implies that the processing of dairy products becomes a complex network of interrelated production processes.

Table 3.1 Literature on the valorization of byproducts (adapted from Galanakis (2012))

Byproduct	References	Objective of the valorization
Citruses (e.g. orange peel as a byproduct of orange)	Chedea et al. (2010)	Characterization of carotenoid pattern in two varieties of orange waste (Valencia and Navel) using different analytical methods
	Farhat et al. (2011)	Optimization of operating conditions for the optimal extraction time of essential oil from orange peel.
Fish (e.g. fish leftovers)	Gehring et al. (2011)	Review of Isoelectric solubilisation/precipitation (ISP) developments to recover proteins and lipids from fish byproducts
Meat (e.g. bovine blood as a byproduct of bovine production)	Darine et al. (2010)	Investigation of protein recovery and physicochemical properties of meat protein concentrates from beef lungs
Cereals (e.g. bran and straw as a byproducts of wheat)	Sun and Tomkinson (2002)	Investigation of the extractability of the wheat straw hemicelluloses using extraction method with and without application of ultrasonic irradiation
	Hollmann and Lindhauer (2005)	Development of an economically viable procedure for the isolation of the glucuronoarabinoxylans from wheat bran
Oil crops (e.g. olive pomace and wastewater as a byproduct of olive production)	Yang et al. (2010)	Investigation of a catalytic decomposition and effects of different solvents on the purity and yield of recover phytosterols from the waste residue of soybean oil deodorizer distillate
	Galanakis (2011)	Review of the compositional and structural characterization of olive dietary fiber, the modifications during olive fruit ripening and processing, the recovery and potential applications of dietary fiber from olive byproducts
Dairy (e.g. whey as byproduct of cheese production)	Koutinas et al. (2009)	Development of an integrated technology for starter culture production from whey for use in cheese ripening
	Guimarães et al. (2010)	Review of fermentation of lactose to ethanol with the focus on wild lactose-fermenting yeasts
	Patel and Murthy (2011)	Investigation of the recovery of lactose from partially deproteinated whey by the use of an anti-solvent
	Prazeres et al. (2012)	Review of four main cheese whey management practices: biological treatments without valorization, biological treatments with valorization, physicochemical treatments and direct land application

Often production of a certain dairy product results in an additional residual dairy flow - a byproduct. For instance, production of cheese results in additional production of whey and cream; production of butter results in additional buttermilk; and production of butter oil results in additional cream serum (see Figure 3.1).

We chose whey byproduct as the subject of this study for 3 main reasons:

1) *The high nutritional content of whey*. Whey is a byproduct of caseinate and cheese manufacturing, although cheese production is its major source (FAO, 2009). During the cheese production process, the fat and casein proteins in raw milk are aggregated into a curd, and the soluble whey proteins, lactose and minerals are contained in whey (González-Martínez et al., 2002). As much as 55% of the total milk nutrients (lactose, hydrosoluble minerals, vitamins and 20% of milk proteins) are retained in whey (González-Martínez et al., 2002; Panesar et al., 2007; Smithers, 2008).
2) *The high environmental impact*. The lactose part of whey, which amounts to 75% of the total whey solids, qualifies whey as a highly polluting product (González-Martínez et al., 2002; Marwaha and Kennedy, 1988; Smithers, 2008). The disposal of whey causes major environmental problems, because it affects the physical and chemical structure of soil (Gonzalez-Siso, 1996; Koutinas et al., 2009; Marwaha and Kennedy, 1988). In fact, whey is considered one of the most polluting food byproduct streams (Gonzalez-Siso, 1996). However, given developments in chemistry and technology, the protein and peptide part of whey protein makes it a potential raw material for the production of various high value products in the agri-food, biotechnology, and pharmaceutical industry (Cuartas-Uribe et al., 2009; Koutinas et al., 2009; Panesar et al., 2007; Smithers, 2008). The lactose part of whey found its application in the production of main dairy products. Lactose is often used to standardize protein levels in milk end products (see Figure 3.1).
3) *The high production volume of whey*. A schematic representation of the increase in value of whey products over the last 60 years is presented in Figure 3.2. It is therefore known which gains could be obtained from transforming whey byproducts into whey-based end products. The interesting question, however, is whether the incorporation of whey valorization affects profit and production of residual non-whey products. For instance, does the production of whey-based products affect produced volumes of cheese? A decision to increase cheese production might be taken in a situation when profit margins of whey end products are high enough.

   Russ and Meyer-Pittroff (2004) estimated a specific waste index that is a ratio of the mass accumulated in waste to the mass of an end product. The authors showed that, depending on the type of cheese, the cheese whey index lies between 4 and 11.3, which is high compared with waste indexes in other industries (i.e., between 0.001 and 0.87). Furthermore, over one third (35%) of worldwide supplied milk is processed into cheese (FAO, 2009). The outlook for production in 2025 indicates an increase of cheese production of 24% in the European Union (Figure 3.3) and 32% worldwide (FAPRI, 2012). Therefore, whey production will also increase.

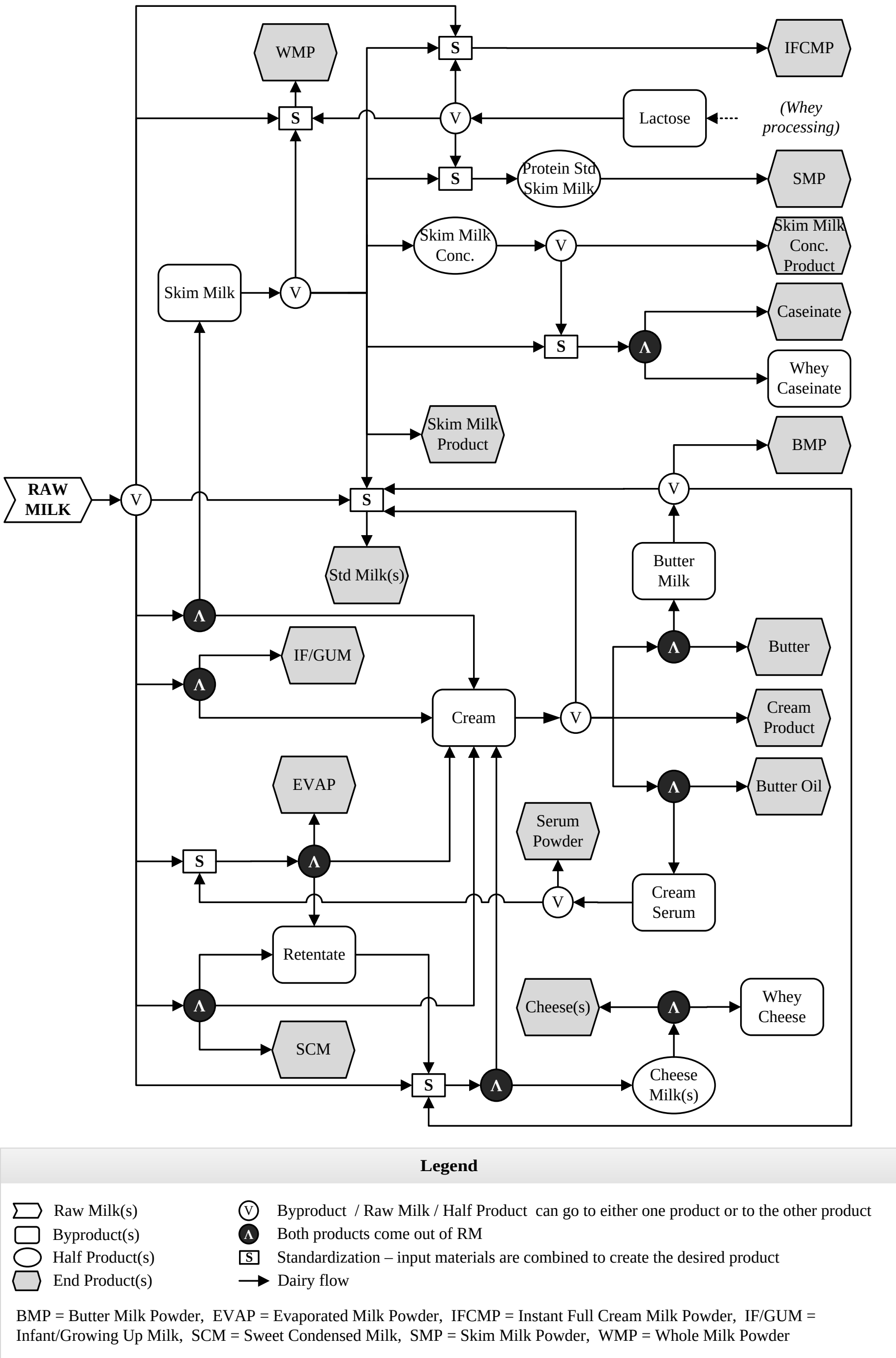


Figure 3.1 Schematic representation of dairy flows (adapted from Banaszewska et al. (2013)).

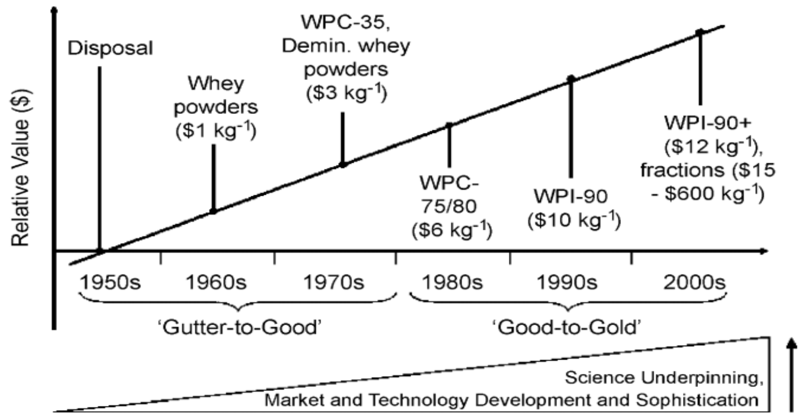


Figure 3.2 Schematic representation of the relative change in the value of whey products. WPC = Whey Protein Concentrates, WPI = Whey Protein Isolates (Smithers, 2008).

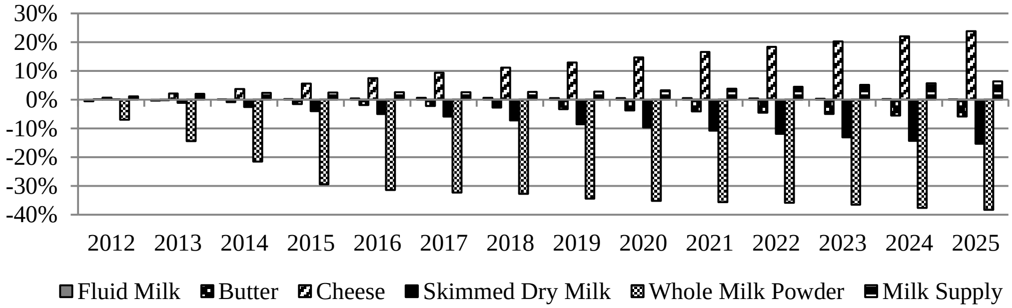


Figure 3.3 Relative percentage changes in the expected dairy production and milk supply in the European Union. Year 2011 used as a base year (FAPRI, 2012).

The high production of whey, its high environmental impact, and its high nutritional content indicate that this byproduct is an important byproduct for which careful valorization is important. The aim of this study is to evaluate the effect of whey valorization on the overall valorization of raw milk. Two valorization techniques were employed and compared: a traditional milk valorization and subsequent separate whey valorization (as now applied in practice to some extent), and an integral valorization (integrated non-whey and whey valorization). The integral valorization is a new approach to valorize milk and whey products in practice. To attain the research aim, we posed 4 questions. First, what is the added value of the whey valorization (i.e., gain in profit)? Second, what is the overall added value of the integral valorization? Third, which input parameters drive the effect of the integral valorization (e.g., prices, demand, capacities)? Fourth, given the highly interrelated production of dairy products, does the integration of the valorization of milk and whey products affect the choice of milk end products to be produced?

3.2 Materials and methods

To evaluate the effect of whey valorization on the overall valorization, we used the Integral Dairy Valorization Model (IDVM), an amended version of the Dairy Valorization Model developed by Banaszewska et al. (2013). The data used for scenario analyses were collected at FrieslandCampina (FC), which is one of the largest dairy companies in the world.

3.2.1 Dairy Valorization Model and Integral Dairy Valorization Model

The DVM is a linear programming model designed to create mid-term valorization plans. The supplied raw milk is allocated to a wide range of dairy products. The products are divided into 4 categories: (1) raw milks, (2) byproducts (products additionally obtained while producing main products and decomposing raw milks), (3) half products (products produced to be used in the production of end products; an intermediate step in the production that is necessary to obtain final end products), and (4) end products (products that are not reused in the production of other products, but are only sold on the market). The assignment of products to the enumerated categories is not always straightforward. Some byproducts such as skim milk and cream can also be perceived as half-products, as they are often intentionally produced to obtain input for the production of main end products. For instance, decomposition of milk is carried out to obtain skim milk and cream. These are usually high-value byproducts. However, in this study, we focused on the valorization of low-value byproducts such as whey.

The DVM maximizes the profit of a producer while accounting for all important constraints. The objective function is the maximization of the difference between the revenue from sales and various costs (production, transport, and purchase). The following constraints are incorporated in the model:

a) Capacities – ensures that amount of capacity of a certain resource used does not exceed the available capacity;
b) Supply of raw milk – ensures that all milk supplied to a producer is either processed into end products or sold directly on the market;
c) Total sales – ensures that total sales of a product do not exceed maximum allowed sales volumes (often limited by contracts or market capacity);
d) Sales and purchase per tranche – ensures that amount of a product sold (purchased) for a certain price does not exceed the maximum sales (purchase) volume assigned to a tranche. A tranche indicates the maximum sales (purchase) volume of a product that can be sold (purchased) for a specific tranche-dependent price;
e) Recipes – maintains the correct relation between the volume of a product produced, the volume of an input material required and the volume of a byproduct obtained;
f) Composition balance – ensures that total volume of dry matter / fat / protein contained in input materials used for a production of a certain product equals the volume of that component present in production's outputs (desired product and byproducts);

g) Inflow volumes – ensures that the volume of a certain material used for a production at a certain location equals the sum of the volume of that material delivered from other locations and the volume purchased on the market;

h) Outflow volumes – ensures that the volume of a certain product produced at a certain location equals the sum of the volume of that product transported to other locations and the volume sold on the market.

Banaszewska et al. (2013) showed that the developed DVM represents the dairy system well when whey processing is not included. To incorporate all whey streams and accomplish the integral valorization, the original DVM was slightly amended, which resulted in the IDVM. The main implications relate to the use of production resources by half and end products, and to the lactose component. The investigation of whey production processes indicated the possibility of producing a certain product at a certain location with multiple production resources. In the DVM it is assumed that each product uses one production resource at a certain location. Consequently, in the IDVM, in the constraints related to capacities, recipes, outflow volumes, and in the objective function, the variable $Xprod_{(t,d,d',i,l)}$ representing the volume of a product d obtained from the production of a product d' with a recipe *i* at a location *l* in a time period *t*, was replaced with $\sum_r Xprod_{(t,d,d',i,r,l)}$ for $d = d'$ and $d \in E \cup H$, where *r* indicates a production resource, *E* set of end products, and *H* set of half products. In constraints related to composition balance, the following changes were made: $\sum_{d \in D \setminus M} Y_{(t,d)} \cdot Xprod_{(t,d,d',i,l)}$ is replaced with:

$$\sum_b Y_{(t,b)} \cdot Xprod_{(t,b,d',i,l)} + \sum_{d \in E \cup H, d=d'} Y_{(t,d)} \cdot \sum_r Xprod_{(t,d,d',i,r,l)},$$

where *Y* = fat, protein or dry matter component, and *b* = a byproduct. The first term of the equation indicates the volume of a component present in byproducts obtained while producing the main product *d'*. The second term indicates the volume of a component present in that main product. Furthermore, since whey products are rich in lactose and, in the DVM, only protein, fat and dry matter components were considered, an additional parameter representing lactose content in a product ($Lac_{(t,d)}$) was added to the IDVM. Moreover, a composition balance constraint related to lactose was also added:

$$\sum_{d \in D \setminus E} Lac_{(t,d)} \cdot Xuse_{(t,d,d',i,l)} = \sum_b Lac_{(t,b)} \cdot Xprod_{(t,b,d',i,l)} + \sum_{d \in E \cup H, d=d'} Lac_{(t,d)} \cdot \sum_r Xprod_{(t,d,d',i,r,l)} + Wlac_{(t,d',i,l')}$$

for $d' \in D \setminus B$ and $\forall d' i, l', t$.

3.2.2 Data collection and results validation

Input data necessary for the study (i.e., recipes, composition, whey markets, production costs, production rates, new capacities, and interrelations between products) were collected at FC. Because data were coming from multiple sources at the company, they were verified during multiple individual and group interviews before being entered into the model. Interviews were held with relevant FC employees, including dairy supply chain manager, technologists, financial employees and the whey valorization planner. Additionally, early

3

outputs of the model and findings were discussed in multiple workshops with company experts to verify whether obtained results were realistic and whether all data were correct.

3.2.3 Evaluation approach

To evaluate the effect of whey valorization and integral valorization on the company performance, the analysis was performed in 2 steps. In the first step (the base scenario analysis), the IDVM was run with the input data representing the production, supply and market situation in 2011. In the second step (the sensitivity analysis), multiple scenarios were defined and run to confirm and refine the conclusions obtained in the first step analysis. In every scenario, values of certain input parameters were altered. To conduct one full scenario analysis, the model had to be run for 3 different cases (see Figure 3.4 for a schematic overview of the analysis approach). In the first case, only the valorization of non-whey dairy products was allowed, called the non-whey valorization (*NW*) case. These are the products included in the study of Banaszewska et al. (2013). In the second case, called the stepwise valorization (*SW*) case, the production levels of non-whey based products were set to the optimal production levels as found in the first case, and additionally the valorization of whey products was allowed. The stepwise valorization represents the situation when the decision on the production of non-whey products does not depend on the possibilities of further processing of whey byproducts. In the third case, called the integral valorization (*Int*) case, all products were valorized at the same time. To summarize, the full analysis of each scenario required 3 model runs, each run relating to a specific case: *NW*, *SW*, or *Int*.

The evaluation of the effect of integral valorization was based on 2 measures: profit and end production volumes. Both measures were expressed as differences between *Int* and *SW* cases. The comparison of the profit of *Int* and *SW* cases indicates the gain that companies achieve by integrating whey valorization into the first step of the milk valorization process. The comparison of production levels of *Int* and *SW* cases indicates the effect of whey valorization on the production of non-whey end products.

3.3 Results and discussion

The effect of whey valorization and the integral valorization were analyzed in detail and presented based on the case study of FrieslandCampina (FC). The analysis of the base scenario for all 3 cases provided a good insight into gains that FC could currently achieve from the valorization of byproducts and from the integration of both valorization processes. To answer the third research question (i.e., to identify input parameters that drive the effect of the integral valorization), sensitivity analysis was conducted on the main constraints. Particular emphasis was placed on the analysis of the effect of integral valorization, because experts from practice expect high gains from the integration of both valorization processes.

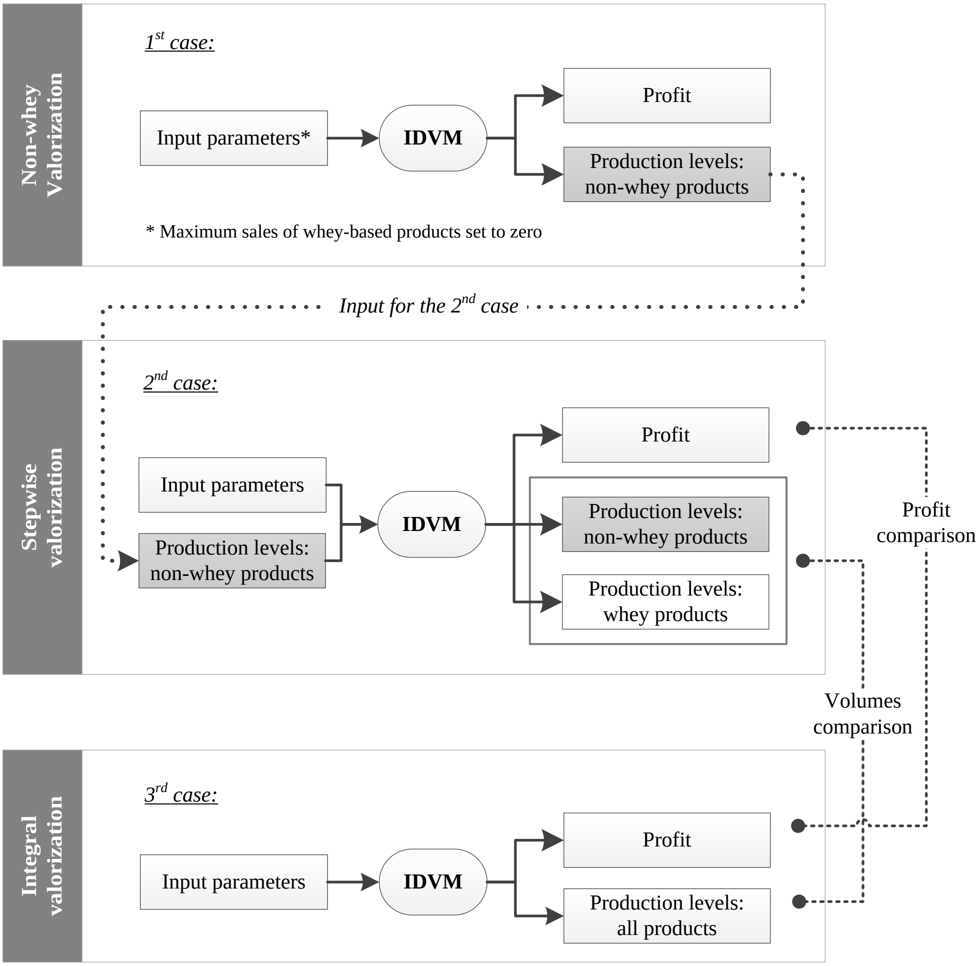


Figure 3.4 Analysis approach used to evaluate the effect of whey valorization on the overall valorization. IDVM = Integral Dairy Valorization Model.

To conduct analyses, several scenarios were defined and built into the Integral Dairy Valorization Model (IDVM). All scenario runs were conducted with the use of the optimization software package called AIMMS 3.12 (Paragon Decision Technology B.V., Haarlem, the Netherlands). The results of the analyses are presented below.

3.3.1 Input data of the case study

The original product portfolio used by Banaszewska et al. (2013) to valorize raw milk was extended with whey products. The set of representative whey products was identified based on the investigation of the whey product portfolio of the stakeholder FC. The list of whey-based end products included in analyses is provided in Table 3.2. The flow diagram of all whey-based dairies is depicted in Figure 3.5.

Table 3.2 Whey-based end products included in the Integral Dairy Valorization Model

Product full name	Abbreviation
Demineralized Whey Powder 50	DWP50
Demineralized Whey Powder 90	DWP90
Delactosed Permeate Powder	DLP
Whey Protein Concentrate 30	WPC30
Galacto-oligosaccharides Product	GOS
Hiprotal30[1]	-
Hiprotal35	-
Hiprotal35BL	-
Hiprotal45_EP	-
Hiprotal60MP	-
Hiprotal75BL	-
Hiprotal80BL	-
Protein Rich Cheese Whey Fat Powder Type I / Type II / Type III	PRChWFP (I) / (II) / (III)
Protein Rich Casein Whey Powder	PRCaWP
Protein Rich Cheese Whey Powder	PRChWP
Permeate Powder Casein	PPCasein
Permeate Powder Cheese	PPCheese
Vivinal Alpha[2]	-
Whey Powder Feed	-
Whey Powder Food	-
Whey Protein Concentrate 80	WPC80

[1] Hiprotal X – special types of whey protein concentrate products, where X indicates product specific percentage of contained whey protein. BL indicate products rich in beta-lacroglobulin.
[2] Vivinal Alpha - a whey protein concentrate product rich in alpha-lactalbumin

The original product IF/GUM included in the DVM was split into 2 end products in the IDVM: Infant Formula (IF) and Growing Up Milk (GUM). The inclusion of whey-based products in the IDVM allowed for the better representation of IF and GUM production recipes, which incorporate the use of 3 different whey-based products. More detailed representation of production processes revealed considerable differences between the recipes of those end products, and thus we decided to split IF/GUM into 2 products.

It is important to note that IF and GUM products use, as input, raw milk and whey-related inputs (Figure 3.5), and thus they can be treated as either non-whey or whey end products, and can be either valorized in the *NW* or the *SW* case. We decided to treat those products as non-whey products because, in practice, the decision on production levels of IF and GUM does not depend on the valorization of whey-based products. In reality, because of high profitability, IF and GUM products are always produced in the highest possible volumes. To allow the production of GUM and IF in the *NW* case (only), their recipes were adjusted; that is, we assumed that only raw milk was used as input, and production costs were increased by the production costs of whey-based inputs. Another assumption was also made on the source cost of Lactose in *NW* cases. In these cases Lactose can be sourced only from the spot market for a high purchase price (mean of €1,438/t), whereas in reality (with the current demand and production capacities), all Lactose is sourced internally from the production of other products. To enable realistic decision making on the optimal production levels of non-whey products using Lactose as input (i.e., Instant Full Cream Milk Powder/Whole Milk Powder/Skim Milk Powder, IFCMP/WMP/WMP), another purchase tranche of Lactose was introduced in the *NW* cases only. The purchase price was equal to the internal cost price of Lactose, and the maximum purchase volume was set to the optimal production level of Lactose, as indicated in the *Int* case of the base scenario. Lactose necessary to produce IFCMP/SMP/WMP in the *SW* cases came from the internal production. Even without the additional assumption on the purchase of Lactose, no differences in the production volumes of IFCMP/WMP/SMP products between *Int* and *SW* cases were observed in the base scenario. Therefore, the effect of the integrated model is not affected. However, comparison of the *SW* and *NW* cases (i.e., the effect of the whey valorization) becomes more realistic, because costs in *NW* cases are much lower due to the lower sourcing cost of Lactose.

3.3.2 First step analysis: base scenario

Three main outcomes of all valorization plans were analyzed: profit, produced end product volumes, and market and capacity limitations. Because of data confidentiality percentage differences in profit were analyzed instead of absolute differences. Before moving to the results of the integral analyses, we first assessed the effect of whey valorization; that is, the overall additional profit dairy companies can reach by explicitly valorizing the whey byproduct.

Differences in profit

Profit percentage differences between the stepwise (*SW*) and non-whey (*NW*) cases of the base scenario are shown in Figure 3.6. On average, the percentage difference in profit amounted to 25.5% per month. The total profit from processing whey byproducts amounted to 24.3% of the profit obtained from producing milk based products. This is a considerable gain for the company, but also a gain for the environment, because disposing of the whey byproduct becomes unprofitable.

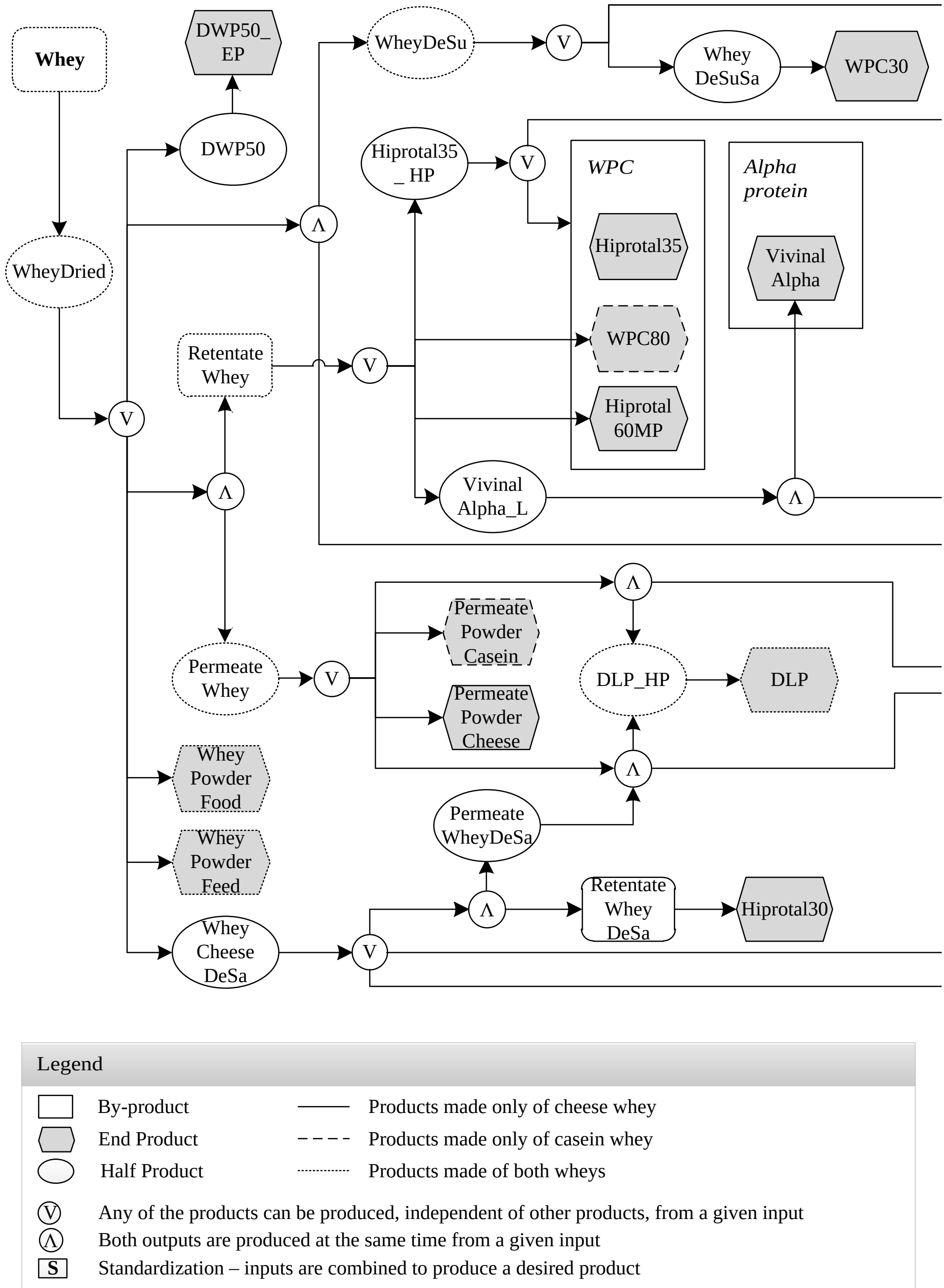
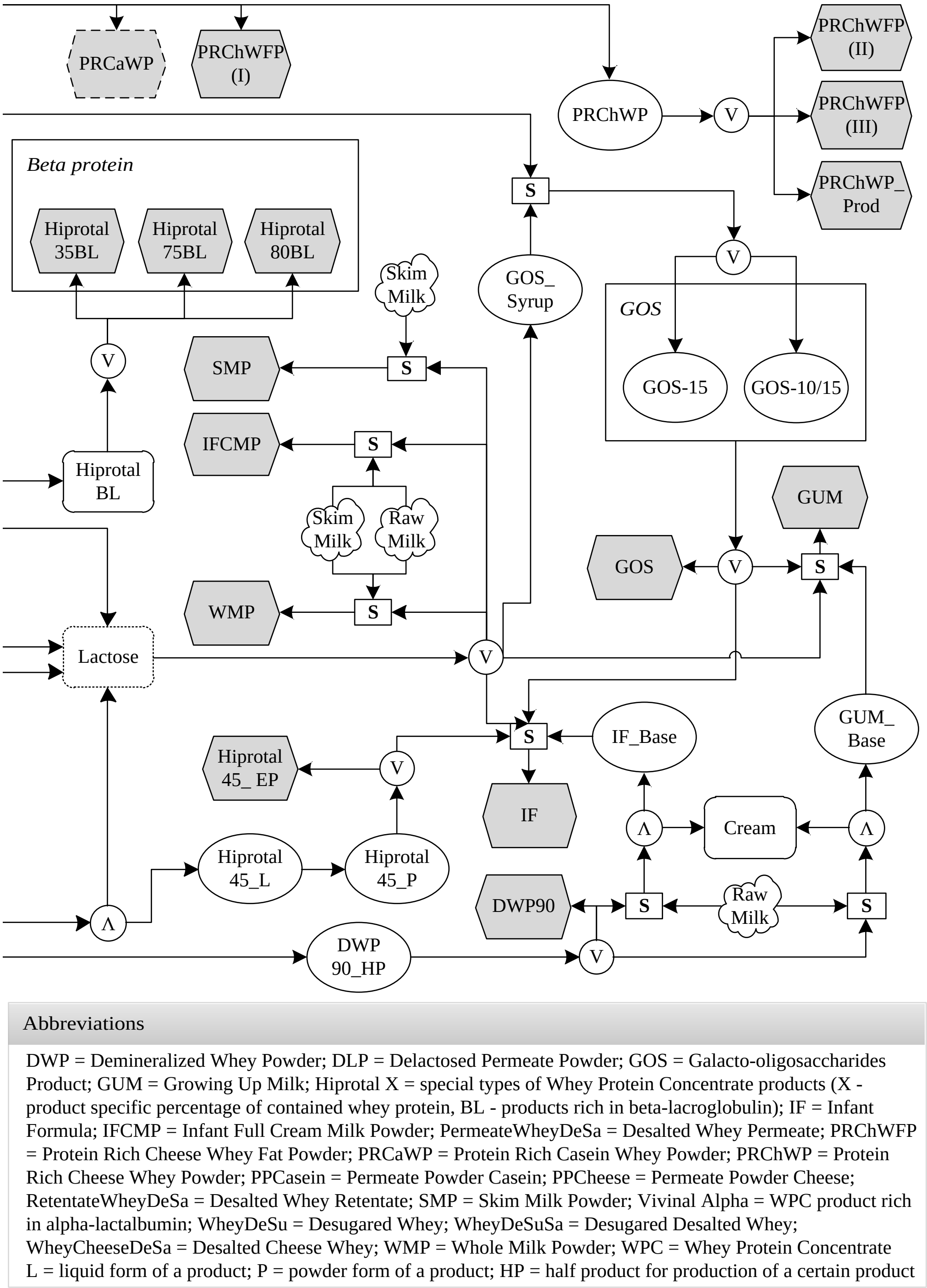


Figure 3.5 Flow diagram of all whey-based diaries.


PRCaWP
PRChWFP (I)
PRChWP
V
PRChWFP (II)
PRChWFP (III)
PRChWP_ Prod
Beta protein
Hiprotal 35BL
Hiprotal 75BL
Hiprotal 80BL
S
GOS_ Syrup
Skim Milk
V
GOS
GOS-15
GOS-10/15
SMP
S
IFCMP
S
Skim Milk
Raw Milk
GUM
Hiprotal BL
GOS
V
S
WMP
S
Lactose
V
S
IF_Base
GUM_ Base
Hiprotal 45_ EP
V
IF
Λ
Cream
Λ
Hiprotal 45_L
Hiprotal 45_P
DWP90
S
Raw Milk
S
Λ
DWP 90_HP
V

Abbreviations
DWP = Demineralized Whey Powder; DLP = Delactosed Permeate Powder; GOS = Galacto-oligosaccharides Product; GUM = Growing Up Milk; Hiprotal X = special types of Whey Protein Concentrate products (X - product specific percentage of contained whey protein, BL - products rich in beta-lacroglobulin); IF = Infant Formula; IFCMP = Infant Full Cream Milk Powder; PermeateWheyDeSa = Desalted Whey Permeate; PRChWFP = Protein Rich Cheese Whey Fat Powder; PRCaWP = Protein Rich Casein Whey Powder; PRChWP = Protein Rich Cheese Whey Powder; PPCasein = Permeate Powder Casein; PPCheese = Permeate Powder Cheese; RetentateWheyDeSa = Desalted Whey Retentate; SMP = Skim Milk Powder; Vivinal Alpha = WPC product rich in alpha-lactalbumin; WheyDeSu = Desugared Whey; WheyDeSuSa = Desugared Desalted Whey; WheyCheeseDeSa = Desalted Cheese Whey; WMP = Whole Milk Powder; WPC = Whey Protein Concentrate
L = liquid form of a product; P = powder form of a product; HP = half product for production of a certain product

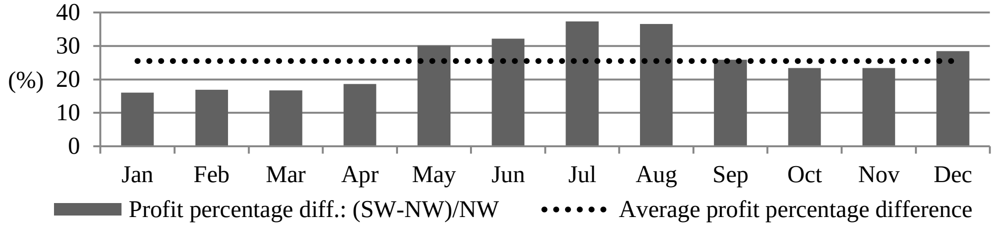
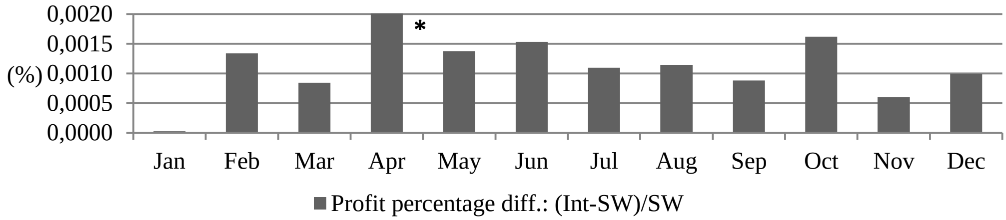


Figure 3.6 Percentage differences in profit between stepwise valorization (*SW*) and non-whey valorization (*NW*) cases of the base scenario.

Figure 3.7 depicts the percentage differences in profit when the integral valorization is applied; that is, the percentage differences between the *Int* and *SW* cases of the base scenario. On average, they amounted to 0.0089% per month. Only in April was the difference higher (i.e., around 0.095%), because of the small difference in the sale prices of IFCMP and Cheese(s) in that month. From a profit perspective, we may conclude that the integral valorization has either a small effect or that in the current settings the dairy system was too restricted by various constraints, and thus there was no room for extra valorization.

3



* Percentage difference in April reached 0.095%

Figure 3.7 Percentage differences in profit between integral valorization (*Int*) and stepwise valorization (*SW*) cases of the base scenario.

Additionally, we analyzed whether patterns of profit (percentage) differences between *SW* and *NW* cases, and between *Int* and *SW* cases follow the seasonality pattern of raw milk. We concluded that the similarities in these patterns were not strong enough to assume well-founded coherency. The analysis was based only on the 2011 data, perhaps additional analysis of patterns from previous years would allow for a stronger conclusion.

Shifts in production planning

Differences in the produced volumes of end products between *Int* and *SW* cases of the base scenario are presented in Figure 3.8. As can be seen from Figure 3.8, in the integral valorization, a shift occurred from the production of Cheese Nature to the IFCMP/WMP products. This can be explained by the relation between the prices of those products.

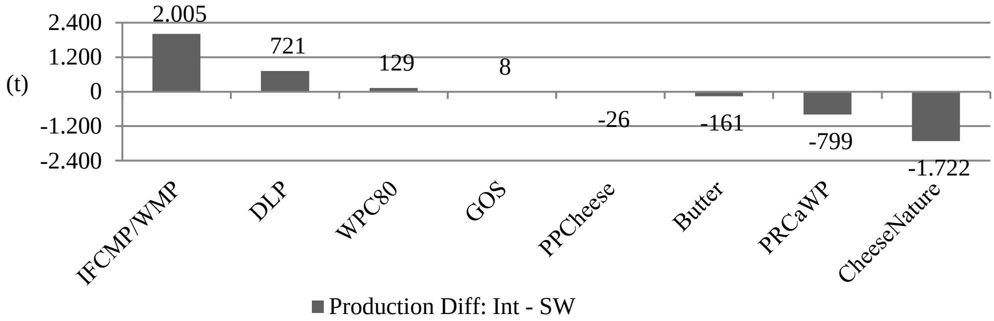


Figure 3.8 Yearly differences in volumes of produced end products between integral valorization (*Int*) and stepwise valorization (*SW*) according to the base scenario. IFCMP/WMP = Instant Full Cream Milk Powder / Whole Milk Powder, DLP = Delactosed Permeate Powder, WPC80 = Whey Protein Concentrate 80, GOS = Galacto-oligosaccharides Powder, PPCheese = Permeate Powder Cheese.

The sale price of Nature Cheese was, in all months but April, €501/t higher, on average, than the prices of IFCMP/WMP. In April, however, the price of Nature Cheese was €10/t lower. Consequently, in the *Int* case profit obtained from 1 ton of Raw Milk used for the production of Nature Cheese was lower than the profit obtained from 1 ton of Raw Milk allocated to IFCMP/WMP production. This situation occurred only in the *Int* case because in the *SW* case, the possibility of internally obtaining Lactose (the input for IFCMP/WMP) was not apparent. Therefore, the decision to switch from the production of Nature Cheese to IFCMP/WMP was not made, because the high production costs (cost of inputs) of IFCMP/WMP negatively affected the profit margin. This switch was made in the *Int* valorization, because the possibility of obtaining Lactose internally was apparent, and therefore each ton of Raw Milk allocated to IFCMP/WMP valorized better than the ton of Raw Milk allocated to Cheese Nature. Differences in the production of residual products visible in Figure 3.8 are linked to the switch from the production of Cheese Nature to IFCMP/WMP and the consequent internal demand for Lactose. We refer the reader to Figure 3.5 to better understand the relations between shifts in production. Consequently, in the *Int* case the model re-allocated Whey Caseinate from Protein Reach Casein Whey Powder (PRCaWP) to Whey Protein Concentrate 80 (WPC80), because the production of WPC80 allows higher production of Delactosed Permeate Powder (DLP) that is driven by the Lactose requirement. Therefore, in the *Int* case we produced less PRCaWP, but more WPC80 and DLP. Furthermore, lower volumes of Permeate Powder Cheese (PPCheese) were produced. This is because the main input of the PPCheese production (i.e., Permeate Whey Cheese) was re-allocated from PPCheese to the production of DLP, again in order to obtain higher volumes of Lactose required for the higher production of IFCMP/WMP.

Lack of the increase in the production of Cheese and Caseinate (source of casein whey) in the *Int* case indicates that the production of whey-based products was not profitable enough to increase the production of Cheese and Caseinate. However, the limitations of the current system caused by various constraints (e.g., capacities, market) may affect this conclusion. To investigate this, we analyzed the numbers of months in which whey-based end products reached full production or market capacity. The results showed that the production of all 23 whey-based products was restricted to a certain extent, and that 17 products were limited in more than 10 months by either or both limitations. We can therefore state that the production of whey-based end products is highly restricted. If whey-based products are profitable enough to increase the production of Cheese, the limiting capacities will not allow for the additional production of whey-based products. It is therefore possible that the effect of the integral valorization would be higher if more production or market capacities were available.

The outcomes of the base scenario analysis revealed 4 main factors that might influence the level of effect of integral valorization: production capacities and 3 market related factors (sale prices, purchase prices and market demand). In particular changes in the enumerated factors of the following products may have a significant impact: Whey Cheese, Whey Casein, Lactose, Cheeses, Caseinates, IFCMP, WMP, SMP, IF, and GUM. The first 3 products listed are byproducts produced during the valorization of non-whey products and used for the valorization of whey products, or vice versa. The first 2 byproducts are byproducts of Cheeses and Caseinates obtained during the non-whey valorization. These byproducts can be processed into whey-based products or can be sold on a market; direct sales, however, are less profitable than the post-processing. The profitability level of whey-based products may therefore affect the production levels of Cheeses and Caseinates. Given the inter-relations in the production of dairy products (Figure 3.1), changes in the production of Cheeses and Caseinates will affect production levels of other products. The third byproduct – Lactose – can be obtained only during the valorization of whey-based products, but it can be used for the production of both whey and non-whey products. It can also be purchased on the market, but the purchase price is much higher than the costs of internal sourcing and processing of related whey flows (production of Lactose requires production of other whey-based products). The non-whey end products that use Lactose as an input are IFCMP, WMP, SMP, IF, and GUM. Depending on the cost of Lactose and on the sale prices of those end products, additional gain could be achieved.

3.3.3 Second step analysis: sensitivity of results

To confirm the conclusions drawn from the base scenario analysis and identify factors that have the greatest impact on the effect of integral valorization, additional scenarios were defined (see Table 3.3). The first scenario represented the base scenario, against which all residual scenarios were compared. The current scenarios represent scenarios in which one input parameter was changed at a time. This allowed us to indicate the direct effect of a particular parameter on the added value of integral valorization, and to indicate the most influential parameters. In residual scenarios, limitations related only to market capacity (group

Table 3.3 Scenarios defined to conduct sensitivity analysis[1]

		System limits			
No.	Change in input data	Current	Group CM	Group C	Group M
1	No change	1[2]	1CM	1C = 8	1M = 9
2	100% higher purchase prices of Lactose	2	2CM	2C	2M
3	100% higher sale price of whey-based products.	3	3CM	3C	3M
4	25% higher sale prices of milk powders[3]	4	4CM	4C	4M
5	50% higher sale price of milk powders	5	5CM	5C	5M
6	25% higher sale prices of Cheeses	6	6CM	6C	6M
7	25% higher sale prices of Caseinates	7	7CM	7C	7M
8	25% higher capacities of resource processing whey-based products	8	-	-	-
9	25% higher maximum sales of second tranche of whey-based products	9	-	-	-

[1]*Four groups of scenarios are distinguished: Current - scenarios with no changes in capacity and market limitations; group CM – scenarios with relaxed capacity and market limitations; group C – scenarios with relaxed capacity limitations: and group M – scenarios with relaxed market limitations.*
[2]*Scenario 1 represents base scenario against which all other scenarios are compared*
[3]*Milk Powders: IFCMP/WMP/SMP/IF/GUM = Instant Full Cream Milk Powder/Whole Milk Powder/Skim Milk Powder/Infant Food/Growing Up Milk*

M), only to production capacities (group C), and to both market and production capacities (group CM) were additionally relaxed. The scenarios of groups M, C, and CM are 2-dimensional. The first dimension represents changes in market prices of particular products and the second dimension defines the limits of the dairy system with regard to capacities ("system limits").

Differences in profit

To evaluate changes in the effect of integral valorization, we first looked at percentage differences among current scenarios (see bold values in Table 3.4). The percentage differences indicate the percentage change between the profit difference between *Int* and *SW* cases of a given scenario and the profit difference between *Int* and *SW* cases of the base scenario. Based on the results presented in Table 3.4, we can state that in the given settings (i.e. production of whey-based products is highly limited by market and capacity), the increase of purchase price of Lactose (Scenario 2), the increase of sale price of Caseinate(s) (Scenario 7), and the increase of production capacities of whey-based products (Scenario 8) had no, or only a small, influence on the effect of integral valorization (percentage changes were small compared with the impact in the base scenario). The increase of sale prices of whey-based products (Scenario 3), and of IFCMP/WMP/SMP/GUM/IF (Scenario 4 and 5) intensified the effect of integral valorization. Finally, it is interesting to note that the increase in sale prices of

Table 3.4 Profit percentage differences between the profit difference (between *Int* and *SW* cases) of a given scenario and profit difference (between *Int* and *SW* cases) of the base scenario

No.	Changes in prices	System limits[1] (%) Current	Group CM	Group C	Group M	Average impact of a parameter (%)
1	No change	**0**	418	**16**	**293**	182
2	100% higher purchase prices of Lactose	**0**	418	16	293	182
3	100% higher sale price of whey-based products	**64**	1,207	-51	987	552
4	25% higher sale prices of milk powders[2]	**92**	312	-23	366	187
5	50% higher sale price of milk powders	**84**	285	-67	176	119
6	25% higher sale prices of Cheeses	**-90**	-86	-87	-89	-88
7	25% higher sale prices of Caseinates	**0**	418	16	293	182

[1]Four groups of scenarios are distinguished: Current - scenarios with no changes in capacity and market limitations; group CM – scenarios with relaxed capacity and market limitations; group C – scenarios with relaxed capacity limitations: and group M – scenarios with relaxed market limitations.
Values in bold indicate percentage differences among current scenarios in which one input parameter was changed at a time.
[2]Milk Powders: IFCMP/WMP/SMP/IF/GUM = Instant Full Cream Milk Powder/Whole Milk Powder/Skim Milk Powder/Infant Food/Growing Up Milk

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Cheeses (Scenario 6) diminished the effect of integral valorization by 90%, whereas the decrease of market limitations of whey-based products (Scenario 9) increased the impact by almost 300%. The stronger effect in Scenario 9 was due to the possibility of producing more DLP and Hiprotal35 products, which are one of the main profitable sources of Lactose. Increasing demand for whey products therefore increased the availability of the Lactose in the integral valorization, and thus allowed for even higher production of IFCMP/WMP products. The increased differences in the production of those products were observed especially in the first 4 months, when differences between sale prices of Cheeses and IFCMP/WMP were the lowest. The lesser effect of Scenario 6 was also due to the relation between Cheeses and IFCMP/WMP prices. In Scenario 6, the differences in all months between Cheeses and IFCMP/WMP were positive and on average they increased by 180% compared with the base scenario. Thus, in both, *Int* and *SW* valorization approaches both Cheeses and IFCMP/WMP were valued in the same way.

Based on the presented analysis of the profit percentage differences, we concluded that the effect of integral valorization does not change much when selling prices or production capacities of relevant products are increased. We did, however, observed a significant increase in profit when additional demand for whey products was present. To investigate whether changes in investigated parameters would have the same impact on the effect of integral valorization, in a situation when the system was less constrained, the outcomes of scenarios of groups M, C, and CM were analyzed. The results are presented in Table 3.4. The strongest effect of integral valorization of all scenarios was observed for Scenario 3CM; that is, 1,207% stronger effect than in the base scenario. In this scenario, prices of whey products, capacity limits, and market limits were increased. This large difference, however, was mainly due to changes in market limits and prices, because in Scenario 3C, in which only capacity limits were increased, the difference in profit was 2 times smaller than in the base case (51% lower). Furthermore, in scenarios in which sale prices of Cheeses were increased, the differences in profit were consistently lower (80 to 90% lower) than the profit difference in the base scenario. The average effect of integral valorization was strongest when prices of whey products were increased (552% stronger than the effect in the base scenario), and weakest when prices of Cheeses were increased (88% weaker; see last column of Table 3.4).

Following the presented analysis, the effect of integral valorization will increase if the prices of whey products also increase. Given developments in the value of whey in recent years (see Figure 3.2 and Figure 3.9), this increase is very possible.

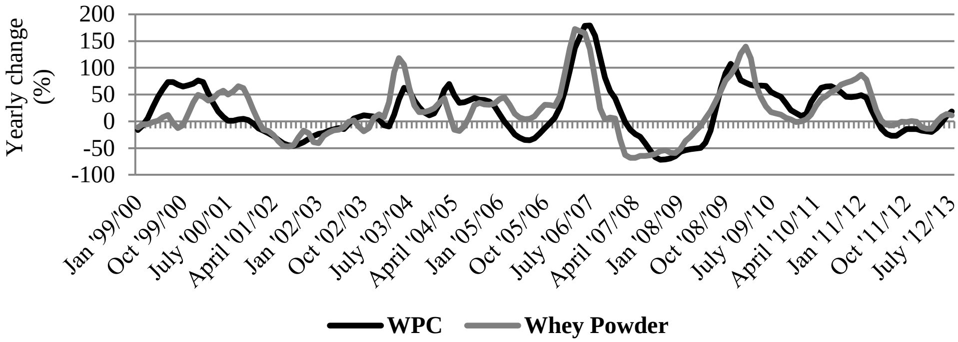

Figure 3.9 Yearly percentage changes in sale prices calculated based on monthly data, e.g. Jan ´10/´11 indicates the following (Price_Jan_ 11 – Price_Jan_2010)/Price_Jan2010. WPC = Whey Protein Concentrate.

As one can see from Figure 3.9, the percentage differences in prices of 2 representative whey end products (WPC and Whey Powder) easily reached 50% in the last 10 years. In 2004, 2009-2010, and in 2012, the percentage differences reached 100%, and in 2007 reached 170%.

Furthermore, if in addition to whey prices, demand for whey products increases, gains from the integral valorization could be even higher. It should be kept in mind that the increase in Cheese prices will decrease the effect of integral valorization.

Shifts in production planning

To investigate whether the integral valorization may lead to different decisions regarding the production of non-whey products, differences in production and total allocation of raw milk between *Int* and *SW* cases were analyzed (see Figure 3.10 with yearly differences).

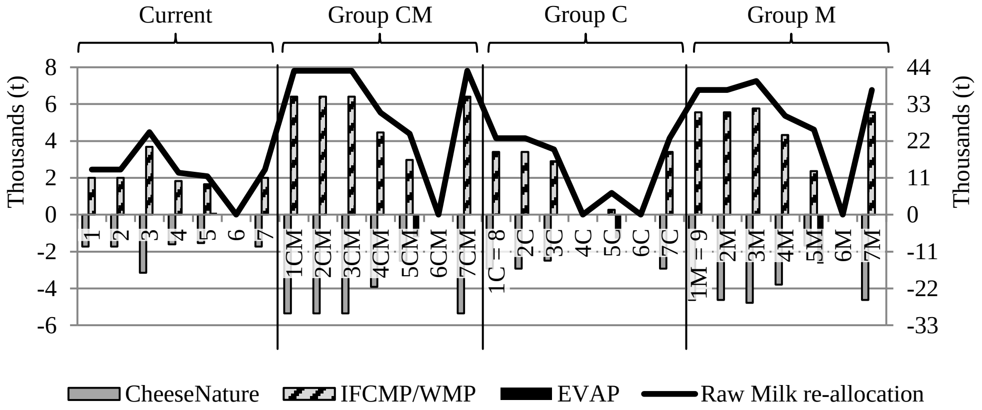

Figure 3.10 Main yearly differences in production of end products (left axis) and allocation of raw milk (right axis) between integral (*Int*) and stepwise (*SW*) cases. Current = scenarios with no changes in capacity and market limitations; group CM = scenarios with relaxed capacity and market limitations; group C = scenarios with relaxed capacity limitations: and group M – scenarios with relaxed market limitations. IFCMP/WMP = Instant Full Cream Milk Powder/Whole Milk Powder; EVAP = Evaporated Milk.

In most scenarios, larger shifts from Nature Cheese production to IFCMP/WMP were observed in the *Int* cases than in the *SW* cases. The differences in shifts did not occur in scenarios with higher sale prices of Cheeses (6, 6CM, 6C, and 6M) or those with higher sale prices of IFCMP/WMP and relaxed capacity constraints (4C and 5C). This is because the differences between prices of Cheeses and IFCMP/WMP increased in those scenarios, and both *Int* and *SW* valorizations valued both product groups similarly. Furthermore, in scenarios 5CM, 5C, and 5M, additional differences in the production of EVAP were observed. These are scenarios with 50% higher sale prices of IFCMP/WMP. In all months, the additional milk required for the production of IFCMP/WMP was withdrawn from Cheese production. In February, Cheese was produced at its minimum required volume (that is necessary to fulfill contracted sales), and thus additional raw milk necessary for the profitable production of IFCMP/WMP was in that month withdrawn from EVAP. This is a product that delivers second lowest return on one ton of raw milk used in the end production (the product with the lowest return is Cheese). Therefore, the positive differences in the production volumes of IFCMP/WMP between *Int* and *SW* cases lead to negative differences in the production volumes of EVAP. Furthermore, the differences presented in Figure 3.10 also lead to differences in Butter production, because lower production of Cheese leads to lower production of Cream, which is the main input for the production of Butter.

An important conclusion from the analysis of the outcome depicted in Figure 3.10 is that incorporation of information on the value of processing whey products in the valorization of main dairy products negatively affects the production of cheese. This means that, currently, whey products are not profitable enough to drive the production of cheese and caseinate products.

Based on this study, we conclude that under the current capacity and market demand limitations, the effect of integral valorization in the dairy case is small. Therefore, the valorization of main products and whey byproducts can be conducted separately without any larger losses. Because of low gains and high integration costs, it is currently recommended to conduct the valorization processes separately, as is the current practice. A large potential of integrating valorization processes is available, however. The possibility of extending markets and sale prices of whey-based products should be investigated. Finally, dairy processing companies should closely monitor the relation of cheeses and milk powders prices. In situations where prices of milk powders considerably increase the gain from integrating valorization processes becomes much higher.

Our conclusions on the effect of whey valorization and integral valorization are based on the dairy industry. Nonetheless, the methodology presented in this work can easily be used to verify whether these conclusions hold for other industries. In this study, we evaluated the effect of prices, demand and capacities on integral valorization. The effect of new whey production recipes should also be investigated. An outcome of such a study could indicate unexplored benefits of integral valorization.

3.4 Conclusions

The aim of this study was to analyze the added value of valorizing byproducts from an economic perspective; that is, the producers' point of view. We used the dairy industry as a case study, and focused on the byproduct of cheese production; that is, whey. This byproduct was chosen because of its important economic and environmental aspects. With the use of multiple scenarios implemented in the IDVM, we have shown the following. Explicit valorization of whey products resulted in considerable additional profit. The effect of integral valorization in the current settings of the dairy system was small (this finding is contrary to the expectations of professionals). The effect of integral valorization can change significantly in case changes in the following key factors occur: demand for or prices of whey-based products increase, sale prices of cheeses increase, or production capacity of whey-based products is extended. We expect these key factors (i.e., capacities, prices and demand of products linking processing of main products with byproducts processing) to also drive the valorization of byproducts in other industries. Finally, we investigated whether the inclusion of whey valorization into the current milk valorization process would affect decisions on production volumes of non-whey end products. We showed that a consistently larger shift from the production of Natural Cheese to the production of IFCMP/WMP occurred in *Int* valorization compared with *SW* valorization. Those shifts were caused by small differences in margin of those products between *Int* and *SW* cases. Although the relation between prices was known in practice, our finding of the impact upon the integral valorization was unknown.

PART II:
Performance Evaluation

Chapter 4

Robustness evaluation of valorization plans: the case of dairy processing industry

This chapter is based on the submitted manuscript:

Banaszewska, A., Cruijssen, F., Ike, M. and van der Vorst, J. G. A. J. *Robustness evaluation of valorization plans: The case of dairy processing industry*. Submitted to a scientific journal

Abstract

Despite the stochastic nature of data, deterministic models are commonly used to support planning processes. Consequently, the robustness of obtained plans is uncertain, i.e. optimal solutions might deviate if realizations of input data turn out to be different than the forecasts. The purpose of this study is to develop a framework for robustness evaluation of valorization plans obtained with deterministic models. Valorization plans are solutions to the planning problem of matching supply and demand, given available resources and constraints, with the emphasis on extracting the maximum value from raw materials. The framework is developed via a literature study and interviews with experts from practice, and is applied to a case company using a scenario planning approach. Multiple scenarios are implemented and assessed in a linear programing valorization model available from literature. The application of the framework showed that to provide robustness degrees, decisions have to be made regarding the grouping approach of Key Performance Indicators, evaluation levels, and robustness bounds. These decisions considerably affect the robustness degree; however, they do not affect parameters indicated as the ones with the largest impact on the robustness degree. The presented framework provides good insights into robustness of valorization plans and sheds light on which parameters considerably affect it. It also helps practitioners to assess if other (stochastic) programming techniques are required.

4.1 Introduction

Matching supply with demand for end products given available resources is one of the most challenging tasks of Operations Managers, mostly because of the large number of uncertainties that have to be taken into account (Chopra and Meindl, 2007). The effectiveness of tactical allocation of resources and preparation of production plans highly depends on the congruence of the planning model with reality, the modeling technique used, and the accuracy of the information that forms the base for a planning process (Mula et al., 2006; Vidal and Goetschalckx, 1997). Despite the stochastic nature of input data, deterministic programming models are the methods commonly used in practice to support planning processes (Verderame et al., 2010). One of the reasons is the intricacy of production processes that limits the possibility of applying complex modeling techniques. On the one hand, deterministic models are able to describe the core planning issues in complex, real-life environments, and thus the congruence of the model with reality is good. On the other hand, they often fail to incorporate uncertainty ingrained in data and specific model parameters. Mathematical programming models with noisy, erroneous, or incomplete data are common in real-life Operations Research applications (Mulvey et al., 1995). As a consequence of neglecting uncertainty of input data, the robustness of solutions, i.e. the degree to which best solutions might change if realizations of certain input parameter turn out to be different than the forecast, becomes questionable (Vlajic et al., 2012). The robustness of a proposed solution is of the same or even of a higher interest for practitioners than the optimality of the solution itself (Jensen, 2001; Kleijnen and Gaury, 2003; Mondal et al., 2013).

Mulvey et al. (1995) distinguish two types of approaches for dealing with data uncertainty: reactive – through sensitivity analysis of deterministic models, and proactive – through incorporating uncertainties in stochastic models. Stochastic programming models can considerably enhance the robustness of solutions (Verderame et al., 2010), however, a priori, they require much input information and in general are difficult to solve (Bredström et al., 2013). Therefore, before decisions on the implementation of stochastic programming are made, it is reasonable to first use reactive approach to properly evaluate the robustness of solutions to current deterministic models, and to focus only on those parameters that affect the robustness of solutions to the largest extent. Although much research is focused on developing methodologies to obtain robust solutions in production planning (Aghezzaf et al., 2010; Bredström et al., 2013; Escudero and Kamesam, 1995; Kazemi Zanjani et al., 2010), and some on evaluating the robustness at the modeling/design level (Fujita and Takewaki, 2011; Jensen, 2001; Mondal et al., 2013; Zakarian et al., 2007), to the best of our knowledge no work has been devoted to the assessment of the robustness degrees of deterministic production plans. A careful evaluation of the robustness of production plans, which is a simple task in theory, may have a large impact on decisions regarding e.g. modeling techniques used to prepare production plans.

The aim of the current research is to propose a framework for the evaluation of robustness of mid-term production plans of deterministic planning models, and to provide recommendations on how the robustness of such solutions could be improved. We focus on a specific type of production plans; that is, on so-called valorization plans. Valorization plans are solutions to the problem of matching supply and demand, given available resources and constraints, with the emphasis on extracting the maximum value from raw materials and byproducts (cf. Banaszewska et al. (2013)). The proposed framework is applied to a case study at FrieslandCampina, which is one of the largest dairy companies in the world. Therefore, all analyses presented in this paper are based on real life data.

The remainder of the paper is organized as follows. In the next section, we discuss definitions and existing robustness evaluation approaches. In the third section, the model used in this study is described. In the fourth section, the proposed framework for the robustness assessment is presented. In the fifth section, a case study is presented and results thereof are discussed. In the sixth section, managerial insights are provided. In the final section, conclusions and recommendations to the industry and on further research are given.

4.2 Theoretical framework

In literature, various definitions of robustness are available. One can refer for instance to the robustness of supply chains (e.g. Vlajic et al. (2012)), robustness of models (e.g. Ben-Tal and Nemirovski (1998)), and robustness of solutions (e.g. Mulvey et al. (1995)). Table 4.1 presents an overview of definitions of robustness available in literature that are most applicable for the context of this paper. For more definitions of robustness we refer the reader to the work of Asbjornslett (1999), Carlson and Doyle (2002), Ali et al. (2003), Kleijnen and Gaury (2003), Vlajic et al. (2010), and Lourenço et al. (2012).

Vlajic et al. (2010) distinguish two main perceptions of robustness: at *conceptual level* and at *modeling level*. Robustness at the *conceptual level* is defined as a property of a system or a strategy to redesign a system so that a higher robustness degree (see definition in Table 4.1) is attained. Robustness at the modeling level is related to properties of the tool (optimization / simulation models) or the solution itself. Two definitions of robustness are linked to the modeling level: *solution robustness* and *model robustness*. Solution robustness occurs when a solution to an optimization model remains “close” to optimal for all scenarios of input data, and model robustness occurs when a solution to an optimization model remains ‘almost’ feasible for all data scenarios (Mulvey et al., 1995). A similar perception of robustness is provided by Van Landeghem and Vanmaele (2002). The authors introduce a *robust planning* approach that addresses the uncertainties (in the context of supply chains at a tactical level) and is aimed at obtaining, with the use of a stochastic model, planning decisions that yield predictable and stable results. Outcomes of a robust planning are ‘close to optimal’ for a predetermined range of realistic parameter values, and thus solution robust (following the definition of Mulvey et al. (1995)). Apart from robust planning, Van Landeghem and Vanmaele (2002) also distinguish *scenario planning*. In scenario planning possible courses of

Table 4.1 Literature on robustness definitions

Reference	Definition
Mulvey et al. (1995)	Solution robustness occurs when the solution to an optimization model remains "close" to optimal for all scenarios of the input data. Model robustness occurs when a solution to an optimization model remains "almost" feasible for all data scenarios.
Gribble (2001)	The ability of a system to continue to operate correctly across a wide range of operational conditions, and to fail gracefully outside of that range.
Jensen (2001)	A robust schedule is a quality schedule expected to still be acceptable if something unforeseen happens.
Snyder (2003)	A solution that performs well under every realization of the uncertain parameters, though not necessarily optimally in any.
Vlajic et al. (2012)	The degree to which a supply chain shows an acceptable performance in (each of) its Key Performance Indicators (KPIs) during and after an unexpected event that caused disturbances in one or more logistics processes.
Mondal et al. (2013)	Robust design is to make a product or a process insensitive to the variation of noise factors.

events are identified and an optimal solution for each scenario is found using a deterministic model. Robust planning on the other hand integrates stochastic outcomes within one scenario.

In this research we do not aim at attaining robust solutions via stochastic programing techniques incorporating uncertainties. Instead, we develop a framework to assess the robustness of valorization plans obtained with the use of deterministic models. Even though the use of deterministic models is sometimes criticized in the literature due to their inability of capturing variability in data (Van Landeghem and Vanmaele, 2002), the large applicability makes them an interesting topic for investigation.

The framework presented in this work is based on scenario planning. A deterministic model is used to run scenarios with various possible realizations of input data. The evaluation of robustness takes place at the modeling level. Thus, while assessing the robustness of valorization plans we look at model robustness (frequency of infeasible solutions) and solution robustness (deviations in the objective function values). Since deterministic models can handle only one scenario at a time, a procedure on how to evaluate the overall robustness of valorization plans based on obtained solutions is required, but not available in the literature. The definition of robustness that we use is based to a large extent on the work of Mulvey et al. (1995) and Vlajic et al. (2012), and is as follows: "*the degree to which selected critical performance measures remain within a predefined robustness range, for different realistic scenarios of input data*".

The degree of robustness is calculated using robustness ranges and values of performance measures (to be indicated per scenario), which are calculated based on the outcomes of valorization plans (e.g. production volumes, profit level, capacity utilization). Key Performance Indicators (KPIs) are used in this study as critical performance measures. A robustness range is given by Lower and Upper Robustness Bounds determined for each performance measure, and it indicates the allowable value of the performance measure so that the solution is still considered robust (Vlajic et al., 2012). Solutions for which a given KPI remains within the robustness range are robust and non-robust otherwise (see Figure 4.1).

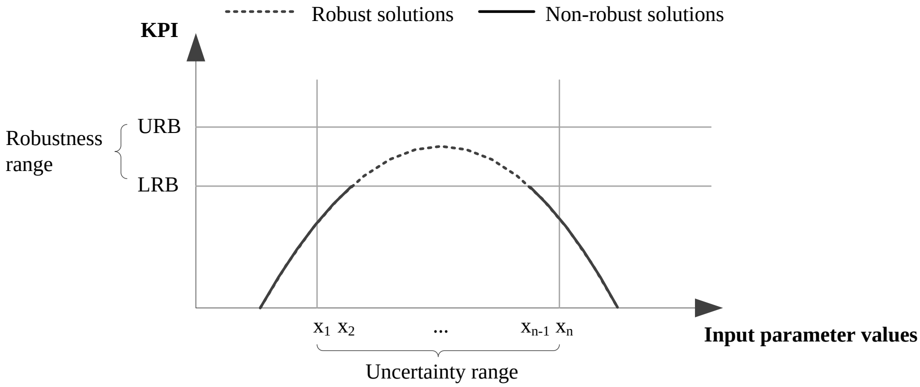

Figure 4.1 Schematic representation of the robustness evaluation based on Key Performance Indicator (KPI) level. URB = Upper Robustness Bound; LRB = Lower Robustness Bound.

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The acceptable robustness ranges and the critical performance measures vary from application to application. Selection of appropriate measures and robustness ranges is therefore an important part of the modeling process (Snyder, 2003). Scenarios created to evaluate the robustness of valorization plans are based on uncertainty ranges of input parameters. An uncertainty range defines the interval within which the realistic value of a parameter can vary.

4.3 The planning tool: Dairy Valorization Model

In this study the Dairy Valorization Model (DVM) was used to generate valorization plans. It is a decision support tool developed by Banaszewska et al. (2013) and implemented in AIMMS 3.11 software. The DVM is a deterministic linear model for tactical allocation and production planning. The model generates valorization plans that maximize the profit of a dairy processing company by determining optimal volumes of raw milk to be allocated every month to the most profitable set of dairy end products. All raw milk that is available as an input should be processed into end products that can be produced with the use of different recipes. The comprehensiveness and completeness of the model assures that all important elements for successful valorization of milk are taken into account, i.e.: recipes based on main milk components (composition), seasonality of raw milk composition and supply, the inter-relations in production due to byproduct utilization, complete product portfolio, and changing market conditions (prices and demand). The input and output parameters included in the DVM are presented on a high level in Figure 4.2. Each input parameter is composed of a number of detailed elements that are not shown in Figure 4.2, for instance the parameter *Sale Prices* is composed of the elements representing specific end products (each end product has its own sale price), the parameter *Milk Composition* is composed of elements related to the main components of raw milk (dry matter, fat, and protein). The term 'element-parameter combination' is used throughout this paper to refer to specific element of a certain parameter.

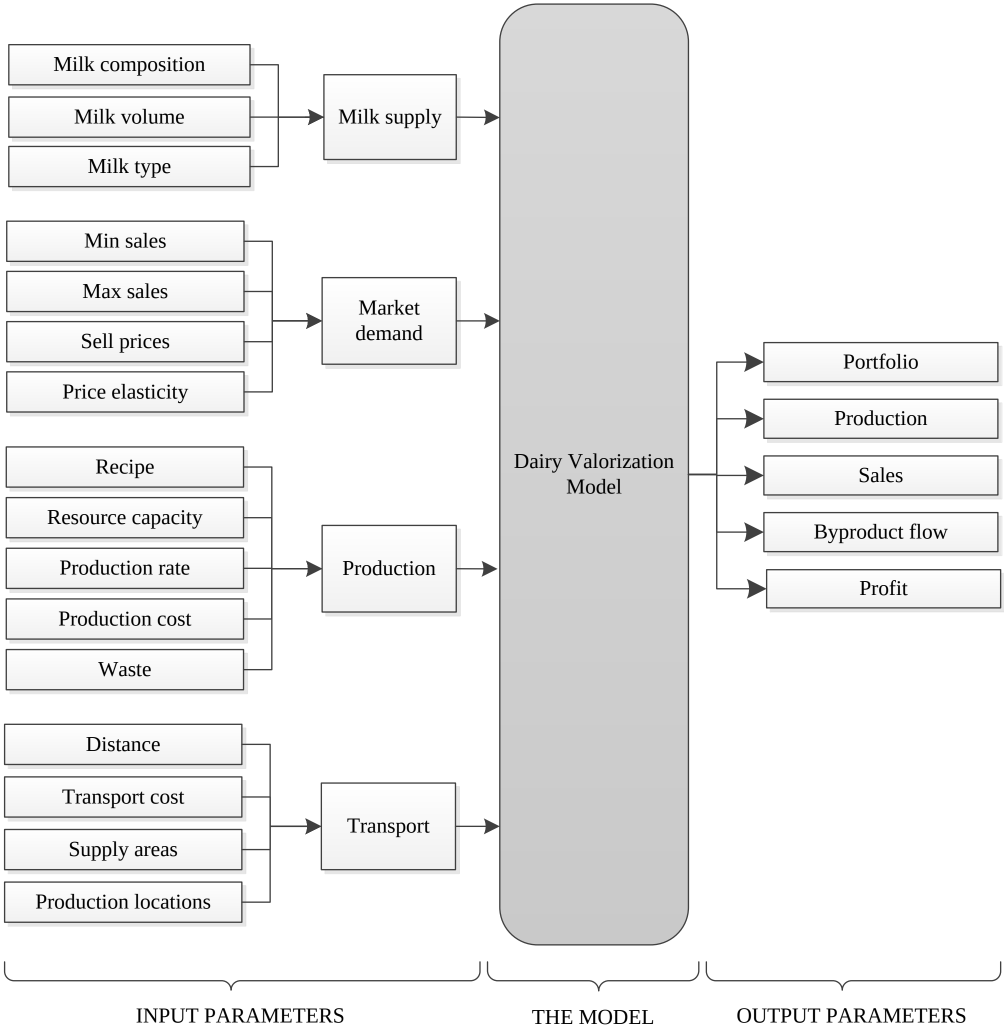

Figure 4.2 Schematic representation of the Dairy Valorization Model (Banaszewska et al., 2013).

The objective function of the DVM is the maximization of the difference between the revenue from sales and various costs (production, transport, and purchase). The main constraints incorporated in the model are: maximum capacity use, complete use of all incoming milk, minimum and maximum sales levels of products, recipes indicating volumes of inputs and outputs obtained in each production process, composition balance assuring right nutritional content of products, and inflow and outflow balance constraints. Certain constraints are 'soft' meaning that constraint violations are allowed, but at a very high cost. The inclusion of 'soft' constraints is important for the robustness assessment, as it allows for quantification of the impact of violated constraints. This information is often of interest to management, because it indicates the limits of the production system, and thus it can be used to better set constraint limits (e.g. increase capacities of certain production resources, decrease volumes of products fixed in contracts) in the future. The output of the model provides valorization plan for every month in the planning horizon. It delivers a good overview of the production, use, purchase, sales, and transportation volumes on different levels. For more information on the characteristics of the model we refer the reader to the original work of Banaszewska et al. (2013).

Even though the DVM represents the dairy system well, the accuracy of many input parameters of the model may affect the robustness of valorization plans, and thus the overall performance of the model. Various external factors affect the accuracy of the input data. For instance, looking at supply, we can distinguish at least three dimensions of uncertainty: (i) raw milk volume, (ii) raw milk quality, and (iii) composition levels of raw milk (Banaszewska et al., 2013; Guan and Philpott, 2009). For example, factors such as weather, feed, biological hazards, and prices of milk and of slaughtering may affect supply. Furthermore, on the processing level, the main sources of uncertainty can be related to the available capacity often affected by unexpected machine breakdowns, and quick deterioration of dairy raw materials and products. Moreover, looking at the market level, there are uncertainties related to e.g. volatile demand and prices (Banaszewska et al., 2013; Geary et al., 2010). Accuracy of input parameters is additionally affected by changing regulations of the European Union that influence guaranteed prices paid to farmers for the delivered raw milk (EuropeanCommission, 2008), maximum volume of milk that can be supplied by individual farmers (EuropeanCommission, 2006), and intervention prices paid for commodity products (Jongeneel et al., 2010).

This uncertainty ingrained in the input parameters may considerably affect valorization plans. It is possible that in the case of the dairy industry a deterministic valorization model is not sufficient to achieve good performance. Robustness of valorization plans must therefore be assessed.

4.4 Proposed framework for robustness assessment

Based on the reviewed literature, the robustness definition, and the selected scenario planning approach, we defined a five-step framework for the assessment of robustness of valorization plans. In Figure 4.3 all actions of the framework and related methodology are presented.

	Actions	*Methods*
1. KPIs	a) Define KPIs relevant for robustness assessment	• Literature study • Experts interviews • Group interviews
2. Parameters	a) Select uncertain input parameters b) Indicate uncertainty ranges per element-parameter combination	• Literature study • Experts interviews • Group interviews
3. Scenarios	a) Define scenarios b) Implement in a valorization tool c) Run scenarios in a valorization tool	• Literature study • Experts interviews • Group interviews • Computer simulations
4. Evaluation procedure	a) Caculate KPIs b) Indicate Robustness Bounds c) Assign 0 to KPIs of infeasible solutions d) Indicate whether scenario is robust or not, based on the KPIs and related Robustness Bounds; and aggregate scenario results	• Output analysis • Expert interviews
5. Conclusions	a) Indicate overall robustness level b) Provide recommendations on further improvement of the robustness	• Experts interviews • Group interviews

Figure 4.3 Framework, including methodology, for the assessment of robustness of valorization plans. KPIs = Key Performance Indicators.

First actions that need to be taken to evaluate robustness are: the definition of KPIs relevant for robustness assessment (Step 1), and the identification of uncertain input parameters and uncertainty ranges per element-parameter combination (Step 2). Afterwards, scenarios are defined based on the uncertainty ranges of element-parameter combinations, (Step 3). A scenario represents a possible realization of input data. In each scenario, a value of a certain element is changed within the indicated uncertainty range. Next, the resulting KPIs levels are analyzed following an evaluation procedure (Step 4) and the overall degree of robustness of valorization plans is provided (Step 5). Furthermore, input parameters that have the largest impact on the robustness of valorization plans are indicated and highlighted to management.

The output obtained in Step 4 is multi-dimensional, as each KPI is calculated per scenario (following the scenario planning approach) and per element-parameter combination. Additionally, KPI levels can be calculated either on a month or year level. An exemplary output (monthly level) is presented in Table 4.2.

Table 4.2 Exemplary output obtained in Step 4 of the proposed framework that is further used to indicate the overall robustness degree

				KPI levels		Robust/Non-robust scenarios[1]		
Month	Parameter	Element	Scenario	KPI_1	KPI_2	KPI_1	KPI_2	All_KPIs
January	Composition	Fat	Fat_s1	90	92	R	R	R
			Fat_s2	85	91	NR	R	NR
			…	…	…	…	…	…
		Protein	Pro_s1	86	91	NR	R	NR
			…	…	…	…	…	…
	Sale Prices	Cheese	Ch_s1	92	95	R	R	R
…	…	…	…	…	…	…	…	…

[1]*Indicated based on the following Lower Robustness Bounds: LRB_KPI_1 = 88, LRB_KPI_2 = 90. KPI = Key Performance Indicator; R = robust; NR = non-robust.*

In order to properly translate the obtained output into the overall robustness degree, an aggregation approach is required. The aggregation can be performed for instance on the parameter level. This would additionally allow for the identification of parameters that have the largest impact on the robustness of solutions with regard to a specific KPI. Nevertheless, since each parameter is composed of a number of elements, more insight can be obtained by conducting analysis on the element level. Moreover, it can happen that valorization plans are robust with regard to a certain KPI and non-robust with regard to another KPI. Thus, the overall robustness degree of valorization plans might be ambiguous if not carefully analyzed on the element level. Therefore, in Step 4 we propose an evaluation procedure and various KPIs grouping approaches to obtain a final assessment of the robustness of valorization plans.

First, the output of every scenario is translated into KPIs (Action 4a). Afterwards, the robustness bounds are indicated (Action 4b). Next, KPIs of infeasible solutions are treated in a particular way, i.e. the value of 0 is assigned to those KPIs (Action 4c). This is because in case violations of (soft) constraints are allowed in a valorization model, KPIs values will also be indicated for solutions that are infeasible in practice. KPIs of infeasible solutions are however unrepresentative and their real values should not be compared with KPIs of feasible solutions. The assignment of 0 to KPIs of infeasible scenarios does not affect the overall robustness degree, as the robustness degree is based on an indication whether a certain scenario is robust or not, and not on nominal values of KPIs. In the next step, it is indicated, based on robustness bounds for each month (or year) of each scenario, whether a solution is robust with regard to each KPI (Action 4d) (see Table 4.2); also, the number of robust scenarios with regard to each KPI is summarized either per parameter or per element-parameter combination. The robustness degrees are expressed as a percentage of all robust scenarios.

In order to provide the final value of the robustness degree it has to be additionally decided, on which KPI or a combination of KPIs, the results will be based. A number of grouping approaches is possible, each with its own practical value, for instance:

- single leading KPI – a selection of a leading KPI, on which the results are based. This KPI will differ per industry and therefore should be selected together with experts from the field;
- (weighted) average of KPIs – a weighted average of all KPIs, where weights represent the importance of each KPI. In practice, however, it can be difficult to assign representative weights to KPIs, even if management is directly involved in a process, and thus simple average can be used instead;
- all KPIs – a scenario can be considered robust if a solution is robust for all KPIs.

After choosing the grouping approach, the overall robustness degree is calculated as the average over input parameters. Input parameters with a percentage of robust scenarios lower than the indicated overall robustness degree are recognized as the critical ones for the robust planning, and thus should receive the most managerial attention. In Table 4.3 we present an example of results – robustness degrees – that would be calculated based on the output example presented in Table 4.2.

To summarize, in order to provide the overall degree of robustness of valorization plans, one has to decide on four evaluation aspects: robustness ranges, evaluation time level (month or year), evaluation depth level (parameter or element), and grouping approach of KPIs. One should remember that these choices will have a considerable impact on the observed overall robustness degree. In the next section, the application of the proposed framework is tested at a case study from the dairy industry. Furthermore, the impact of choices related to evaluation aspects and the identification of the most influential parameters are discussed.

Table 4.3 Exemplary results: robustness degree of valorization plans, based on month level and element-parameter combination, calculated according to various grouping approaches

			Grouping approach			
Month	Parameter	Element	KPI_1	KPI_2	All_KPIs	Avg_KPIs[1]
January	Composition	Fat	88	92	85	90
		Protein	85	91	83	88
			…	…	…	…
	Sale Prices	Cheese	90	96	89	93
…	…	…	…	…	…	…
Robustness degree			*89*	*91*	*85*	*90*

[1]*Calculated as the average of robustness degrees of investigated KPI_1 and KPI_2. KPI = Key Performance Indicator.*

4.5 Case Study

In this section all steps necessary to evaluate the robustness of valorization plans are presented and illustrated with the use of a case study. Before that a description of the case company is provided.

4.5.1 Case company

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FrieslandCampina (FC) is one of the world's largest dairy processing company. The company originated from the merger between Friesland Foods and Campina in 2008. FrieslandCampina has 14.132 member farms in the Netherlands, Belgium and Germany, and every year it processes more than 10 billion kg of milk (FrieslandCampina, 2012). The company employs almost 20.000 employees in 28 countries. It transforms raw milk into multiple end products such as cheese, butter, milk powders, infant food and butter, and holds more than 40 brands (e.g. Campina, Chocomel, Vifit, Milner, and Mona). The company wants to expand, create more profit, and more value out of milk. Therefore, the improvement of milk valorization lies at the core of the business of FC.

4.5.2 Robustness assessment – application to dairy valorization plans

All steps of the framework presented in Figure 4.3 are discussed below.

Step1: KPIs

Based on discussions with experts, and on the outputs produced by the DVM, five KPIs were identified: profit, re-allocation of raw milk, volumes of end products, volumes of byproducts, and capacity utilization. In workshops with the experts mentioned before, a choice for the KPIs that best reflect the impact of uncertainties in input parameters was made: changes in profit, re-allocation of raw milk, and volumes of end products. Volumes of byproducts were not chosen, since changes in produced byproduct volumes are directly related to changes in production volumes of end products. Capacity utilization was not selected, because it was decided to use this element as an input parameter for scenarios. We investigated the impact of sudden decreases in capacities on the robustness due to, for instance, unexpected breakdowns. The KPIs were calculated in the following manner:

a) Percentage difference in profit (*KPI_Profit*)

Percentage differences between the profit of the evaluated scenarios and of the base scenario were calculated. The sum of 1 and the calculated percentage difference represent the *KPI_Profit* level, i.e.:

$$KPI\_Profit = 1 + (Profit\_EvaluatedScenario - Profit\_BaseScenario) / Profit\_BaseScenario.$$

The higher the KPI the more robust the solution is.

b) Percentage difference in allocated milk (*KPI_RM re-all*)

Re-allocation of raw milk is used as the second KPI. This information is important, since changes in RM allocation influence transport, capacity use, factory planning, demand fulfillment, etc. The total re-allocation is an absolute number, e.g. re-allocation of 10t of milk from cheese to milk powder results in a value of (|-10| + |10|) / 2 = 10, since 10t is withdrawn from cheese and 10t more is allocated to milk powder. In calculating the KPI, apart from differences in RM allocated to end products, differences in RM supply and in RM sales are taken into consideration. The change in RM supply is deducted, since this is not a re-allocation, but simply additional allocation of milk. Also, the difference in sales is added (sales on market are treated as a dummy product to which milk is allocated). The difference between 1 and calculated percentage difference represents the *KPI_RM re-all* level, i.e.:

$$KPI\_RM\ re\text{-}all = 1 - [\ \textstyle\sum_{EndProd} (\Delta RMallocToEndProd - \Delta RMsupply + \Delta RMsold) / \sum_{EndProd} (RMallocToEndProd\_BaseScenario - RMsupply\_BaseScenario + RMsold\_BaseScenario)\ ],$$

where Δ indicates the difference between the evaluated scenario and the base scenario.

c) Percentage difference in end production (*KPI_EP prod*)

This KPI represents a change in the optimal product portfolio. Similarly to the *KPI_RM re-all*, absolute differences in production levels of end products are used to calculate the *KPI_EP prod*. The difference between 1 and the calculated percentage difference represents the *KPI_EP prod* level, i.e.:

$$KPI\_EP\ prod = 1 - [\ \textstyle\sum_{EndProd} (EndProdVol\_EvaluatedScenario - EndProdVol\_BaseScenario) / \sum_{EndProd} (EndProdVol\_BaseScenario)\ ].$$

<u>*Step2: Parameters*</u>

The identification of uncertain input parameters was made based on the work of Banaszewska et al. (2013), and four semi-structured expert interviews and one group interview at FC. The following company experts were involved: supply planner, dairy market analysts, financial accountant, production planners, and supply chain manager. Five main

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categories of input parameters relevant for milk valorization were identified: milk supply, demand, capacities, production and transport. In the *Milk Supply* category, input parameters as Raw Milk (RM) volumes and Raw Milk composition (dry matter, fat, and protein) fluctuate the most. The changes in RM can either reflect the equally higher or lower milk supply (component) content, or different seasonality of RM supply / component content (changing peaks and dips within the year). In the *Demand* category, changes can occur in contracted sales volumes and additional sales volumes that can be sold on a spot market, as well as in prices of single products and of multiple interrelated products. Interrelatedness of prices implies that when a price of one dairy product changes, price(s) of another dairy product(s) also change(s) (in a certain sequence and with a certain time lag). In the *Capacities* category, the available production capacities at different production locations can change. In the *Production* category, changes can occur in production recipes, production rate and production costs. In the *Transport* category, changes in transport costs, division of supply areas, and the number of production locations are possible.

The input parameters that belong to production and transport categories are mostly fixed on a tactical level and therefore are less interesting to investigate in this research. Hence, the three other categories of input parameters were selected for careful evaluation of the robustness of valorization plans. The selected parameters are the base for the definition of scenarios (Step 3 of the framework). Within the category demand, four input parameters can be investigated. It was however decided to investigate only prices of single products and fixed sales volumes. Even though the interrelatedness of prices is an interesting subject for investigation, the possible combination of products would lead to an unmanageable number of scenarios. To limit the scope of this research, we have decided to exclude this aspect from the investigation. Furthermore, in the investigated case company the additional sales volumes of selected products are unlimited (those products are sold on a spot market). Therefore, changes to maximum additional sales volumes are not meaningful in this case.

To summarize, five input parameters (Raw Milk volumes – *Supply*, Raw Milk composition - *Composition*, prices of single products - *Prices*, contracted sales volumes - *MaxSales*, and available production capacities - *Capacities*) were used to evaluate the robustness degree of valorization plans and to assess the impact of those parameters on the indicated robustness degree

Step3: Scenarios

In Table 4.4 all scenarios are enumerated. Scenarios were constructed with the use of historical data gathered at FC. The data were analyzed and possible changes in parameters were indicated based on fluctuations in the past. Scenarios are dependent on variations in input data of element-parameter combinations, e.g. *Composition-DryMatter*, *Composition-Fat*, *MaxSales-BMP*. In each scenario, data related to only one element-parameter combination are changed. The same number of scenarios is defined per each combination (in total 208 scenarios). Manners of arriving at percentages used in these scenarios were discussed with FC employees and are described below for each parameter.

Table 4.4 Defined scenarios and related changes in input elements of parameters with regard to the base scenario

Scenario specification	Changes in data[1]
Supply	
Supply increased or decreased equally	[1] +2.5%, [2] +5%, [3] -2.5%, [4] -5%;
Seasonality of supply intensified	[5] +2.5% and – 2.5%, [6] +5% and –5%;
Seasonality of supply smoothened	[7] CWMA(1), [8] CWMA(3);
Composition	
Dry matter increased or decreased equally	[9] +1.95%, [10] +0.97%, [11] -2.98%, [12] -1.49%;
Seasonality of dry matter intensified	[13] +1.95% and – 2.98%, [14] +0.97% and -1.49%;
Seasonality of dry matter smoothened	[15] CWMA(1), [16] CWMA(3);
Fat increased or decreased equally	[17] +6.65%, [18] +3.33%, [19] -6.4%, [20] -3.2%;
Seasonality of fat intensified	[21] +6.65% and –6.4%, [22] +3.33 and -3.2%;
Seasonality of fat smoothened	[23] CWMA(1), [24] CWMA(3);
Protein increased or decreased equally	[25] +4.35%, [26] +2.17%, [27] -4.86%, [28] -2.43%;
Seasonality of protein intensified	[29] +4.35% and –4.86%, [30] +2.17 and -2.43%;
Seasonality of protein smoothened	[31] CWMA(1), [32] CWMA(3);
All components increased or decreased equally	[33] – same as in scenario [9], [17], and [25]; [34] – same as in scenario [10], [18], and [26]; [35] – same as in scenario [11], [19], [27]; [36] – same as in scenario [12], [20], [28];
Seasonality of all components intensified	[37] - same as in scenario [13], [21], and [29]; [38] - same as in scenario [14], [22], and [30];
Seasonality of all components smoothened	[39] - same as in scenario [15], [23], and [31]; [40] - same as in scenario [16], [24], and [32];

Continued on the next page

[1]*CWMA = central weighted moving average; [X] = scenario number X.*

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Scenario specification	Changes in data[1]
Prices[2]	
Prices of SMP, WMP, IFCMP increased or decreased	[41] +13.14%, +12.05%, +12.05%; [42] +9.85%, + 9.03%, +9.03%; [43] +6.57%, +6.02%, +6.02%; [44] +3.28%, +3.01%, +3.01%; [45] -13.14%, -12.05%, -12.05%; [46] -9.85%, - 9.03%, -9.03%; [47] -6.57%, -6.02%, -6.02%; [48] -3.28%, -3.01%, -3.01%;
Prices of Butter increased or decreased	[49] +21.26, [50] +15.95%, [51] +10.63%, [52] +5.32%; [53] -21.26, [54] -15.95%, [55] -10.63%, [56] -5.32%;
Prices of Cheese Foil increased or decreased	[57] +10.24%, [58] +7.68%, [59] +5.12%, [60] +2.56%; [61] -10.24%, [62] -7.68%, [63] -5.12%, [64] -2.56%;
Prices of Cheese Nature increased or decreased	[65] +11.43%, [66] +8.58%, [67] +5.72%, [68] +2.86%; [69] -11.43%, [70] -8.58%, [71] -5.72%, [72] -2.86%;
Prices of Whey Powder increased or decreased	[73] +19.37%, [74] +14.53%, [75] +9.69%, [76] +4.84%; [77] -19.37%, [78] -14.53%,[79] -9.69%, [80] -4.84%;
MaxSales[3]	
Contracted sales of selected products increased or decreased	[81-127] +25%, +20%, +15%, +10%; [128-176] -25%, -20%, -15%, -10%;
Capacities[4]	
Capacity of Location1 decreased	[177] -9.5%, [178] -8.3%, [179] -7.1%, [180] -5.9%, [181] -4.7%, [182] -3.6%, [183] -2.4%, [184] -1.2%;
Capacity of Location2 decreased	[185] -36.8%, [186] -32.2%, [187] -27.6%, [188] -23.0%, [189] -18.4%, [190] -13.8%, [191] -9.2%, [192] -4.6%;
Capacity of Location3 decreased	[193] -8.8%, [194] -7.7%, [195] -6.6%, [196] -5.5%, [197] -4.4%, [198] -3.3%, [199] -2.2%, [200] -1.1%;
Capacity of Location4 decreased	[201] -6.2%, [202] -5.5%, [203] -4.7%,[204] - 3.9%, [205] -3.1%, [206] -2.3%, [207] -1.6%, [208] -0.8%;

[1]*CWMA = central weighted moving average; [X] = scenario number X.*
[2]*SMP, WMP, IFCMP = Skim Milk Powder, Whole Milk Powder, Instant Full Cream Milk Powder.*
[3]*Selected products: Butter Milk Powder (BMP), Butter, Butter Oil, Caseinate Roller, Evaporated Milk (EVAP), IFCMP, Raw Milk, Serum Powder, SMP, WMP, Cheese Foil, Cheese Nature.*
[4]*Changes in available capacities were applied to all resources processing milk at a given location.*

Supply scenarios represent four types of situations: (1) supply is higher in every month, (2) supply is lower in every month, (3) yearly seasonal pattern of supply is intensified, and (4) yearly seasonal pattern of supply is smoothened. First, second and third situation scenarios were created with the use of percentages indicated by experts. The highest realistic decrease and increase were indicated. To smoothen seasonal pattern of supply (situation 4) Central Weighted Moving Averages were used.

Composition scenarios represent the same four situations as scenarios related to *Supply*. Instead of milk supply level, levels of dry matter, fat, protein, or all components at once were changed (Scenario [9] – [40]). To indicate the maximum level of changes in component, weekly data from January 2007 to December 2012 were analyzed in case of fat and protein; for dry matter only the data from 2011 were available.

Prices of second tranche of selected commodity products were increased and decreased (Scenarios [41] – [80]). Commodities are products that are sold on a spot market for a price, which is a priori not agreed upon, and therefore, can fluctuate considerably. To indicate maximum realistic variations in prices, forecast data from March 2010 to September 2012 were analyzed.

MaxSales (volumes fixed in contracts) of selected products were changed. Since contracted volumes strongly depend on management decisions, changes that were applied to input parameters were indicated closely with experts from FC (Scenarios [81] – [176]).

Capacities scenarios were defined based on disturbances data, which are the volumes of raw milk that locations could not have processed due to unexpected events (e.g. machine breakdown). Disturbances data from January 2010 to September 2012 were analyzed per production location. Four locations with the highest total disturbances were selected for the analysis. The maximum monthly disturbance per location was expressed as a percentage of location-dependent total possible raw milk processing volume. This percentage was used to create scenarios with lower available production capacities (Scenarios [177] – [208]).

Step4:Evaluation procedure

The robustness of valorization plans was evaluated with the use of the proposed evaluation procedure. The results are presented below step-by-step.

- *Action 4a*

KPIs for all scenarios were calculated based on results obtained with the DVM. The most important statistics on robustness degrees, that is the average and the minimum of scenarios per parameter, are presented in Figure 4.4 and Figure 4.5. Only values of feasible scenarios are taken into account. Infeasible scenarios per parameter and per element are discussed in Action 4c of the evaluation procedure.

As one can see from Figure 4.4, uncertainty in *Capacities* has the smallest average impact on all three investigated KPIs (robustness degrees of around 99.9%). The highest average impact of uncertainty is observed for milk supply scenarios, of which robustness degrees related to profit and end production are 95.3% and 97.2%. This means that the uncertainties in milk supply volumes lead to an average deviations of 4.7% from the optimal

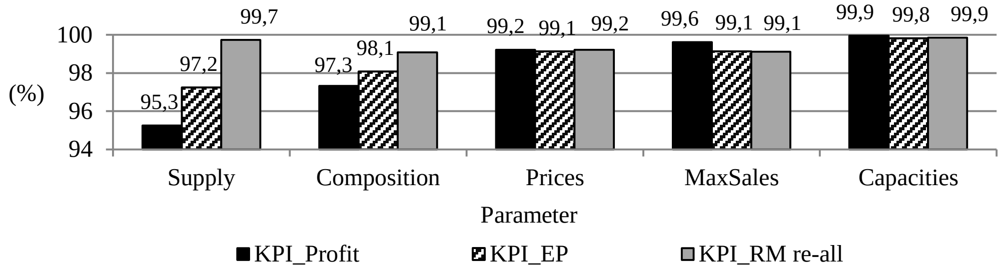


Figure 4.4 Average monthly robustness degrees among investigated feasible scenarios, per Key Performance Indicator and input parameter.

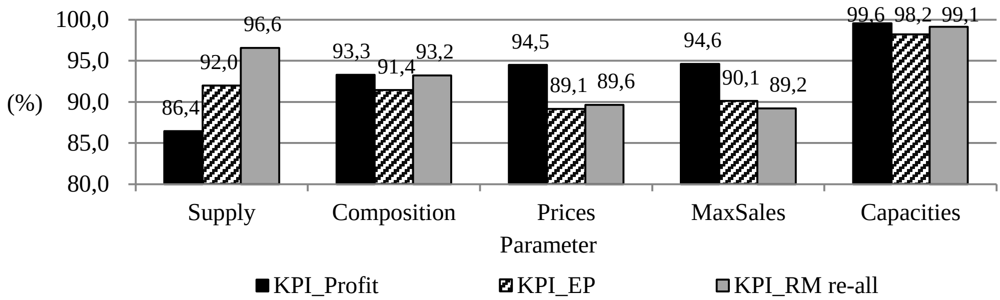


Figure 4.5 Minimum monthly robustness degrees among investigated feasible scenarios, per Key Performance Indicator and input parameter.

4

profit and of 2.8% from the optimal production plan. The impact of uncertainty in milk composition is also relatively high for those outputs (97.3% and 98.1%). Given the fact that the averages do not incorporate KPIs of infeasible scenarios and that the percentage of infeasible scenarios is the highest (19%) for the parameter *Composition* (see Table 4.5), one can argue that this parameter has one of the highest impacts on the robustness of valorization plans, since any infeasible solution is a non-robust solution.

Looking at Figure 4.5, the lowest robustness degree of 86.4%, with regard to profit, is observed for a milk supply scenario. This change is reasonable since, in the investigated case study, with the additionally supplied volume of milk more products can be produced and more profit can be made due to positive sales margins of products. A large change in the KPI related to end production (*KPI_EP*) is observed for a sale price scenario, i.e. 89.1%, and in the KPI related to the re-allocation of milk (*KPI_RM re-all*) for a contracted sales scenario, i.e. 89.2%. Both changes are related to the same end product. The impact of uncertainty in sale price of that product is high on the end production volume, but also on the re-allocation of milk. This is reasonable, since changes in end production volumes are directly related to changes in milk allocation.

Table 4.5 Percentage of infeasible monthly solutions in scenarios per parameter and element

		Solutions		
Parameter	Element	Infeasible	All	Percentage of infeasible
Supply		*0*	*96*	*0%*
Composition		*72*	*384*	*19%*
	Dry	0	96	0%
	Fat	33	96	34%
	Pro	23	96	24%
	All	16	96	17%
Prices[1]		*0*	*480*	*0%*
	Price_Product_6_9_10	0	96	0%
	Price_Product_2	0	96	0%
	Price_Product_11	0	96	0%
	Price_Product_12	0	96	0%
	Price_Product_13	0	96	0%
MaxSales		*27*	*1152*	*2%*
	Sale_Product_1	0	96	0%
	Sale_Product_2	0	96	0%
	Sale_Product_3	0	96	0%
	Sale_Product_4	0	96	0%
	Sale_Product_5	27	96	28%
	Sale_Product_6	0	96	0%
	Sale_Product_7	0	96	0%
	Sale_Product_8	0	96	0%
	Sale_Product_9	0	96	0%
	Sale_Product_10	0	96	0%
	Sale_Product_11	0	96	0%
	Sale_Product_12	0	96	0%
Capacities		*7*	*384*	*2%*
	Location_1	0	96	0%
	Location_2	0	96	0%
	Location_3	7	96	7%
	Location_4	0	96	0%

[1]In scenario Price_Product_6_9_10 prices of Product6, Product9, and Product10 were changes at the same time.

The presented analysis of robustness degrees with regard to various input parameters and KPIs gives managers good insights into causes and magnitude of unexpected changes in their planning process. Furthermore, it indicates those parameters of which uncertainties are having the highest impact on robustness. As such it is already a first indicator of directions for improvements.

- *Action 4b*

Lower Robustness Bounds (LRB) were determined per KPI. Based on discussions with experts from FC, the LRB of the *KPI_RM re-all* was set at the level of 95%. They indicated that an average re-allocation of raw milk higher than 5% of the monthly supply may cause severe planning problems, because of insufficient flexible processing capacity. For the *KPI_Profit* and *KPI_EP prod* no precise LRBs could be provided by the experts, and thus LRBs of 95% were also used. Another approach could be, for instance, to use as the LRB a certain percentile of outcomes per KPI.

- *Action 4c*

For certain scenarios, soft constraints related to maximum purchase of input materials, feasibility of producing end products, and maximum available capacity were violated. Scenarios in which the maximum purchase was violated in the first two months, end production feasibility or productions capacities were violated in any month, were treated as infeasible. In case of maximum purchase, only two first months were taken into account, because in practice, starting from the third month in planning horizon, additional purchase contracts can be set up without significant negative impacts on profit. KPIs of infeasible solutions were assigned the value of 0. The percentages of infeasible scenarios were analyzed and are presented in Table 4.5. The third column indicates the number of infeasible scenarios, the fourth column indicates the total number of scenarios, and the last column indicates the percentage of infeasible scenarios per parameter (values indicated with italic font) and per element. For confidentiality reasons actual names of products and locations were replaced with representative names.

As one can see the highest percentage of infeasible scenarios is observed for the parameter *Composition* (19%). It is important to notice that the infeasibilities are caused by changes in the *Fat* and *Protein* elements (34% and 24% of infeasible solutions), and not by changes in *Dry matter* (0% of infeasible solutions). It means that valorization plans are very sensitive to changes in *Fat* and *Protein* content in raw milk. The level of *Fat, Protein* and *Dry matter* in raw milk affects the volumes of input materials required for, and volumes of byproducts obtained from the production of a certain product. Large deviations from forecasted levels of *Fat* and *Protein* might make the production of certain products impossible due to the restricted number of recipes incorporated in the model, and thus result in an infeasible valorization plan. Furthermore, 2% of infeasible scenarios are also observed for parameters *MaxSales* and *Capacities*. Again notable is that the infeasibilities in *MaxSales* are all related to the element *Product_5*, due to insufficient production capacity to produce contracted volumes. The infeasibilities caused by the element *Location_3* of the parameter

Capacities indicate this production resource as an important one to fulfill all contracted volumes.

Analysis of the number of infeasible scenarios on the element level provides additional insight into model's robustness. In the presented case, for instance, more focus should be placed on improving forecast accuracies of the *Fat* and *Protein* components, than of the *Dry matter* component, because uncertainties in the *Fat* and *Protein* components often lead to infeasible valorization plans.

- *Action 4d*

Lower Robustness Bounds calculated in Action 4b were used to indicate whether a scenario (on a monthly and yearly level) was robust or not. Next, decisions on how to aggregate the obtained output had to be made. In the previous section, we have indicated that the final evaluation of robustness requires decisions to be made on: the robustness ranges, the evaluation levels, and the grouping approach for KPIs. These decisions are strictly related to managers' interests and preferences, and should be made before the results are obtained, to avoid biased decisions. In this study, together with the experts from FC, it was decided to evaluate the robustness of valorization plans based on the 95% LRB, monthly parameter level, and the average KPI. The results are presented in Table 4.6.

Table 4.6 Monthly robustness degrees of dairy valorization plans per parameter with regard to the selected KPIs grouping approach (RD_Average_KPI – average robustness degree) and the Lower Robustness Bound (95%)

KPIs grouping approach	Input parameter					
	Supply	Composition	Prices	MaxSales	Capacities	Average
RD_Average_KPI (%)	83	78	93	95	98	**90**

Results show that the average robustness degree (at FC) of dairy mid-term valorization plans is 90% (value in bold). The robustness degree differs considerably depending on the parameter, i.e. from 78% (*Composition)* to 98% (*Capacities*). These parameters are therefore indicated as the ones with the highest and lowest impact on the robustness of valorization plans. Since the robustness degree of the parameter *Supply* (83%) is also lower than the average robustness degree, we consider both *Composition* and *Supply* as the parameters that need the most managerial attention. This means that in order to improve the robustness of dairy valorization plans the uncertainty of those parameters should be decreased, and thus forecast accuracy should be increased. However, since there are many elements belonging to a specific parameter, the identification of most influential parameters might not be sufficiently informative. Not all elements belonging to a certain parameter might have the same impact on the robustness degree. For instance, numbers of infeasible scenarios, with regard to elements of the parameter *Composition*, indicate already that changes in *Fat* and *Protein* have more severe impact on the feasibility, and thus on the robustness of production plans, than changes in *Dry matter* (see Table 4.5). Therefore, additional analysis of robustness on the element level is recommendable in case management wants to take specific actions towards the improvement of robustness of valorization plans. Below we show an example of such additional analysis.

4.5.3 Impact of choices related to evaluation aspects

In order to show how robustness degrees can differ depending on the choices made with regard to the previously indicated four evaluation aspects (robustness ranges, evaluation time level, evaluation depth level, and grouping approach of KPIs results), we briefly analyze Table 4.7, in which robustness degrees for selected LRBs are presented. In the Appendix A and B, the complete results for LRBs (higher than 85%) are presented with regard to various KPIs grouping approaches and parameters.

Analyzing the information presented in Table 4.7 one can see that yearly average robustness degrees for a LRB of 99% are in most cases higher than the monthly ones. However, while looking at the LRB of 95% one can observe the opposite. This indicates that monthly robustness degrees are more sensitive to changes in the selected level of LRB. This is also visible from the data in the last row of the table, where the average spread between maximum (for LRB <= 85%) and minimum (for LRB = 99%) robustness degrees is depicted. Larger spreads are observed for monthly robustness degrees, thus indeed monthly results are more sensitive to the selection of the appropriate LRB.

Analyzing the robustness degrees of different KPIs grouping approaches, one can see a considerable difference in the average robustness degrees. For instance, for a LRB of 95% the monthly average robustness degree varies from 82% to 92%, the yearly average varies from 77% to 86%. Differences between various KPI grouping approaches increase for higher LRBs. This highlights the importance of the appropriate selection of the KPIs grouping approach before any results on robustness degrees are obtained. Furthermore, the relative robustness degrees are different for monthly and yearly robustness degrees, as well as for 95% and 99% LRBs. Therefore, the choice on the appropriate aggregation level and LRB level should also be made upfront together with the selection of KPIs grouping approach. All decisions should be well motivated, based on practical knowledge and experience, since they will significantly affect final conclusions regarding the robustness degree of valorization plans.

Finally, when it comes to the identification of critical parameters, looking at different KPI grouping approaches and two selected LRBs, in most cases both monthly and yearly robustness degrees indicate the same parameters, *Supply* and *Composition*, as the most influential ones. Therefore, based on the presented case, one can state that the identification of critical parameters is not dependent on the selection of the LRB, of the aggregation level, and of the KPIs grouping approach. Yet robustness degrees per parameter can differ significantly, e.g. looking at *RD_All_KPIs* the monthly robustness degree with regard to the parameter *Composition* at the LRB of 95% is 73% (53% for yearly), and at the LRB of 99% the monthly robustness degree is 3% (34% for yearly). As one can see the change in the robustness degree is much more severe for the monthly robustness.

Table 4.7 Monthly (yearly) selected robustness degrees per input parameter, for different Key Performance Indicators (KPIs) grouping approaches

	KPIs grouping approach[1]				
Parameter	RD_Average_ KPI	RD_All_ KPIs	RD_KPI_ Profit	RD_KPI_EP prod	RD_KPI_RM re-all
LRB = 95					
Supply	83 (83)	56 (75)	65 (75)	85 (88)	99 (88)
Composition	78 (57)	73 (53)	76 (59)	78 (59)	80 (53)
Prices	93 (94)	88 (83)	98 (98)	91 (100)	92 (85)
MaxSales	95 (91)	93 (82)	98 (96)	94 (94)	94 (82)
Capacities	98 (91)	98 (91)	98 (91)	98 (91)	98 (91)
Average	*90 (83)*	*82 (77)*	*87 (84)*	*89 (86)*	*92 (80)*
LRB = 99					
Supply	48 (50)	3 (13)	40 (63)	11 (13)	92 (75)
Composition	27 (47)	3 (34)	6 (53)	17 (47)	57 (41)
Prices	86 (82)	74 (65)	90 (90)	83 (78)	86 (78)
MaxSales	80 (77)	70 (67)	92 (89)	74 (73)	73 (69)
Capacities	96 (88)	92 (81)	98 (91)	92 (91)	98 (81)
Average	*67 (69)*	*48 (52)*	*65 (77)*	*56 (60)*	*81 (69)*
Spread between max (for LRB = 85) and min (for LRB = 99) robustness degree					
Supply	51 (38)	90 (75)	59 (25)	88 (75)	7 (13)
Composition	55 (13)	79 (25)	75 (6)	65 (13)	24 (19)
Prices	14 (18)	25 (35)	10 (10)	17 (23)	14 (23)
MaxSales	18 (19)	28 (29)	6 (7)	23 (23)	25 (27)
Capacities	2 (3)	6 (9)	0 (0)	6 (0)	0 (9)
Average	*28 (18)*	*45 (35)*	*30 (10)*	*40 (27)*	*14 (18)*

[1]RD_Average_KPI = average robustness degree; RD_All_KPIs = robustness degree based on the assumption that a solution should be robust for all KPIs; RD_KPI_Profit = robustness degree based on profit KP; RD_KPI_RP prod = robustness degree based on end production; RD_KPI_RM re-all = robustness degree based on re-allocation of milk.

4.6 Managerial insights

The outcomes of the proposed framework were discussed with experts from practice (dairy supply chain manager and valorization planners of FrieslandCampina), and it was concluded that the presented framework, in particular the evaluation procedure, provides good insights into the robustness of valorization plans and sheds light on which parameters considerably affect production planning. Additional analyses of results indicated the importance of appropriate decisions with regard to robustness evaluation: selection of the robustness ranges, evaluation time level, evaluation depth level, and grouping approach of KPIs. Although the conclusions regarding the overall robustness degree of valorization plans are considerably affected by those aspects, the identification of parameters with the highest impact on the robustness degrees is independent of those decisions. Therefore, any steps taken towards the improvement of the accuracy of those parameters should result in a higher robustness degree of valorization plans. In addition, it is recommended to conduct further analysis of results on the element level of these most important parameters. Every parameter is composed of multiple elements, for instance the parameter *Prices* encompasses changes in prices of various end products. In this case, the analysis of robustness degrees on the element level will indicate individual products, for which sales price (forecast) accuracy is more important than for other products.

Finally, whether the obtained robustness degree of valorization plans is sufficiently high is very much dependent on management policies of the company in focus. It can be difficult for managers to make a statement whether valorization plans are robust enough to conduct successful allocation and production planning. It is therefore recommended to, with the use of the proposed approach, conduct a benchmark study aiming at the evaluation of robustness of valorization plans in other dairy companies. Such a study would provide information on whether the indicated robustness degree of valorization plans is sufficiently high. Furthermore, in case of differences in robustness degrees of the same parameters among compared companies, knowledge on how to increase forecast accuracies, specifically of the most influential parameters, can be gained.

4.7 Conclusions and recommendations

The problem of matching supply and demand for end products, given the available resources and uncertainties related to relevant system parameters is a very challenging task. Deterministic models often fail to incorporate those uncertainties. Therefore, the question on the robustness of such solutions is relevant. In this study, we have proposed a framework for the evaluation of robustness of valorization plans (plans of matching supply and demand to maximize profit) obtained with deterministic models. To the best of our knowledge, no alternative evaluation approach that is also capable of solving real-life problem instances is currently present in the literature.

The outcome of the proposed evaluation procedure, developed to aggregate scenario results, is multi-dimensional. We have shown that to provide the overall robustness degree of valorization plans, decisions regarding the following four aspects have to be made upfront: the grouping approach of Key Performance Indicators, the evaluation time level (month or year), the evaluation depth level (element or parameter), and the robustness ranges. The analysis of the case study results indicated the importance of the appropriate selection of those aspects, since they can significantly affect the final robustness degree of valorization plans. Nevertheless, they do not affect the identification of the most influential parameters. Interviews at FrieslandCampina confirmed that the proposed evaluation procedure provides good insights into the robustness of valorization plans and into which parameters affect most its robustness degree.

The presented work shows that even though deterministic models are not designed to incorporate the uncertainties of input parameters, and thus to create robust solutions, the developed framework for the robustness evaluation may help in getting more insight into the robustness of plans. Moreover, it can also help in answering the question related to the necessity of using stochastic programming techniques in the planning process. Those techniques should be implemented in case of constantly low robustness degrees. In the presented dairy case study a robustness degree of 90% was obtained. This level was indicated as sufficiently high for valorization plans to be successfully implemented in practice. Therefore, no actions towards the development of a stochastic valorization model were taken. However, in case the robustness of valorization plans is not sufficiently high, at least three steps can be taken by management to improve it. First, accuracy of input data can be improved, especially of input elements that have the highest impact on robustness. Second, a benchmark of robustness degrees of other dairy companies can be carried out in order to decide whether the indicated robustness degree is sufficiently high. And third, decision support tools can be extended to incorporate the inaccuracy of input parameters. For instance stochastic programming techniques or robust optimization can be used for this purpose.

In this research, to evaluate the robustness degrees we analyzed the impact of changes in, among others, sale prices of specific products. Nevertheless, in reality prices of certain products are correlated, therefore an additional analysis of the impact of those scenarios might be an interesting addition to the current study. Next, in this study, we have used Key Performance Indicators to assess the robustness degree of valorization plans. The overall robustness degree was based, among others, on the scenarios average robustness degree. Since the probability of changes occurring in input parameters differs (e.g. the probability of forecast inaccuracy of 10% might be lower than the one of 5%), scenarios weighted average robustness degree could be used to improve the accuracy of robustness of valorization plans. However, a large set of input data per parameter is required to obtain representative weights.

Appendix A

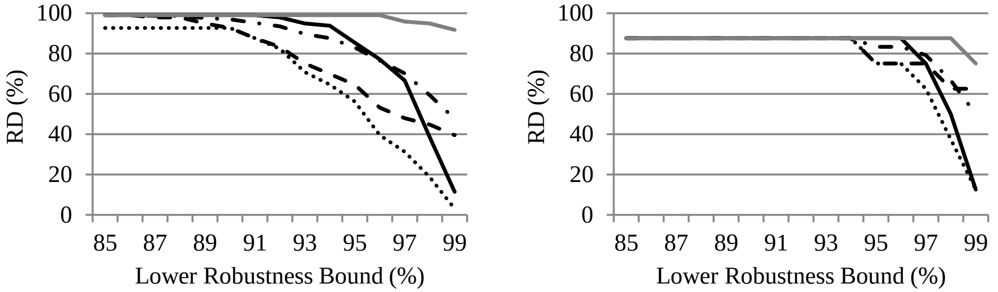
Figures A.1 – A.6 depict the impact of different Key Performance Indicators (KPIs) grouping approach on the robustness degree of valorization plans. To achieve better transparency of results, the impact was presented for a specific parameter, and either month or year level. The legend for Figures A.1 – A.6 is provided below.

Legend[1]:

– · – RD_Average_KPI ········ RD_All_KPIs – – – RD_KPI_Profit

——— RD_KPI_EP prod ——— RD_KPI_RM re-all

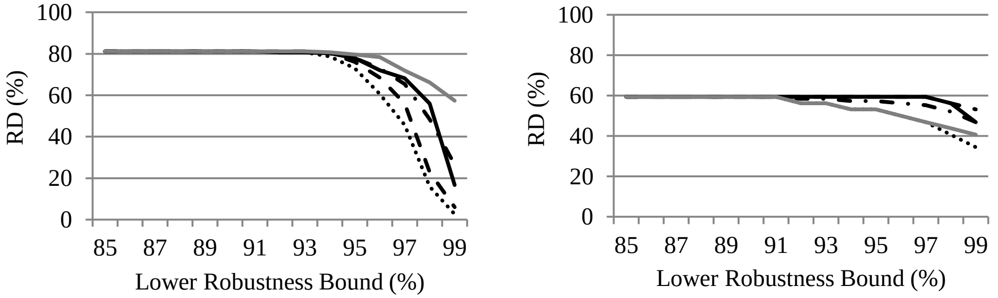
[1]*RD_Average_KPI = average robustness degree, RD_All_KPIs = robustness degree based on the assumption that a solution is robust for all KPIs, RD_KPI_Profit = robustness degree based on profit KPI, RD_KPI_RP prod = robustness degree based on end production, RD_KPI_RM re-all = robustness degree based on re-allocation of milk*



a) Month level

b) Year level

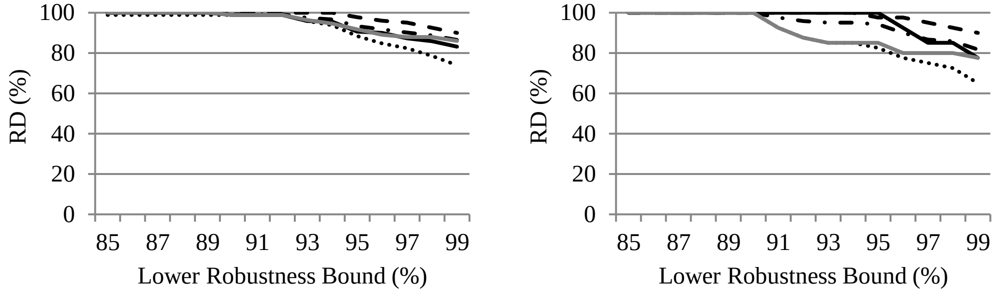
Figure A. 1 Robustness degree (RD) according to the parameter *Supply*.



a) Month level

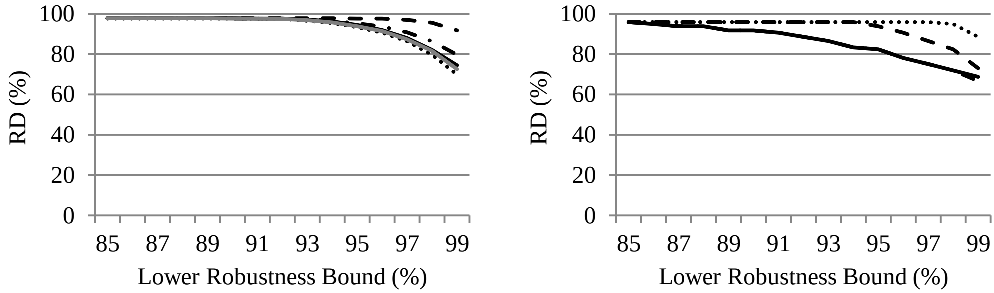
b) Year level

Figure A. 2 Robustness degree (RD) according to the parameter *Composition*.



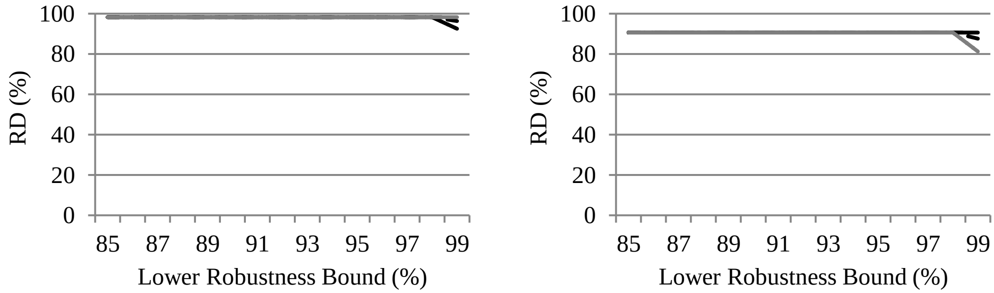
a) Month level b) Year level

Figure A. 3 Robustness degree (RD) according to the parameter *Prices.*



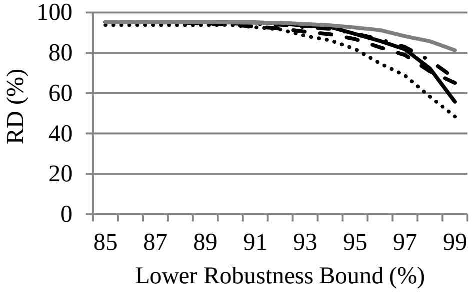
a) Month level b) Year level

Figure A. 4 Robustness degree (RD) according to the parameter *MaxSales.*

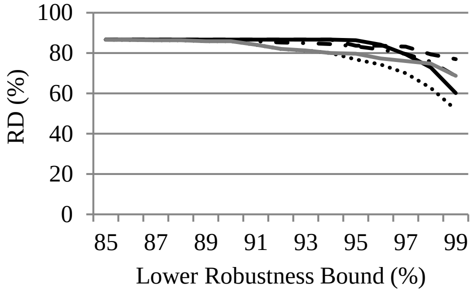


a) Month level b) Year level

Figure A. 5 Robustness degree (RD) according to the parameter *Capacities.*



a) Month level



b) Year level

Figure A. 6 Average robustness degree (RD) of all parameters.

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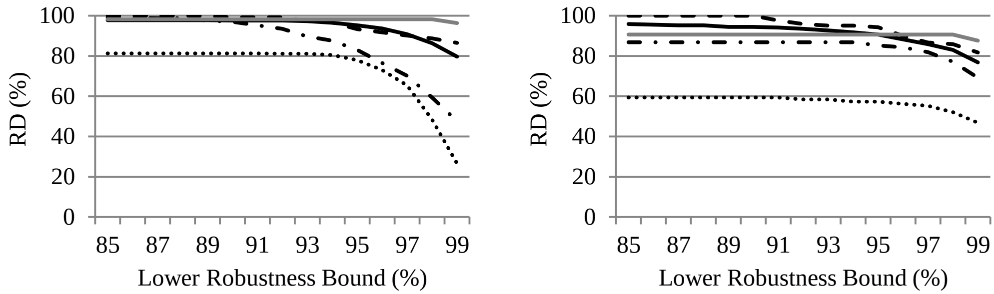
Appendix B

Figures B.1 – B.5 depict the impact of different parameters on the robustness degree of valorization plans. To achieve better transparency of results, the impact was presented for a specific Key Performance Indicators (KPIs) grouping approach, and either month or year level. The legend for Figures B.1 – B.5 is provided below.

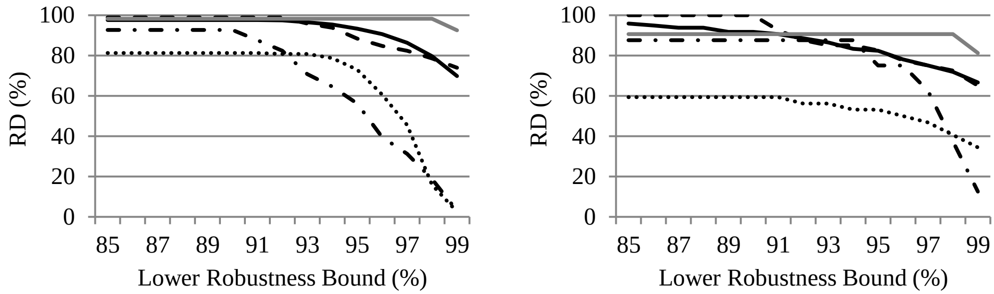
Legend:

– · – Supply ········ Composition – – – Prices —— MaxSales —— Capacities



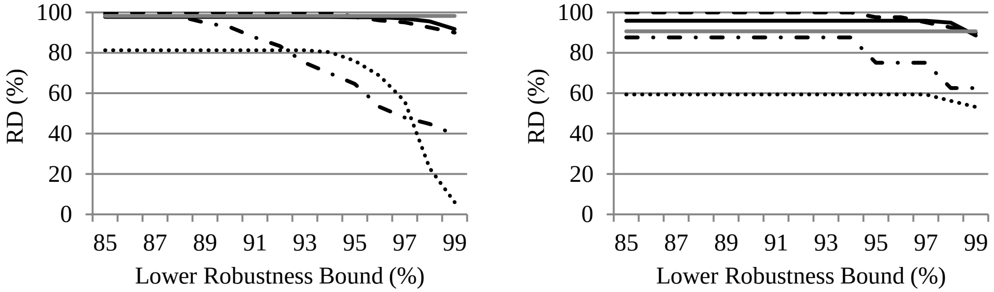
a) Month level b) Year level

Figure B. 1 Robustness degree (RD) according to the grouping approach *Average_KPIs* (average robustness degree).



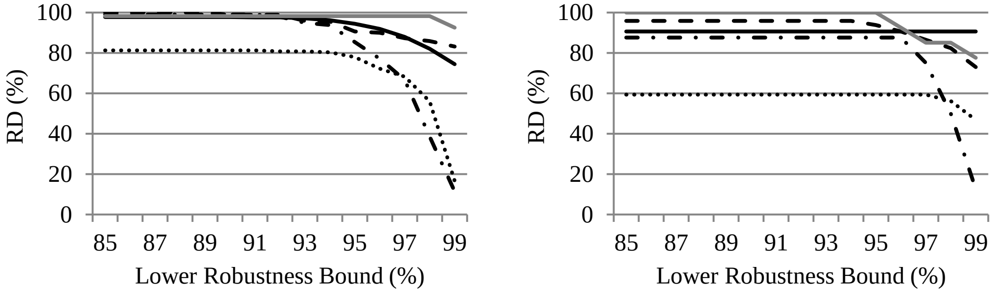
a) Month level b) Year level

Figure B. 2 Robustness degree (RD) according to the grouping approach *All_KPIs* (robustness degree based on the assumption a solution is robust for all KPIs).



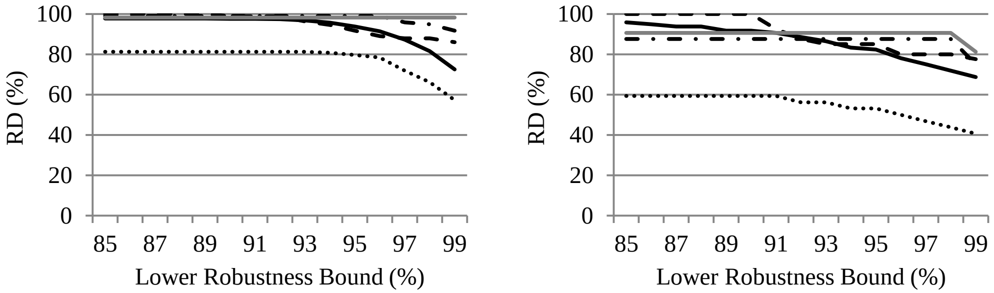
a) Month level b) Year level

Figure B. 3 Robustness degree (RD) according to KPIs grouping approach *KPI_Profit (*robustness degree based on profit).



a) Month level b) Year level

Figure B. 4 Robustness degree (RD) according to KPIs grouping approach *KPI_EP prod* (robustness degree based on end production).



a) Month level b) Year level

Figure B. 5 Robustness degree (RD) according to KPIs grouping approach *KPI_RM re-all* (robustness degree based on re-allocation of milk).

Chapter 5

A framework for measuring efficiency levels of processing units

This chapter is based on the following journal paper:

Banaszewska, A., Cruijssen, F., Dullaert, W. and Gerdessen, J.C., 2012. *A framework for measuring efficiency levels—The case of express depots*. International Journal of Production Economics, 139(2): 484-495

Abstract

The efficiency and effectiveness in any distribution network is largely determined by the performance of depots in such a network. The purpose of this study is to develop a methodological framework to evaluate the performance of distribution centers of express companies. The framework is based on Data Envelopment Analysis and was validated on a set of 44 depots of a large express service provider situated in the United Kingdom. The analysis revealed that 31 depots out of 44 are efficient. Furthermore, statistical analyses identified four factors influencing the efficiency scores of express service depots.

5.1 Introduction

Express companies focus on quick and on-time deliveries. To organize high-value express services, such companies need a well-organized logistics network of hubs and depots. A depot, in the literature also referred to as a warehouse or a distribution center (DC), is a multifunctional part of an express network that is responsible for the majority of operations in the express supply chain, i.e.: picking up, receiving (unloading), processing (weighing, labeling, sorting), shipping (loading) and delivering parcels. Since the efficiency and the effectiveness in any distribution network is largely determined by the operation of the nodes in such a network i.e. the warehouses (Chandra et al., 1998; Rouwenhorst et al., 2000), depots are one of the key elements of the express network. Consequently, a depot's performance strongly influences services delivered to customers. To keep the network and services on a high level, companies have to monitor the efficiency of depot's operations. Experience from practice indicates that currently the efficiency of an individual depot is mostly measured based on a single measure, such as the percentage of parcels delivered on time. Certainly, this measurement provides significant information on the depot's performance, but it disregards other important aspects of a depot's true efficiency level. According to Nutt (2000), half of the decisions in organizations fail mostly because of the focus on a single aspect. Ross and Droge (2004) state that "the genesis of poor/superior performance is multi-faceted: operations size, workforce knowledge, direct salaries, market differences, vehicle costs, customer densities and many other factors can influence financial and time-based performance." Thus, to accurately assess a depot's performance level, an adequate measure that captures all relevant elements is needed. This measure should take into consideration all services and products delivered by a certain depot, as well as its regional characteristics and restrictions. Moreover, it should also provide managers with information on which factors lead to high or low efficiency levels, to suggest both depot-specific improvement areas and guidelines for network redesign projects, which are the key to high long-term performance of the organization.

A warehouse may perform different functions depending on the supply chain, to which it belongs, e.g.: inventory holding point, consolidation center, cross-dock center, sortation center, assembly facility, trans-shipment point and return goods center (Rushton et al., 2006). Consequently, the performance of different types of warehouses is affected by different factors. For instance, in a distribution center that functions as an inventory holding point the efficient allocation of a storage area will be one of the most important elements, whereas in a sortation center a type of sorting equipment. Therefore, to accurately assess performance levels, warehouse-type specific measures are required. A number of studies carried out in the past focus on the evaluation of various types of warehouses (Chan and Qi, 2003; De Koster and Balk, 2008; Hamdan and Rogers, 2008; Kayakutlu and Buyukozkan, 2011; Ross and Droge, 2002; Ross and Droge, 2004; Schefczyk, 1993). However, to the best of our knowledge no research especially focused on the investigation of distribution centers of express shipping companies was carried out. A number of characteristics that distinguish express depots from other types of warehouses are as follows: cross-docking policy that excludes storage possibilities, continuous flow of goods (receive, sort and ship) that requires synchronized and flawless operations, lack of upfront information on characteristics of incoming products that hinders the processing of parcels (e.g. suboptimal allocation of parcels to specific shipping vehicles due to the unavailability of information on parcels' sizes).

Given the multi-functionality and the importance of express depots, and the existing knowledge gap on measuring the efficiencies of such depots, the aim of this research was to develop a framework for measuring a depot's true efficiency level. To achieve this aim we have posed the following questions:

- what is the most suitable method for a depot's efficiency measurement?
- which depots are the best and the worst performers?
- what are the critical factors that contribute to the successful performance?

The outcome of this study enriches the express company's knowledge on its depots. The outcomes can form the basis for improvement programs, which in turn can have a positive influence on the overall company's service level. Moreover, gained knowledge would have an important input in the strategic decision making (e.g. re-design of the network).

The remainder of this paper is organized as follows. Section 5.2 is focused on a literature review of performance practices used in logistics with a special focus on the performance measures used for the distribution centers' assessment. In Section 5.3 the method most suitable for the express depots evaluation is chosen and described. In Section 5.4 this method is applied to our case study, and thus the final model is developed. In Section 5.5 the results of the model and the analyses of these results are presented. In Section 5.6 the conclusions are drawn and the recommendations are provided.

5.2 Literature review

In this section, taking into consideration the problem and the research questions, the relevant existing literature is discussed. First, a number of studies regarding the performance measurement is introduced. Next research focused especially on the warehouse measurement is described. Finally, an approach and methods suitable for the measurement of depots efficiency are presented.

5.2.1 Performance measurement

Performance measurement of a supply chain network

Fawcett and Cooper (1998) state that the "performance measurement is critical to the success of almost any organization because it creates understanding, molds behavior, and leads to competitive results." It is readily understood that during the last decades huge emphasis has been placed on determining the best methods to evaluate the performance of logistics supply chains, networks, warehouses etc.

Ross et al. (1998) developed a methodology to reconfigure a supply chain network. The authors discuss and depict sequential steps and methods that should be used in order to evaluate the efficiencies of the system e.g. Data Envelopment Analysis (DEA), linear programming (LP), and integer programming (IP). Furthermore, Talluri et al. (1999) proposed a DEA based framework for the design of efficient value chain networks with a third party service provider selection. Then, similar approach to Ross et al. (1998) can be found in Chan and Qi (2003). The authors designed a process-based approach for mapping and analyzing supply chain networks. In their paper they present a process-based performance measurement system. Another approach, taken by Park et al. (2000), is based on a productivity analysis. The authors use the Free Disposal Hull (FDH) method to evaluate the productivity and efficiency levels of production units. Two years later Kall and Mayer (2011) published a paper that provides guidelines for improving performance of warehouses. The study is based on the benchmark analysis of 45 Finnish warehouses. Factors affecting warehouse operations and efficiency are identified. The efficiency of the warehouse is measured as work efficiency, cost efficiency and space utilization. Looking from another angle, Voss et al. (2005) focused their research on investigating the influence of front-line employees on service, financial performance of distribution facilities and on a whole supply chain. The analysis is based on the canonical correlation method. Furthermore, Vaidyanathan (2005) used a set of theories established in the literature to design an evaluation criteria framework for assessing the third-party logistics provider. Finally, Garcia et al. (2012) developed a framework for the performance measurement and benchmarking in the wine industry. A number of KPIs for measuring logistics was used to evaluate each actor in the supply chain.

Depot's efficiency measurement

Schefczyk (1993) compared two performance analyzing techniques: productivity ratios and Data Envelopment Analysis (DEA). For a set of 16 warehouses in a service parts distribution network, inputs-outputs sets were defined and used in four productivity measures: two ratio measures (labor productivity and warehouse operations productivity) and two DEA measures (single input–single output DEA and multiple input-multiple output DEA). Based on the case study under the consideration, the four methods brought the author to similar conclusions. One of the conclusions states that larger warehouses appear to be less efficient than smaller ones. In the research of Kuo et al. (1999) measurement systems of five distribution centers were compared and analyzed by means of a cross-case analysis. The researchers distinguished six measurement categories (finance, operations, quality, safety, personnel and customer satisfaction) and identified 86 measures used for evaluating the depots performance. In 2004, Ross and Droge (2004) conducted a DEA research to evaluate efficiency levels of 207 petroleum distribution centers. The model used for the estimation of DC's performance level contains nine variables, i.e. three inputs (fleet size, driver experience, and a regional index factor) and six outputs (four types of commodity, vehicles run-miles, and vehicles deliveries). The model is also used to distinguish and assess the causes of low/high efficiencies: managerial effectiveness, scale of operations and efficiency of resource allocation with regard to a given scale. DEA was also applied by Hackman et al. (2001) to benchmark 57 warehouses and distribution facilities from different industries. The research revealed that a smaller size, a lower automation level and unionization may contribute to higher efficiency levels of warehouses. Hamdan and Rogers (2008) examined the efficiency of 19 storage warehouses. The authors distinguish six groups of processes: receiving, put-away, picking, packing, shipping and “other processes” e.g. cycle counting, physical inventory. Furthermore, the study confirmed the results of Schefczyk (1993) and Hackman et al. (2001) that smaller warehouses are more efficient than larger ones. The efficiency of European distribution centers was furthermore estimated in the study of De Koster and Balk (2008). As in the previous research, the authors used DEA for benchmarking the warehouses and assessing their efficiencies. Finally, Xu et al. (2009) discussed the applicability of DEA to general supply chain performance evaluation, and they applied their approach to a furniture manufacturing industry.

The above discussion illustrates that the measurement of warehouse performance is well studied and that different methodologies are used. Nevertheless, Data Envelopment Analysis seems to be commonly accepted as the best approach. For a detailed discussion of the pros and cons of DEA to benchmark activities we refer to Homburg (2001).

5.2.2 Approach and measures

Approach: benchmarking

Apart from identifying the best measure for depots performance assessment, this paper also aims at indicating an adequate approach that would set measurement guidelines. Consequently it was decided to base the depots measurement process on benchmarking. In this paper, we define benchmarking as the process of identifying one’s own shortcomings, identifying the best peer performers, understanding their best practices and finally implementing them. In the literature, various classification schemes and benchmarking models have been proposed (Wang and Fang, 2001), but a straightforward classification distinguishes internal benchmarking and external benchmarking. In internal benchmarking, the units from one organization are compared with each other; whereas in external benchmarking, the units of one organization are compared with the units of an external organization (it can be a competitor or an organization from another industry).

This research addresses the internal benchmarking of a large express service provider in the United Kingdom. All depots are compared with each other and performance levels are used as a measurement base. A depot’s performance is assessed with the use of a productivity measure that is a ratio of outputs (services and products delivered) to inputs (resources consumed to produce these outputs). Furthermore, this productivity measure is used to calculate an efficiency score, which is a ratio of a unit’s actual productivity to standard productivity. This standard productivity is based on the productivity level of the best operating depots. The higher the productivity or efficiency of a certain depot, the better performer it is.

Therefore the terms “performance”, “productivity” and “efficiency” are used alternatively in this paper.

Measures

To support the development of the internal benchmarking tool for express companies and to facilitate the choice of the most appropriate methodology, the measures used in the literature for evaluating DC’s efficiency are classified and reviewed. Chow et al. (1994) divide performance measures into soft and hard ones. The first refers to mostly qualitative methods that by means of surveys, interviews, site visits and questionnaires measure less tangible areas e.g. customer satisfaction. The second refers to mostly quantitative measures e.g. accounting figures or figures collected via archival and simulation methods. Stainer (1997) links performance with productivity and classifies performance measures into three main types: “partial measures being a ratio relating output to a single input, such as labor, materials or capital; total factor or value-added productivity being based on sales less bought-in goods, materials and services; total productivity measures being a ratio of total output to total input.”

In this research, in order to group all identified methods, we have used a combination of the Chow et al. (1994) and Stainer (1997) classifications. Our classification initially distinguishes managerial and mathematical approaches to a depot’s performance measurement (see Figure 5.1).

The first group includes integrated managerial tools, which during the evaluation phase often rely on personal estimates e.g. include self-assessment based on the employees’ perception, on customers’ opinion (satisfaction, impact on society, etc.). It can be said that these are rather qualitative methods. Although methods from this group are often used to assess logistics organizations, they are rarely used to evaluate distribution centers. More information on methods from the “managerial approach” group can be found in Gharakhani et al. (2010), Franceschini and Rafele (2000), and Lai et al. (2002). The second group relies on usually raw data and mathematical tools such as: single input-output measures and multiple input-output measures. For the multi input-output measures, in order to reflect the differences in statistical assumptions on the input and output data, a further distinction can be made into parametric and nonparametric models. The literature study revealed that methods from the mathematical group are mostly used for the warehouses performance assessment. Below we elaborate on methods that are commonly used in practice.

Single input-output ratios that focus on the most critical aspects of a successful management are called Key Performance Indicators (KPIs). The KPIs that may be used for the assessment of logistics companies are among others: productivity ratios (e.g. number of shipments per vehicle-mile), raw financial ratios (e.g. net income), cost accounting statistics (e.g. return on investments), and quality (e.g. fraction of accurate orders). Fawcett and Cooper (1998) divide traditional logistics into five measurement areas: asset management, cost, customer service, productivity, and quality. Frazelle (2002) suggests similar measurement areas that focus especially on the warehouse performance assessment: finance (e.g. total cost per order, line item), productivity (e.g. total lines shipped per total man-hour), utilization (e.g.

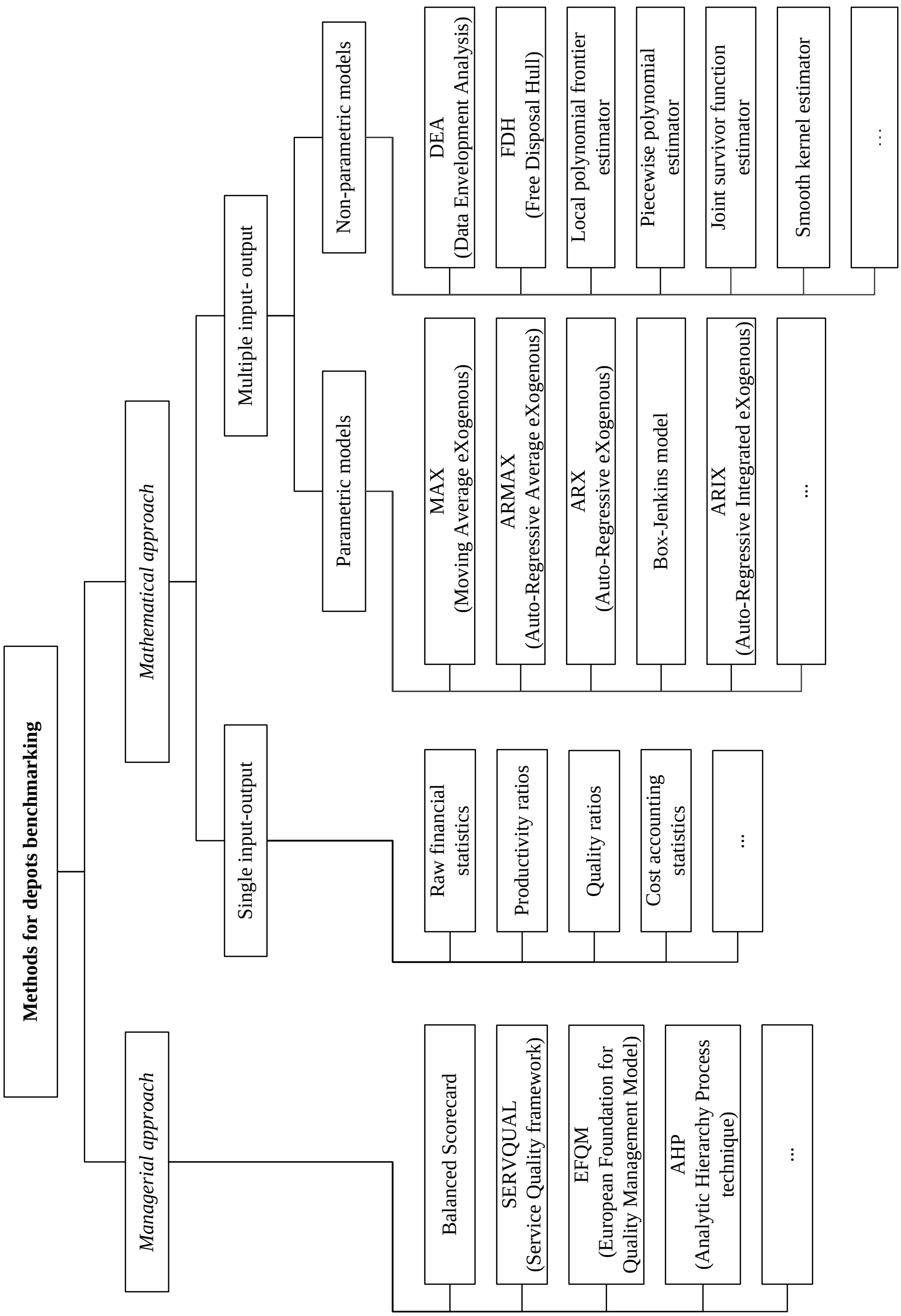


Figure 5.1 Methods used for the assessment of warehouses performance.

utilization of total throughput and storage capacity), quality (e.g. percentage of perfect warehouse orders) and cycle time (e.g. total warehouse cycle time). Warehouse KPIs are simple to evaluate and interpret. However, to find out how a warehouse performs, it is necessary to calculate most of these measures, if not all of them. Furthermore, it has to be analyzed which of these metrics has the biggest influence on the depot's overall performance. This would render a comparison of depots performance levels rather difficult. A solution for this is the use of multi input-output methods, which are discussed below.

Multi input-output methods are able to cope with multiple inputs and multiple outputs simultaneously. These are mostly statistical and econometrical models. In case of the warehouse performance assessment only non-parametric models are being used. The reason is that interrelations between input and output variables and probability distributions of gathered data are often not known upfront. Furthermore, non-parametric models are more robust than parametric ones; this means that results might still be valid even if some assumptions are somehow unwittingly violated. In the literature mainly two non-parametric methods are used to estimate efficiency levels: DEA and FDH (Park et al., 2000). Both methods are based on a production possibility set (pps) and an efficient frontier. The production possibility set is the smallest set of inputs and outputs that are technically feasible. Once the pps is known the efficient frontier, which is a set of the most efficient units, can be derived. The distance from a certain point in the pps to the efficient frontier is called the relative efficiency of the unit under consideration. The difference between FDH and DEA method lies in the estimator of the production possibility set. The pps estimated with DEA must be additionally convex. Consequently the DEA pps is smaller than the FDH pps. In fact the DEA estimator is the smallest free disposal convex set that covers all data (Park et al., 2000). Green and Cook (2004) state that "the pps that achieves the best fit to the observation is the free disposal hull (FDH)." However the authors also state that the effect of a finite sample error in case of FDH is exacerbated in comparison with DEA method. Furthermore, FDH for its implementation requires access to binary programming software, whereas DEA method uses linear programming software, making it easier applicable in business.

5.3 Data Envelopment Analysis

In this study, we decided to use DEA for the evaluation of depots performance levels. The choice is driven by the way, in which the interrelated factors are handled during calculations. The DEA method allows for a correlation between inputs and outputs. Furthermore, no a priori assumptions on the probability of the distribution of used inputs and outputs are needed. For more information on advantages and disadvantages of the method we refer the readers to the following papers: Dyson and Thanassoulis (1988), Bowlin (1998), Sarkis (2000) and Zhu (2003). The extensive literature on DEA and its wide application is the additional advantage. Furthermore, the reason why single KPIs were not sufficient for the evaluation is that we seek for a measure that can include all factors affecting depots services, and can capture all inputs, outputs and the final assessment in one single value.

DEA is a fractional programming technique used to evaluate and compare the performance of a set of similar units: decision making units (DMUs). DEA indicates a set of best performers, i.e. the most efficient units from the total set. Subsequently, it calculates efficiency levels of the remaining DMUs based on the deviation from the efficient units. A DMU is defined as an entity that converts inputs into outputs. It is assumed that an investigation set consists of *n* units (DMU_1, DMU_2, ..., DMU_n), each unit consumes *m* inputs to produce s outputs. A certain unit *DMUj* consumes input i in a quantity of x_{ij} and produces output *r* in a quantity of y_{rj} ($x_{ij} \geq 0$ and $y_{rj} \geq 0$ for all i, j, r). It is assumed that each DMU consumes at least one input and produces at least one output. DEA models can be divided into constant returns-to-scale models (CRS), which are known as CCR models (Charnes et al., 1978) and variable returns-to-scale models (VRS), which are known as BCC models (Bakker et al., 2012). Determination of the type of returns-to-scale (RTS) is very important, because it outlines the shape of the efficient frontier and therefore indicates which DMUs are efficient. The choice of the type of the DEA model used in this study is elaborated in the Section 5.5.

Although DEA is a very flexible method, each DEA model has to fulfill four requirements: positivity property, isotonicity property, number of DMUs, and homogeneity of DMUs. The first restriction requires all inputs and outputs to be positive. The second states that an increase in any input should result in an increase in some output. The third constraint refers to the number of inputs and outputs, which should be at least three times lower than the number of DMUs. The last limitation states that all DMUs should use the same inputs and produce the same outputs. More information on model requirements as well as on possible ways of proceeding in case any of assumptions is violated can be found in Bowlin (1998).

In the previous section the literature on performance measures was presented. Based on this literature, the method most suitable for the evaluation of express depots was chosen and described. In the next section, factors that affect the express depots performance are presented. Afterwards, a DEA model used in our case study is formulated.

5.4 Case study

5.4.1 Identified factors

An input and an output are either a combination of factors (e.g. ratio of the number of consignments processed to the number of employees working) or a single factor (e.g. traffic congestion level). Factors should be perceived as elements of the internal and external environments that affect depot’s performance. To identify these factors for the express company of our case study, a desk research was carried out and interviews with employees were held.

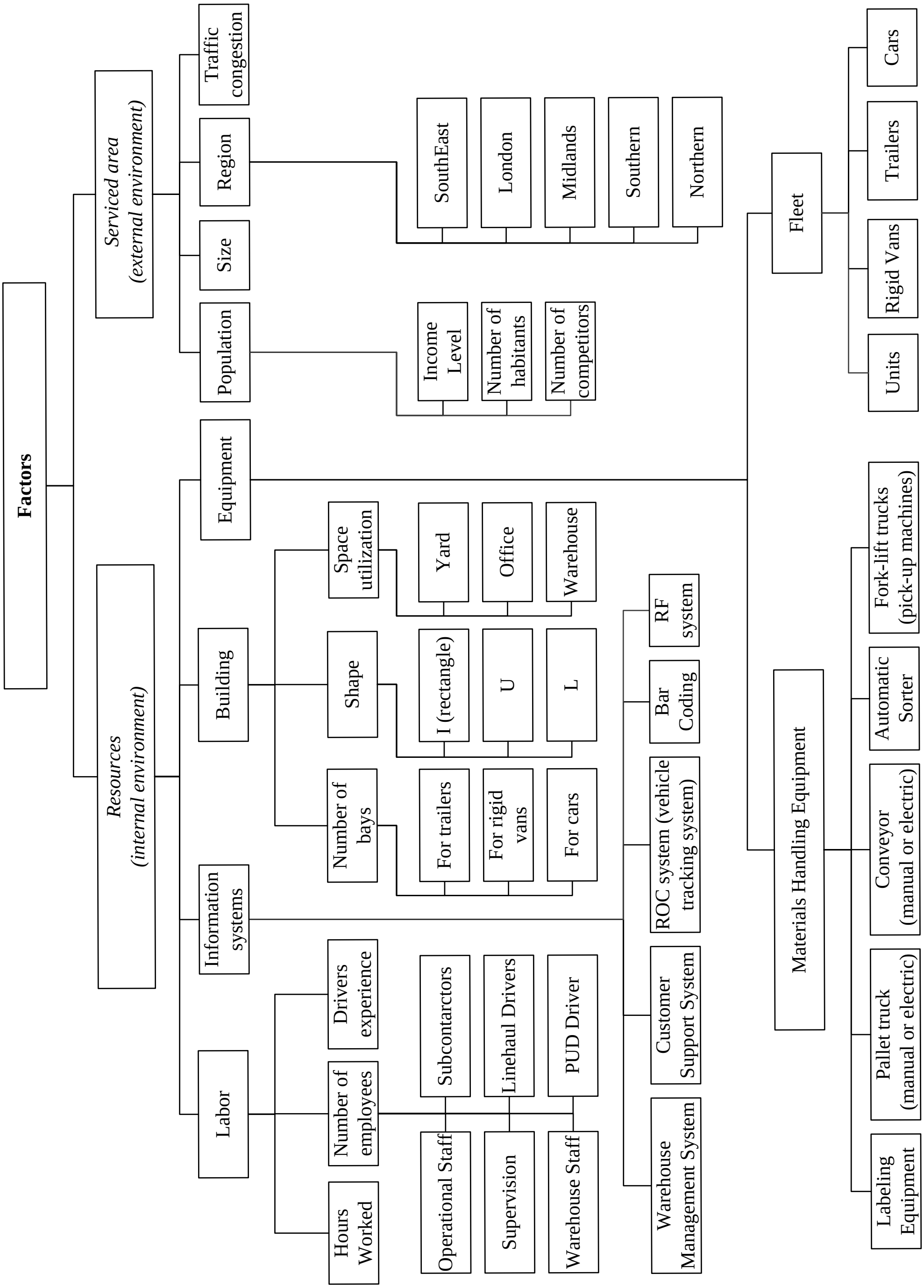


Figure 5.2 Factors affecting depots performance.

Internal factors are represented by resources that are being used during the processes. The identification of relevant resources was based on a literature study (Barros and Peypoch, 2009; Gunasekaran et al., 1999; Hamdan and Rogers, 2008; Jayaram and Tan, 2010; Rouwenhorst et al., 2000; Schefczyk, 1993). The external factors are related to the service area of a certain depot. The identification of outside resources was based on the literature study as well as on the depot's environment study (Jayaram and Tan, 2010; Lebas, 1995; McKinnon, 1999; Ross and Droge, 2004; Stainer, 1997; Van Landeghem and Persoons, 2001). The results of the investigation are presented in Figure 5.2.

5.4.2 Selection of inputs and outputs

Based on the identified factors, 7 outputs and 14 inputs applied to the case at hand were defined and are presented in Table 5.1 and Table 5.2. Additional interviews held during the data gathering phase excluded four inputs: *IT*, *automation*, *MHE*, *experience*. The former input was excluded, because all depots, in order to create a coherent network, use the same systems. The remaining three inputs were excluded due to the lack of data. Furthermore, the investigation sample in this study is a set of 44 depots of the express service provider in the United Kingdom (see Figure 5.3 for the locations of depots).

Table 5.1 Defined outputs

Output	Definition
Service	The customer service level expressed as a percentage of premium parcels delivered on time.
Production	The total number of processed parcels expressed as a sum of parcels that were picked up and delivered.
Productivity rate	The productivity rate expressed as a number of consignments processed per warehouse employee.
Driving efficiency	The driving efficiency expressed as a number of stops per round.
Rounds efficiency	The rounds efficiency expressed as the average number of consignments picked up and delivered per pickup and delivery (PUD) round.
Customers served	The average number of customers that were successfully served; expressed as the average number of successful stops per PUD round.
Stops efficiency	The stops efficiency expressed as the ratio of the average number of successful stops to the total number of stops.

Table 5.2 Defined inputs

Input	Definition
Labor	The direct labor input in picking up, processing and delivering consignments; it is expressed as the number of employees directly related to these operations, i.e. PUD drivers, warehouse and operational staff.
Fleet	The fleet input expressed as a weighted sum of vehicles with regard to a vehicle type. Weights are assigned to each vehicle type based on its average capacity pieces.
Material Handling Equipment (MHE)	The material handling equipment input (electric pallet truck, manual pallet truck, fork-lift truck) expressed as a weighted sum of the MHE with regard to a MHE type. Weights are assigned to each MHE type on the basis of its book value.
Information Technology (IT)	The number of information systems available at a depot; the input is presented on an ordinal scale and it is expressed as a sum of zero-one values (zero – a depot does not possess a certain information system, one – a depot possesses a certain information system).
Automation	The number of automated machinery available at a depot; the input is calculated similarly to the IT input, i.e. it is expressed as a sum of zero-one values, which indicate whether or not a depot possesses certain automated machinery.
Experience	Represents "the maturity of a depot", i.e. employees' knowledge of the environment, processes, operating "customs". It is expressed in depot-years (number of years a depot exists).
Depot	Represents depot's physical properties. Depending on the correlation with the outputs, the input would be expressed as one of the three available values: number of doors, warehouse size, and shape of a depot.
Subcontractors	The number of subcontractors hired by a depot expressed as a ratio of the subcontracted fleet to the whole depot's fleet.
Hub distance	The distance between a certain depot and the central national hub, through which all long-distance consignments flow; it is expressed in kilometers.
Area size	The depot's service area size expressed in square kilometers.
Inhabitants	The number of inhabitants in a depot's service area.
Income	The income level of the population from a depot's service area expressed in pounds per person.
Gross Value Added (GVA)	The value of goods and services produced in the depot's service area expressed in pounds per person.
Traffic	Represents the traffic congestion in the depot's service area, expressed as the average yearly number of vehicles per km of road in the depot's service area.

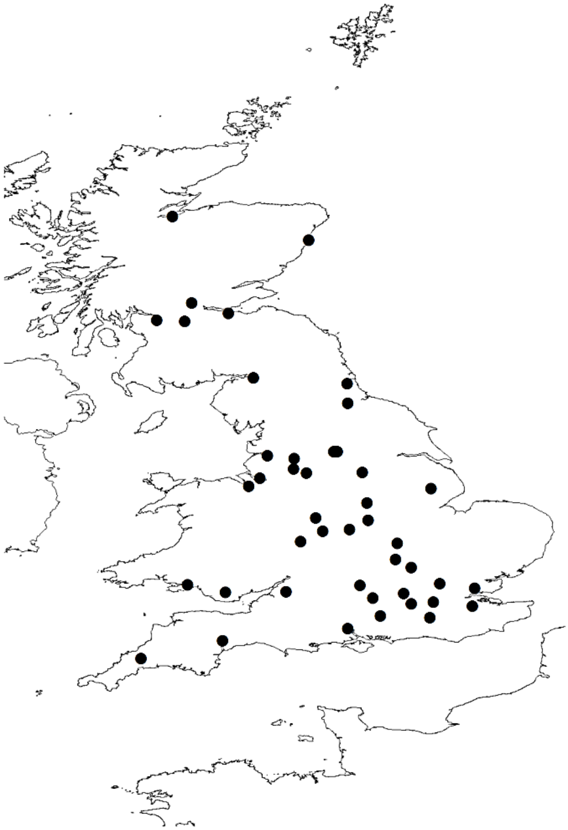


Figure 5.3 Location of depots.

5

Given the assumption regarding number of variables in the DEA model, the number of variables in our model had to be decreased to 14. Consequently, a selection process indicating the most influential inputs and outputs had to be applied. Since no rules regarding the variables' selection for DEA models are available in the literature, we decided to base the selection on Pearson correlation coefficients supported by background information gather during the research. The analysis was conducted in two steps: first correlations between inputs, between outputs and between inputs-outputs were analyzed, and then the isotonicity assumption was examined.

Inputs/outputs correlations

Highly correlated inputs and highly correlated outputs were excluded from the input set, because they bring the same information into the model. For the input set very strong correlations, at the 0.01 level of significance, were noticed between: *labor* and *fleet* ($r = 0.86$), *doors* and *warehouse size* ($r = 0.70$), *income* and *GVA* ($r = 0.77$), *area size* and *traffic* ($r = -0.72$). For the output set very high correlations, also at the 0.01 level of significance, were noticed between: *customers served* and *rounds efficiency* (r = 0.80), *customers served* and *driving efficiency* (r = 0.69), *customers served* and *production* (r = 0.50), *driving efficiency* and *rounds efficiency* (r = 0.57).

Input-output correlations

In contrast to correlations between pairs of inputs and pairs of outputs, input-output pairs with high correlations were kept in the variables' set. The correlations are presented in Table 5.3. The output that correlates the strongest with the input set is *production*. Furthermore, *round efficiency* and *customers served* correlate quite strongly with the input set. *Service level* correlates only with *hub*, yet this correlation is very strong, a similar situation is in case of the output *productivity rate*.

Table 5.3 Person correlations between inputs and outputs

	Output						
Input	Service level	Production	Productivity rate	Driving efficiency	Rounds efficiency	Customers served	Stops efficiency
Labor	0.08	0.60**	-0.36*	0.01	0.41**	0.36*	-0.26
Fleet	-0.08	0.42**	-0.37*	-0.08	0.28	0.23	0.31*
Doors	0.16	0.55**	0.20	0.10	0.27	0.31*	0.00
Warehouse size	0.21	0.30*	0.12	0.07	0.26	0.24	-0.04
Subcontractors	-0.01	0.12	0.65**	0.00	-0.37*	-0.20	0.26
Hub distance	-0.72**	-0.53**	-0.07	0.01	-0.51**	-0.45**	-0.03
Area size	-0.27	-0.38*	0.16	-0.33*	-0.49**	-0.39**	0.12
Inhabitants	0.16	0.56**	0.06	0.12	0.29	0.43**	-0.04
Income	-0.09	0.26	0.03	0.04	-0.05	0.02	-0.12
Gross Value Added	-0.10	0.26	0.17	0.20	0.06	0.09	-0.05
Traffic	0.25	0.49**	0.14	0.21	0.40**	0.34*	-0.13

*** Correlation is significant at the 0.01 level (2-tailed).*
** Correlation is significant at the 0.05 level (2-tailed).*

Based on the correlations analysis presented in Table 5.3, the input set was restricted to six inputs: *labor*, *doors* representing depot, *subcontractors*, *hub* representing hub distance, *area* representing area size, and *population* representing inhabitants. The output set was restricted to five outputs: *service* representing service level, *production*, *productivity* representing productivity rate, *customers* representing customers served, and *stops efficiency*. Although *stops efficiency* weakly correlates with the input set, we decided to include it in the output set, as it may be of particular interest of managers.

The second step was the examination of the isotonicity property, which assumes that directions of input-output correlations cannot be substantially negative. Three input variables are highly, negatively correlated with outputs: (1) *labor* with *productivity*; (2) *hub* with *service*, *production* and *customers*; (3) *area* with *production* and *customers*. To solve the isotonicity violation, a data transformation, i.e. the use of complements, should be applied (Bowlin, 1998). *Hub* varies from 23 to 684, thus complements to 1000 were used. *Area* varies from 0.2 to 26.5, thus complements to 100 were used. As a result directions of correlations of these inputs changed from negative to positive. However, a relation between *labor* and *productivity* remained negative. The transformation of *labor* data would result in the positive correlation between *labor* and *productivity*, but also in the negative correlation between *stops efficiency* and *labor*. Data transformation of *productivity* would have similar consequences. Consequently, the *productivity* output was excluded from the set.

Summarizing, in the final model we included six inputs: *labor* (x_1), *subcontractors* (x_2), *doors* (x_3), *hub* (x_4), *population* (x_5), *area* (x_6); and four outputs: *service* (y_1), *production* (y_2), *customers* (y_3), *stops efficiency* (y_4). All outputs are considered to be controllable, i.e. output levels are the result of managers' decisions, except for *production*. This is because *production* mainly depends on regional demand. Nevertheless, similarly to the profit of an organization, which in many studies is used as a controllable output (Liang et al., 2006; Ross and Droge, 2004; Sarkis, 2000; Wang and Fang, 2001) we decided to treat *production* as controllable. Unlike the output set, the input set can be divided into controllable (x_1, x_2) and uncontrollable (x_3, x_4, x_5, x_6) inputs. Although *door* input can be perceived as controllable, we decided to treat it as an uncontrollable input, because the developed model is designed for a short-term performance (e.g. based on the monthly data). Furthermore, this input is a proxy of warehouse size and both the number of doors and the warehouse size are not modifiable in a short term. Therefore, to evaluate the managerial performance, a model that distinguishes between controllable and uncontrollable inputs was formulated and evaluated.

Furthermore, the developed DEA models fulfill all DEA requirements, i.e. all inputs and outputs are positive, none inputs and outputs are substantially negatively correlated, the number of variables is more than 4 times lower than the number of depots, and all depots consume the same inputs and produce the same outputs.

5.5 Results

In this study, we decided to use an input-oriented DEA model. Such models aim at the minimization of inputs' use. In other words, they indicate the possible decrease in inputs that still allow attaining currents output levels. Therefore, they indicate the source of inefficiencies, and thus provide a possibility to minimize costs. Furthermore, the investigated depots exhibit various RTS (20 depots exhibit VRS, 24 depots exhibit CRS), hence the BCC model was selected to analyze depots performances. However, the CCR model was also constructed in order to extract scale inefficiencies.

In this section, the results of the developed DEA models are presented. First, depots are evaluated with regard to technical efficiency (TE) and aggregate efficiency (AE) (both efficiencies are explained in the following section). Next, a model that takes into account the environmental influence (i.e. uncontrollable inputs) on the performance is developed. By means of this model, the role models of inefficient depots as well as required target levels are indicated. Subsequently, efficient depots are investigated and their benchmark shares are calculated. Finally, statistical tests are run to examine the relations between regions and efficiency scores as well as between depots sizes and efficiency scores.

5.5.1 Technical efficiency and aggregate efficiency

Depending on the efficiency type that is being used in the analysis, different units are identified as efficient i.e. efficient frontiers are different and consequently different target values are obtained. Pure technical efficiency can be calculated with the use of the BCC model. The technical efficiency measures the efficiency of using available inputs to produce given output levels. It takes into account the possibility that the average productivity at a most productive scale size (MPSS) may not be attainable for a DMU operating at other scale sizes. A unit operates at the most productive scale size if it exhibits CRS (Cooper et al., 2000). The aggregate efficiency that includes scale efficiency (SE) and technical efficiency can be calculated with the use of the CCR model. Efficiency scores obtained with this model are smaller or equal to those obtained with the BCC model, because the aggregate efficiency also takes the scale inefficiency into account. The scale efficiency measures the average productivity at the observed input scale relative to what is attainable at the MPSS (Ray, 1999). It is calculated as the ratio of the aggregate efficiency to the technical efficiency.

The aggregate efficiency scores of the depots were estimated with the use of the input oriented CCR model and the technical efficiency scores with the use of the output oriented BCC model with VRS. As a result 31 depots (70%) are indicated to be technically efficient and 24 depots (55%) to be both technically and scale efficient. In Table 5.4, the efficiency scores of inefficient depots are provided. The depots indicated in bold are technically efficient, but in order to be also scale efficient their input levels have to be additionally decreased.

The average efficiency scores of the inefficient depots are as follows: $TE = 0.973$, $AE = 0.961$ and $SE = 0.978$. Furthermore, to make all the inefficient depots technically efficient an input reduction of 1.8% (1 – 0.982 = 0.018) is needed; whereas to attain additionally the scale efficiency an additional input reduction of 2.1% (0.982 – 0.961 = 0.021) has to be applied. This means that every depot that has decreasing or increasing returns to scale should be able to deliver the current level of service with the 1.8% lower input consumption. Moreover, every depot that operates at constant returns to scale should be able to deliver the current service level with the 3.9% lower input consumption.

The obtained percentages depict possible savings. It should be kept in mind that not all the inputs are controllable by managers (e.g. *hub*, *population*, *area*) or can be adjusted in a short-term (e.g. *doors*). Therefore, while estimating the possible input reduction managers should look only at inputs that they can influence e.g. labor, fleet usage. For this purpose, a model that distinguishes between controllable and uncontrollable inputs will be calculated in the next section.

Table 5.4 Technical, aggregate and scale efficiencies of inefficient depots

Depot	Efficiency		
	Technical	Aggregate	Scale
Depot3	0.975	0.969	0.994
Depot4	**1.000**	**0.967**	**0.967**
Depot6	0.999	0.998	0.999
Depot8	0.965	0.962	0.997
Depot9	0.969	0.937	0.967
Depot11	0.973	0.965	0.991
Depot14	0.989	0.989	1.000
Depot15	**1.000**	**0.993**	**0.993**
Depot18	**1.000**	**0.921**	**0.921**
Depot22	0.995	0.994	0.999
Depot23	**1.000**	**0.968**	**0.968**
Depot25	0.967	0.966	0.999
Depot26	0.909	0.899	0.988
Depot27	0.947	0.935	0.987
Depot28	**1.000**	**0.960**	**0.960**
Depot29	**1.000**	**0.918**	**0.918**
Depot30	0.983	0.961	0.978
Depot35	**1.000**	**0.982**	**0.982**
Depot36	0.979	0.954	0.974
Depot39	0.996	0.988	0.993
Average (listed units)	*0.982*	*0.961*	*0.979*
Average (all units)	*0.992*	*0.982*	*0.990*

5

5.5.2 Influence of controllable and uncontrollable inputs on efficiency scores

In case uncontrollable variables exist in the production process, the estimated efficiency score captures not only the managerial inefficiency, but also the environment's effect on the production process. The elimination of the influence of uncontrollable variables allows estimating the efficiency level that is mainly the merit of a depot's manager. Consequently, depots technical efficiencies were again estimated, but this time with the use of a model that considers uncontrollable variables as fixed. The first DEA model taking into account only controllable variables was presented by Wang and Fang (2001). The model is a modification of the input oriented BCC model with VRS (see formula 6.1).

Banker and Morey model:

$$\min\left[\theta - \varepsilon \cdot \left(\sum_{i \in I_c} s_i^- + \sum_{r=1}^{s} s_r^+\right)\right]$$

$$s.t.$$

$$\sum_{j=1}^{n} x_{ij} \cdot \lambda_i + s_i^- = \theta \cdot x_{i0} \qquad \text{for } i \in I_c$$

$$\sum_{j=1}^{n} x_{ij} \cdot \lambda_i + s_i^- = x_{i0} \qquad \text{for } i \in I_u$$

$$\sum_{j=1}^{n} y_{rj} \cdot \lambda_j - s_r^+ = y_{r0} \qquad \text{for } r = 1,2,\ldots,s$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j, s_i^-, s_r^+ \geq 0 \qquad \forall\, j,i,r \tag{6.1}$$

The value of θ^* represents the efficiency score of the DMU and is lower or equal one. The DMUs with $\theta^* < 1$ are inefficient, while the DMUs with $\theta^* = 1$ lie on the efficient frontier and thus are efficient. The vector of optimal λ_j represents weights that are used to project the inefficient DMUs on the efficient frontier. The new position of this DMU is calculated as a linear combination of the adjacent efficient peers using the λ_j as weights. The slack variables s_i^-, s_r^+ are used to convert inequalities of the dual model into equalities in the final DEA model. They are also introduced in the objective function with a smallest positive number as a multiplier $\varepsilon > 0$.

The input set in this model is divided into two sets: I_c with controllable variables and I_u with uncontrollable variables. Furthermore, $I_c \cap I_u = \emptyset$ and $I_c \cup I_u = I$, where I represents a set of all input variables. Consequently, in our model $I_c = \{x_1, x_2\}$ (x_1 - *labor*, x_2 - *subcontractors*) and $I_u = \{x_3, x_4, x_5, x_6\}$ (x_3 - *doors*, x_4 - *hub*, x_5 - *population*, x_6 - *area*). In the model only variables that are associated with I_c are optimized (first constraint in formula 6.1) and variables associated with I_u are kept at their actual levels (the second constraint in formula 6.1). Moreover, slacks associated with uncontrollable inputs, s_i^- and $i \in I_u$ do not enter into the efficiency score.

Table 5.5 presents the efficiency scores estimated with the use of the old model with all controllable inputs (VRS1) and the new model discriminating between controllable and fixed inputs (VRS2). Both models indicated the same depots as technically inefficient; however the VRS2 model estimated lower efficiency scores, on average 14.1% lower. This means that the performance level of depots is in 14.5 % (0.141/0.973) due to favorable external environment (e.g. low level of traffic congestion, small service area, high population's income), and in 85.4% (0.832/0.973) due to the management techniques (e.g. quality of training programs for employees, breakdown occurrences, percentage and quality of subcontracted fleet, etc.). The lower values in the VRS2 can be explained as follows. In the VRS1 model all inputs are minimized, whereas in the VRS2 only controllable inputs are minimized. Consequently, fixed input levels (uncontrollable input levels) in the VRS2 are

Table 5.5 The efficiency scores of inefficient units according to VRS1 and VRS2 models

Depot	Model		Difference
	VRS1 - normal	VRS2 - modified	
Depot3	0.975	0.825	0.150
Depot6	0.999	0.995	0.004
Depot8	0.965	0.728	0.236
Depot9	0.969	0.887	0.082
Depot11	0.973	0.685	0.288
Depot14	0.989	0.826	0.163
Depot22	0.995	0.933	0.062
Depot25	0.967	0.743	0.224
Depot26	0.909	0.812	0.097
Depot27	0.947	0.655	0.292
Depot30	0.983	0.862	0.121
Depot36	0.979	0.920	0.059
Depot39	0.996	0.947	0.049
Average	*0.973*	*0.832*	*0.141*

higher than the estimated input levels of the VRS1. Given the negative correlations between fixed variables and efficiency scores (see Table 5.6), higher levels of fixed inputs will result in a lower efficiency level. Furthermore, the inefficiency scores $(1-\theta^*)$ that indicate the reduction in controllable input required to become efficient are higher in VRS2. This is because the reduction in controllable variables (*labor* and *subcontractors)* has to account for inefficiencies caused by the high values of fixed inputs.

Table 5.6 Person correlations between efficiency score (VRS1) and variables

Pearson Correlation	x_1	x_2	x_3	x_4	x_5	x_6	y_1	y_2	y_3	y_4
θ (VRS1)	-0.206	0.009	-0.125	-0.141	-0.022	-0.201	0.083	-0.031	0.193	0.136

The use of the VRS2 model is more logical, because it is impossible for a depot's manager to decrease the uncontrollable inputs. Stated differently, the target levels calculated with the use of VRS2 are theoretically possible to attain by a depot manager's decisions (model optimizes only controllable inputs). Consequently, the VRS2 model is used in the further analyses of the depots performance.

5.5.3 Inefficient depots: peers and target values

The VRS2 model identified 31 depots as efficient and 13 as inefficient. To transform inefficient DMUs into efficient ones, it is very worthwhile for a depot manager to know his referent DMUs and target levels. Referent DMUs are identified by means of lambda values. If $\lambda_j^* > 0$ then the j-th efficient unit is a referent DMU of the inefficient DMU_0. Lambdas are expressed in percentages and presented column-wise in Table 5.7. The first column includes only 20 efficient depots, the remaining 11 depots were not indicated as peer DMUs for any inefficient depot. This means that the respective output levels of these 11 depots differ considerably from the service levels of inefficient depots. Therefore, these depots should not be taken into consideration during the learning stage.

Table 5.7 Lambda values of referent DMUs of inefficient depots (%)

	Inefficient												
Efficient	Depot3	Depot6	Depot8	Depot9	Depot11	Depot14	Depot22	Depot25	Depot26	Depot27	Depot30	Depot36	Depot39
Depot1	18.3	-	9.8	-	7.6	-	-	12.2	0.4	2.7	-	1.5	9.7
Depot2	-	13.2	-	-	-	5.9	-	11.0	-	34.6	5.2	-	39.2
Depot5	-	11.9	5.4	12.0	-	-	-	10.0	46.7	12.6	28.5	2.7	-
Depot7	10.3	7.2	-	-	-	-	-	-	-	-	-	-	19.9
Depot10	-	-	-	-	-	-	0.2	-	-	-	-	-	-
Depot13	-	-	-	0.9	4.8	-	23.8	-	-	-	-	-	-
Depot16	-	9.6	-	-	17.0	-	23.1	-	28.9	-	-	-	-
Depot17	-	-	-	-	-	1.5	-	-	-	-	-	-	4.0
Depot21	-	-	-	-	0.7	0.0	11.5	-	0.2	-	-	62.6	-
Depot24	-	-	-	-	2.3	-	-	-	-	-	-	-	-
Depot31	-	15.8	31.3	13.4	32.2	3.1	31.9	29.2	-	28.1	35.3	-	-
Depot32	-	-	-	17.6	-	-	-	-	-	-	23.1	-	-
Depot33	-	-	27.1	-	-	-	-	21.5	-	-	6.1	29.7	-
Depot34	-	-	-	-	1.3	-	-	-	-	-	-	-	-
Depot37	60.3	42.4	-	-	-	55.9	-	-	-	-	-	-	27.2
Depot38	11.1	-	6.5	25.5	34.1	-	-	-	23.8	-	1.8	3.4	-
Depot40	-	-	-	-	-	33.6	-	-	-	-	-	-	-
Depot42	-	-	-	-	-	-	-	16.1	-	-	-	-	-
Depot43	-	-	20.0	-	-	-	-	-	-	22.0	-	-	-
Depot44			-	-	-	30.6	-	-	9.6	-	-	-	-

Based on the linear combination of the referent DMUs' input values, using lambdas as weights, the inefficient DMU is projected on the efficient frontier. The projection values are treated as target levels. Another approach to estimate target values is the use of efficiency scores and slack values. The "CCR projection formula" (formula 6.2) calculates target levels for inefficient DMUs.

CCR projection formula:

$$\hat{x}_{i0} = \theta_0^* \cdot x_{i0} - s_i^{-*}, \quad i \in I_c$$
$$\hat{x}_{i0} = x_{i0} - s_i^{-*}, \quad i \in I_u$$
$$\hat{y}_{r0} = y_{r0} + s_r^{+*}, \quad r = 1,2,\dots,s \qquad (6.2)$$

The $\hat{x}_{i0}, \hat{y}_{r0}$ values represent the coordinates of a point on the efficient frontier. The inclusion of slacks in this formula ensures that inefficient depots become efficient (not weakly efficient), i.e. depots are situated on the efficient frontier and an additional possible input reduction represented by s_i^{-*} is taken into account. To illustrate this, Table 5.8 presents calculations for Depot3.

Table 5.8 Target levels for Depot3

Depot3 (θ = 0.825)	x_1	x_2	x_3	x_4	x_5	x_6
Initial level	142.00	0.32	60.00	771.00	1436.64	96.74
Slack	3.83	0.00	0.00	0.00	0.00	0.00
Target level	113.32	0.26	60.00	771.00	1436.64	96.74
Required decrease	28.68	0.06	0.00	0.00	0.00	0.00
Required decrease (%)	20.20	18.80	0.00	0.00	0.00	0.00

The value of the slack s_1^{-*} = 3.83 (in Table 5.8) indicates that the projection of Depot3 on the efficient frontier makes Depot3 weakly efficient. Therefore, in order to make Depot3 efficient an additional reduction of 3.83 in *labor* input should be accomplished. Similar calculations were conducted for every inefficient depot. As a result, it is possible to estimate the overall potential for input reduction of the express company. For the inefficient depots, labor input can be decreased on average by 17.0% and the number of subcontractors can be decreased by 16.9%. Therefore, only the replication of efficient processes of the efficient depots by the inefficient depots can lead to possible reductions of 239 staff members and of 918 subcontracted routes.

The replication of processes of efficient depots should be based on interviews with managers and employees, as well as on regular visits to the efficient depots. These actions can reveal different management practices e.g. a high number of employees training programs, higher educated employees, divers sources of subcontracted fleet, own fleet with subcontracted and experienced drivers, etc. The enumerated examples may contribute to more efficient employees, and thus improve the depot's performance level.

5.5.4 Benchmark share

A benchmark share reflects the importance of an efficient DMU as a referent DMU for inefficient DMUs. The benchmark shares were calculated, following Zhu (2003), in two steps. First, measure specific models were calculated for each inefficient depot (formula 6.3). These models determine maximal possible decrease in a certain input, while keeping the remaining inputs and all outputs at the initial level. Next, input-specific benchmark shares for each efficient unit were evaluated (formula 6.4). The measure specific efficiency score is defined as $\theta_d^{k^*}$, where k indicates the k-th input that is optimized and $d \in N$ indicates the inefficient unit d that belongs to the set of inefficient units N. The benchmark share of j-th efficient unit is defined as Δ_j^k and a set of efficient units is defined as E.

$$
\begin{aligned}
&\min\left(\theta_d^k\right) \rightarrow \theta_d^{k^*}, \qquad d \in N \\
&\text{s.t.} \\
&\sum_{j \in E} x_{kj} \cdot \lambda_j^d = \theta_d^k \cdot x_{kd} \qquad for \quad k \in \{1, \dots, m\} \\
&\sum_{j \in E} x_{ij} \cdot \lambda_j^d \leq x_{id} \qquad for \quad i \neq k \\
&\sum_{j \in E} y_{rj} \cdot \lambda_j^d \geq y_{rd} \qquad for \quad r = 1, \dots, s \\
&\sum_{j \in E} \lambda_j^d = 1 \\
&\lambda_j^d \geq 0 \qquad for \quad j \in E
\end{aligned}
\tag{6.3}
$$

$$
\Delta_j^k = \frac{\sum_{d \in N} \lambda_j^d \cdot \left(1 - \theta_d^{k^*}\right) \cdot x_{kd}}{\sum_{d \in N} \left(1 - \theta_d^{k^*}\right) \cdot x_{kd}} \tag{6.4}
$$

Benchmark shares for 11 selected efficient depots are presented in Table 5.9, each of these depots is at least in one "top five role models for benchmarking" with regard to a specified input (values in bold), e.g. Depot2 is in the top five role models for labor and subcontractors emulation. The values in brackets indicate the best role model for emulating a specific input. The next to last column summarizes the benchmark share for each depot only with regard to controllable inputs, whereas the last column depicts the overall benchmark share of each depot. As can be seen Depot31, Depot2, Depot37, Depot21, and Depot38 are the leading depots. They are respectively the best role model for *labor* (x_1), *subcontractors* (x_2), *doors* (x_3), *hub* (x_4) and *area* (x_5), *population* (x_6) emulation respectively. This means that these depots play leading roles in setting benchmarks with respect to a certain input, given the current level of other inputs. Furthermore, Depot31 leads in the total benchmark share for controllable inputs and for all inputs, and as such can function as a role model for the other depots in the United Kingdom.

Table 5.9 Benchmark shares of 11 selected depots (%)

Depot	Input x_1	x_2	x_3	x_4	x_5	x_6	Total (controllable)	Total (all)
Depot2	**14.15**	**(16.22)**	0.13	2.87	1.02	1.94	**30.37**	36.34
Depot5	**10.84**	7.17	4.50	**11.95**	4.20	1.04	**18.01**	39.70
Depot7	2.58	**9.15**	1.65	**14.02**	**8.18**	**8.12**	11.73	43.70
Depot10	1.10	0.38	**10.35**	0.00	1.60	**10.22**	1.48	23.66
Depot16	**10.34**	1.00	**8.86**	1.43	0.87	0.20	11.34	22.70
Depot21	2.83	3.84	1.19	**(19.19)**	1.33	**(23.96)**	6.66	**52.34**
Depot31	**(18.73)**	**15.64**	8.52	6.92	**9.13**	**9.12**	**(34.37)**	**(68.05)**
Depot33	**10.57**	1.85	**17.97**	4.52	2.89	**10.81**	**12.42**	**48.60**
Depot37	2.65	8.71	**(25.65)**	**9.66**	**6.58**	5.28	11.36	**58.54**
Depot38	8.82	**10.24**	**8.68**	**7.67**	**(22.28)**	2.17	**19.07**	**59.86**
Depot43	0.45	**9.62**	0.00	0.00	**16.41**	4.45	10.07	30.94

Each of these role model depots can be treated as a master depot in using efficiently a certain input. Consequently, the investigation of the practices used in these depots is a crucial part of the learning stage.

5.5.5 Relationship between the efficiency score and variables

A linear regression model is an effective way of measuring relations between dependent and independent variables. However, it assumes variables to be normally distributed. Since a large proportion of the efficiency scores is clustered at a value of 1, the assumption of a normal distribution of residuals is violated. The solution is to use a logistic regression (logit or probit model) (Cooper et al., 2000; Hackman et al., 2001). Consequently a logit model that measures the relations between variables and efficiency scores was constructed. For this purpose, a new dependent variable E_j was introduced, which was assigned a value of one if ${\theta_j}^* = 1$ and a value of zero if ${\theta_j}^* < 1$. Three regression models with the dependent variable E_j and the following independent variables were calculated: (1) model A – $x_1, \dots, x_6, y_1, \dots, y_4$; (2) model B – $x_1, \dots, x_6$; and (3) model C – $y_1, \dots, y_4$. The model A was chosen based on the following criteria:

- the highest log-likelihood ratio value;
- the lowest Akaike information criterion (Hirotugu, 1974);
- the Chi-square statistic, which should be higher than the critical value: $\chi^2 > {\chi^2}^*$ and $p - value < 0.05$.

The parameters of the regression model were estimated with the use of maximum likelihood estimation. The results of the model A are presented in Table 5.10.

5

Table 5.10 Results of logistic regression

Variable	Coefficient (β_i)	Std. Error	t stat	$p - value$
Const	-37.315	48.421	-0.771	0.441
x_1 labor	-0.083	0.037	-2.228	0.026**
x_2 subcontractors	-9.101	4.854	-1.875	0.061*
x_3 doors	0.053	0.059	0.898	0.369
x_4 hub	-0.010	0.008	-1.363	0.173
x_5 population	-0.003	0.002	-1.673	0.094*
x_6 area	-0.263	0.249	-1.053	0.292
y_1 service	22.385	45.662	0.490	0.624
y_2 production	0.063	0.030	2.090	0.037**
y_3 customers	0.009	0.096	0.089	0.929
y_4 stops efficiency	59.615	38.561	1.546	0.122

*** Significant at the 0.01 level (2-tailed)*
** Significant at the 0.05 level (2-tailed)*

According to the results only *labor, subcontractors*, *population* and *production* have a significant influence on the efficiency score ($p - value < 0.05$). This means that the reduction in *labor*, *subcontractors* and *population*, and the increase in *production* can significantly increase depot's probability of being efficient. In practice, it means that a depot manager can achieve higher performance levels by improving the controllable factors of *labor* and *subcontractors*. Furthermore, the location of a depot in an area with a lower population's level can also contribute to a better performance.

The variables determined by the model as significant can be perceived as critical factors that influence the performance levels of depots. Therefore, the appropriate input and output levels of these variables are critical for efficient operating and should get relatively more focus.

5.5.6 Regional differences in efficiency scores

To identify whether the efficiency scores depend on the depot's region, four non-parametrical tests were run: Kruskal-Wallis, Mann-Whitney, Kolmogorov-Smirnof and Wald-Wolfowitz. These tests verify whether two (or more) groups follow the same distribution. In our case, tests indicate whether the efficiency scores differ between subgroups. The non-parametrical tests were chosen instead of the more popular variance analysis, because the tested efficiency scores are not normally distributed. The UK was divided into five regions: London, Midlands, North, South East and South. The number of depots per region and the average efficiency score for each group are presented in Table 5.11.

Table 5.11 Average efficiency scores according to regions

Region	London	Midlands	North	South East	South
Number of units	4	9	14	7	11
Average efficiency	0.846	0.960	1.000	0.948	0.923

First the Kruskal-Wallis test was run. The results of the test are presented in Table 5.12. The p-value of 0.076 indicates that there are no reasons for rejecting the null hypothesis, thus there are no significant difference in efficiency scores between five regions.

Table 5.12 Results of Kruskal-Wallis test

Kruskal-Wallis test (grouping variable: region) (α = 0.05)		
Chi-square	df	$p - value$
8.455	4	0.076

To confirm this result, the remaining tests were also run with the same significance level of $\alpha = 0.05$. The result of the Kruskal-Wallis test was entirely confirmed by Kolmogorov-Smirnof and Wald-Wolfowitz test, and partly by Mann-Whitney test. The latter indicated that the distribution of the efficiency score of 3rd region differs from the distributions of the remaining regions. Nevertheless, given the results of all four tests, we concluded that there are no differences in the efficiency scores across regions.

5.5.7 Depot's size and efficiency score

Many past studies showed that larger warehouses seem to be less efficient than the smaller ones (De Koster and Balk, 2008; Hackman et al., 2001; Hamdan and Rogers, 2008; Schefczyk, 1993). To verify this on our data, statistical tests were run. Since in our model a variable that represents a depot's size was not included, the *door* variable was used as a proxy. The correlation between the warehouse size (m^2) and the number of doors is high, $r = 0.703$. Two approaches dividing depots into a different number of groups were used:

- two groups: small depots with a number of doors lower or equal 39, and large depots with a number of doors higher than 39;
- three groups: small depots with a number of doors lower than 36, medium depots with a number of doors lower than 46, and large depots with a number of doors higher than 46.

The average efficiency scores and number of units are presented in Table 5.13. Similarly to the "regional differences" four tests were run to investigate whether the efficiency scores differ among groups. The null hypothesis was not rejected by any test. Thus it cannot be stated that depots with higher number of doors (consequently larger depots) are significantly more efficient than the smaller ones, neither can it be stated that larger depots are significantly less efficient than the smaller ones. The statement regarding higher efficiency of

Table 5.13 Average efficiency scores according to a depot's size

	Testing approach				
	2 groups		3 groups		
Size	Small (1)	Large (2)	Small (1)	Medium (2)	Large (3)
Number of units	24	20	17	12	15
Average efficiency	0.947	0.954	0.972	0.920	0.950

small distribution centers is rejected in case of distribution centers of express companies.

In this section, the performance levels of depots were estimated and analyzed from five different angles: the depots technical efficiency versus the scale efficiency, the managerial efficiency, the identification of critical factors, the relationship between the depot's region and the resulting efficiency score and the relationship between the depot's size and its efficiency level. In the next section, the results of this study are summarized and conclusions are drawn.

5.6 Conclusions and recommendations

The goal of this study was to develop a methodological framework for assessing the efficiency levels of express companies' depots. The literature study showed that DEA is the most suitable methodology for the problem. The developed DEA model includes two controllable inputs (*labor*, *subcontractors*), four uncontrollable inputs (*doors*, *hub*, *population*, *area*) and four controllable outputs (*service*, *production*, *customers*, *stops efficiency*). Literature reviews revealed that such models, for sorting distribution centers with no storage, are lacking in the area of the performance measurement.

By means of DEA models, technical efficiencies and scale efficiencies were calculated. According to the results, 31 (70%) depots are technically efficient and 24 (55%) depots are technically and scale efficient. After calculating the efficiency levels, the required target levels necessary for the inefficient depots to become efficient were indicated. We have shown that an average decrease of 16.9% in *subcontractors'* usage and of 17.0% in *labor* units is possible. Before this model was developed, there was no clear method for estimating the savings potential of bringing the inefficient depots up to a standard. Next, the model revealed the overall worst performing depots and the depots with the highest benchmark share.

The next step was the identification of critical factors. For that, a logit model that estimates the influence of input and output variables on the final efficiency scores was constructed. In the last phase statistical tests were used to investigate whether the differences in efficiency scores exist among regions and depots sizes.

The next step for the investigated company is to start a learning process for the inefficient depots by working together with their referent depots. The inefficient depots have to learn how to use fewer resources and still obtain the required output levels.

The study revealed a gap in the availability of important data at the express company, which could have a significant influence on the calculated efficiency scores (e.g. customers' views on express company's services, employees' satisfaction). Additional studies in this direction can reveal interesting relations e.g. a relation between a high employees' satisfaction and a high efficiency level.

Chapter 6

General conclusions and discussion

6.1 Context of the research

The overall objective of this research was to contribute to the improvement of milk valorization in the dairy industry. We had the advantage of a close cooperation with FrieslandCampina (FC), one of the largest dairy companies in the world. This gave us useful insights into the dairy world in practice and thus allowed us to better address the most relevant issues. We approached FC challenges in milk valorization from a Logistics Management (LM) perspective. With the use of Operations Research (OR) techniques, we developed quantitative models and frameworks to improve milk valorization process. This process was defined as the *optimal allocation of milk to the most profitable dairy products while taking all important constraints and requirements into account*.

The investigation of the case company indicated that large gains in valorization can be achieved at the tactical planning level. The additional investigation of the available literature revealed the lack of an appropriate and comprehensive tool to support mid-term planning. As a result, in the first part of this research, we focused on the development of the mid-term valorization model for the optimal allocation of milk and production planning. Furthermore, since monitoring, feedback, learning and re-planning are vital components of the planning process (Gibson, 1991), and knowing that milk valorization is affected by various uncertainties related to demand, supply, process, planning and control (Lee, 2002; Stevenson and Spring, 2007; Van der Vorst, 2000; Van Donk, 2001), the second part of the research we devoted to performance evaluation.

To achieve the research objective, we posed four research questions. The first two questions are related to the development of the valorization tool (part I):

1) Which elements should be included in the model to properly represent the complete dairy system and allow for efficient milk valorization?
2) What is the added value of integrating byproducts valorization into the main valorization process and does it affect the production of main milk products?

and the last two questions are related to performance evaluation (part II):

3) How can we assess the robustness of valorization plans obtained with deterministic models?
4) How can the performance of processing units be measured and improved?

A separate study (and chapter) was devoted to each of the research questions. The outcomes of the studies resulted in recommendations on how the valorization of milk can be improved. The main findings and conclusions following from the studies are presented in the following section. Afterwards, the scientific contribution, limitations and opportunities for the further research, as well as managerial implications are discussed.

6.2 Main findings and conclusions

Study 1: Dairy Valorization Model (Chapter 2)

The aim of the first study was the development of a comprehensive Dairy Valorization Model (DVM) that creates optimal mid-term plans for the allocation of milk and production of end products and byproducts while considering all relevant constraints. The main question to be answered was: *"Which elements should be included in the model to properly represent the complete dairy system and allow for efficient milk valorization?"*

The final list of important elements affecting the valorization of raw milk was identified based on a literature study and interviews with experts. Models available in the literature that focused on the allocation of raw milk to end products were investigated based on elements they included. To verify the list of elements, the environment and processes of FC were studied in detail. Additionally, iterative sessions with relevant employees (dairy supply chain managers, production planners, technologists, and market analysts) were held. During these sessions intermediate results were also discussed. This pragmatic stepwise approach resulted in a final list of elements that are important for successful valorization of milk and should be included in the model. These are: recipes based on raw milk composition, seasonality of raw milk composition and supply, complete dairy product portfolio, byproducts utilization, network of supply regions and production locations, byproducts and raw milk transportation, and changes in sale prices (see Figure 2.1 on page 28 for the input and output parameters of the model).

The discussions with experts indicated that the seasonal composition of raw milk (dry matter, fat and protein content) plays an important role in the valorization process, because it affects, among others, volumes of raw milk necessary for the production of specific end products. The large impact of the fat and protein components on the valorization of milk was also confirmed by the conducted study on the robustness assessment presented in Chapter 4. Therefore, apart from identifying the elements that should be taken into account during the valorization of milk, the impact of seasonality of raw milk's composition on the valorization process was evaluated with the use of the developed DVM. The results showed that monthly percentage differences in profit between a scenario that incorporates the seasonal composition of milk and a scenario that neglects the seasonal composition of milk, can differ up to 4% (see Figure 2.6 on page 42). Given the turnover of a large company as FC, this 4% is a considerable difference when translated into monetary value. Furthermore, monthly percentage differences in production volumes of end products (aggregated in clusters) of the two indicated scenarios can differ up to 50% (see Figure 2.8 on page 43). These large differences in profit and in the allocation of milk to different end products showed that seasonal composition of raw milk has a considerable impact on the valorization decisions.

Based on the findings of this study, we concluded that in order to successfully valorize milk a comprehensive milk valorization model that incorporates the elements indicated in this study is necessary. It is especially important to base the production process (production recipes) on the components present in raw milk and not only on the volumes of input materials (as in the majority of current literature), as they considerably affect valorization plans.

Study 2: Whey valorization (Chapter 3)

The DVM developed in the first study aims at the valorization of main milk products. The production of main products, however, results in additional large volumes of byproducts. Further processing of those byproducts may affect the valorization of main products and thus it may be valuable to incorporate it in the main valorization process. Therefore, the aim of the second study was the evaluation of the effect of byproducts valorization on dairy processing companies measured via changes in profit (economic impact) and changes in the production of main milk products. As a case study, we used cheese and casein whey that is an important byproduct in the dairy industry. The following question was answered in this study: *"What is the added value of integrating byproducts valorization into the main valorization process and does it affect the production of main milk products?"*

To answer the research question, we used the Integral Dairy Valorization Model (IDVM), which is an amended version of the DVM. Multiple scenarios defined with data gathered at FC were implemented in the IDVM. Next, we developed a three step evaluation approach to compare results of integral valorization (simultaneous valorization of whey and main milk products) and stepwise valorization (valorization of whey follows the valorization of main milk products). For the schematic overview of the approach see Figure 3.4 on page 57.

The analysis of the outputs of stepwise valorization indicated that the explicit valorization of whey byproduct, as currently executed in practice, leads to significant economic gains, which in turn leads to environmental and social gains. The overall profit obtained from stepwise valorization of milk and whey byproducts is attributed for 80.4% to milk based end-products and for 19.6% to whey-based end products. In other words, the profit obtained from post-processing of whey flows (whey valorization) amounts to around 24.4% of the profit made on main milk products. We define profit from main milk products as a profit obtained from sales of milk-based end products, excluding the value of whey byproduct and reduced by costs of raw milk. The possibility of obtaining this additional profit provides incentives to producers to continue exploring further possibilities of byproducts valorization. Additionally, more focus on byproducts valorization will decrease the environmental impact (less byproducts disposed into the environment) and the social impact (less food wasted in the supply chain). The analysis also indicated that the effect of integral valorization is small; that is, on average 0.0089% increase in the monthly profit. This finding is contrary to the expectations of company experts interviewed. Nevertheless, the effect can change significantly in case the demand for whey-based products is 100% higher (293% stronger effect in comparison to the initial effect), sale prices of milk powders are 25-50% higher (84-92% stronger effect), or sale prices of Cheeses are 25% higher (90% weaker effect). It was surprising to observe that the increase in prices of Cheeses decreases the differences in profit between integral and currently used stepwise valorization. This is related to changes in the sale prices ratio of Cheeses and IFCMP/WMP. This result emphasized the importance of relation between sale prices of those products, as it can easily affect raw milk allocation decisions. The effect of integral valorization is even stronger if the increase in market demand for whey-based products occurs at the same time as the increase in sale prices of those products (even up to 987% stronger effect). If additionally capacities for whey-based products are expanded the effect increases with 1,207% (in comparison to the current situation). Finally, the analysis of outcomes indicated that while integral valorization is applied less Nature Cheese and more IFCMP/WMP (milk powders) is produced in comparison to stepwise valorization. Thus, the incorporation of the information on the value of processing of whey flows in the valorization of main dairy products negatively affects the production of cheese.

Based on the conducted study, we concluded that:

- the mid-term valorization model combined with the developed three-step evaluation approach is a suitable method for the evaluation of the effect of byproducts valorization on the valorization of main products and of the added value of integral valorization;
- the added value of byproducts valorization can be high (processing of whey flows accounts for 19.6% of the total profit obtained with the stepwise valorization);
- effect of integral valorization depends on four main factors: (1) market demand and (2) sale prices of end products made from byproducts, (3) sale prices of main products using byproducts based inputs or producing byproducts, (4) processing capacities for byproducts flows;
- in the case of the dairy industry, application of integral valorization affects the production of main milk end products to a little extend (shifts only from the production of Nature Cheese to the production of IFCMP/WMP);
- whey products are currently not profitable enough to drive the production of source milk products: Cheese and Caseinate.

The discussed results show that numerical analyses, as the one presented in this study, are essential for managers to give indications where most benefits can be obtained. Furthermore, as indicated, currently both valorization processes can be conducted separately. In case strong developments in prices of end products related to byproducts occur and possibilities for extending markets or capacities of whey-based products emerge, a reassessment is advised.

Study 3: Robustness evaluation (Chapter 4)

The outcomes of the first and the second study indicated that the developed DVM is a suitable tool for mid-term valorization as it optimally allocates milk to end products. Furthermore, by means of various analyses, important insights into the interrelated processes of a dairy system can be obtained. The fact that the developed DVM is a linear programming model, on the one hand facilitates the analyses process, but on the other hand it neglects the uncertainty ingrained in the input data. As a result, the robustness of obtained solutions, that is, the deviations in optimal solutions resulting from wrongly forecasted input data, is questionable. The robustness of valorization plans is important, because the valorization plans that are initially indicated as optimal can easily become sub-optimal or costly. The additional costs can be incurred due to necessary and considerable adjustments of plans that have to be made ad hoc in case realizations of uncertain parameters deviate from the forecasted values. Therefore, the overall goal of the third study was to develop a framework for robustness evaluation of valorization plans obtained with deterministic models. The following question was answered in this study: "*How can we assess the robustness of valorization plans obtained with deterministic models?*"

The most suitable approach for the evaluation of deterministic valorization plans was identified via literature study. We researched definitions, methodologies and approaches used for the evaluation of robustness of quantitative decision support models. Furthermore, we analyzed the suitability of available methods for the evaluation of robustness of valorization plans of deterministic models. The following definition of robustness was used: *the degree to which critical performance measures remain within a predefined robustness range, for different realistic scenarios of input data*. The evaluation framework developed in this study is based on the *scenario planning* approach discussed by Van Landeghem and Vanmaele (2002). Multiple scenarios with various possible realizations of input data were implemented in the DVM. While assessing the robustness of valorization plans, we also looked at *model robustness* (frequency of occurrence of infeasible solutions) and *solution robustness* (deviations in the objective function values with regard to the optimal solution obtained with the forecasted input data). Since deterministic models can handle only one scenario at a time, we proposed a procedure on how to evaluate (aggregate) the overall robustness of valorization plans based on obtained solutions for various (input) scenarios. In order to receive feedback on the suitability of the proposed approach, we conducted a number of interviews and discussions with experts from FC.

The developed framework for the evaluation of robustness of valorization plans obtained with deterministic models comprises five steps: (1) Key Performance Indicators (KPIs) definition, (2) input parameters selection, (3) scenarios definition, (4) robustness evaluation, and (5) conclusions (see Figure 4.3 on page 81). The key step in the proposed framework is the evaluation of the robustness based on the obtained multidimensional outcomes (Step 4). Multidimensionality is related to the fact that KPIs, which are directly linked to the robustness degree, are obtained per parameter (or element), per month (or year), and per scenario. Thus, a specific KPIs grouping approach has to be selected. For instance, a robustness degree can be expressed as a (weighted) average of KPIs. The study indicated that the selection of the following four aspects can significantly affect the final robustness degree of valorization plans: (1) the accepted KPIs limits (so called robustness bounds), (2) evaluation time level (month or year), (3) evaluation depth level (parameter or element), and (4) grouping approach of KPIs. Together with the relevant employees of FC, the following aspects were chosen to evaluate the robustness of valorization plans obtained with the DVM: (1) Lower Robustness Bounds of 95%, (2) monthly level, (3) parameter level, and (4) the average of KPIs. The overall robustness degree of valorization plans (at FC) obtained with the DVM was 90% and was indicated by FC as sufficiently high to attain successful milk valorization. We also observed that depending on the selection of listed aspects, the average robustness degree varied from 48% to 92%. This difference is significant, as the robustness degree of 48% indicates valorization plans as non-robust and of 92% as robust; and thus the final conclusions regarding the robustness degree of plans is affected. In case the robustness degree is too low, managers should take different actions to improve it. For instance, more attention can be given to the improvement of forecasts or investigation of the possibility of applying other modeling techniques that incorporate input data uncertainties. The calculated robustness degrees were also used to identify parameters with the highest impact on the robustness. The results showed that *composition* and *milk supply* were indicated as the most influential parameters, regardless the initial decisions made on enumerated aspects. The interviews at FC confirmed that the presented evaluation approach provides good insights into the robustness of valorization plans and into parameters that can considerably affect it.

Based on the findings of this study, we concluded that the robustness degree of valorization plans obtained with deterministic models can be sufficiently high to successfully valorize input materials; and thus it is not always necessary to implement in practice complex valorization models, such as stochastic or fuzzy models, that directly incorporate uncertainties of input parameters. The developed framework can be easily applied in practice to indicate the robustness degree of valorization plans of deterministic models; and thus it can indicate the necessity of applying complex techniques. Furthermore, by focusing on the improvement of forecast inaccuracies of most influential parameters, the robustness degree of valorization plans can be increased.

Study 4: Benchmarking efficiencies (Chapter 5)

The fourth study dealt with the efficiency measurement of general processing units that transform inputs into outputs. Next to improvements obtained by the development of a comprehensive valorization model (e.g. selection of the best products), additional gains can be achieved in a situation when all processing units are operating efficiently; and thus members´ milk can be better valorized. Hence, the aim of the fourth study was to develop a framework for efficiency measurement of processing units. The following question was answered in this study: "*How can the performance of processing units be measured and improved?"*

The low availability of data made the development of the framework based on the dairy case difficult. Therefore, to develop the framework for efficiency measurement, we used a case study of a global express service provider (TNT Express). Nonetheless, steps indicated in the framework developed for efficiency measurement of express depots can easily be applied to other industries, such as the dairy industry.

An extensive literature study on performance practices used in logistics, with a special focus on efficiency measurement of logistics depots, indicated Data Envelopment Analysis (DEA) as the most suitable method. The method allows for a simultaneous inclusion of all relevant factors that affect performance. Furthermore, it expresses the final performance level in one single value; thus it can be a one-dimensional substitute for a number of different KPIs. Apart from the ability to handle multiple inputs and outputs at the same time, DEA is an easy and convenient method that does not require various statistical assumptions (e.g. normally distributed data) to be fulfilled, which is not the case for most econometric models.

To construct the DEA model, factors affecting performance had to be identified. We conducted a literature study, interviews, and additionally investigated Pearson correlations to include only the most relevant factors. Two DEA models were developed with the following selected factors: inputs – labor, subcontractors, doors, hub, population, area; and outputs – service, production, customers, stops efficiency. The first model treats all factors similarly; the second model distinguishes between factors that are uncontrollable (doors, hub, population, area) and controllable (residual inputs and outputs) by management. The second DEA model was used for further analysis. The output of the DEA model allowed for the identification of:

- efficient and inefficient units: 13 out of 44 depots were indicated as technically inefficient with the average efficiency score of 0.832;
- parts of efficiency levels (of inefficient units) that are the merit of management practices (on average 85.4%) and of a favorable external environment (on average 14.6%);
- potential reduction in consumed input resources that would allow for the same output levels if the inefficient units become efficient: on average labor use can be reduced with 17% and subcontractors use with 16.9%;
- and role models: 20 out of 31 efficient units were indicated as role models; role model can be treated as a master unit in efficient use of certain inputs.

Additionally we have also conducted a number of statistical analyses to investigate the relation between:

- efficiency scores and factors: labor, subcontractors, population and production have a significant influence on efficiency scores and therefore increase or decrease unit´s probability of being efficient;
- efficiency scores and region sizes: no significant differences in efficiency scores among regions were identified;
- efficiency scores and size of processing units: no significant differences in efficiency scores among units of different sizes were identified.

The findings of this study confirmed the suitability of the DEA method for the assessment of performance (efficiencies) of processing units. With the use of outputs of DEA models, we showed how to identify and evaluate efficient and inefficient units, and how to improve the performance of the inefficient units. New target levels of consumed inputs indicate the overall input reduction that can be achieved while still producing the same output levels; and thus they indicate potential gains a company under investigation can achieve. The improvement of the performance of inefficient units should be based on the investigation or replication of processes of units indicated as role models. This can reveal different management practices. The investigation of practices applied by these units is therefore a crucial part of the learning stage for less efficient units.

6.3 Scientific contribution

In this research, we have approached the issue of milk valorization from a Logistics Management perspective, which until now was not thoroughly discussed in literature. With the use of OR techniques, a number of decision support models has been developed to improve management decision making on the valorization of milk. The scope of the thesis was limited to those issues that are most relevant for successful tactical milk valorization. The emphasis was placed on: (1) the development of a comprehensive valorization model that creates optimal allocation and production plans, and (2) the improvement of performance of the model and of processing units. The research presented in this thesis contributes to the overall field of Decision Support Modeling and aims at the efficient use of food resources. Furthermore, each of the presented studies contributes to specific parts of Food Logistics Management and Performance Management. The scientific contribution per study is provided below in more detail.

Study 1: Dairy Valorization Model (Chapter 2)

To improve the valorization of milk we started with the development of a comprehensive dairy valorization model using proven OR techniques. The model creates optimal mid-term plans for the allocation of milk and the production of end products and byproducts while considering all constraints. The comprehensiveness of the model allows for a full understanding of the impact of various changing parameters on milk valorization; thus, it provides a good understanding of occurring processes. A list of factors necessary for successful valorization was indicated based on literature study and experts interviews. The important factors – elements that must be included in the model - were indicated. The list of factors and their relevance for the valorization of milk are presented in Table 2.1 on page 23.

We investigated scientific publications of the last 25 years and based on that we concluded that none of the models presented in literature is suitable for a successful comprehensive milk valorization, because none of them includes all relevant factors (see Table 2.2 on page 25 for the complete overview of relevant studies). At most five out of the nine enumerated factors are incorporated in existing models. For instance, in the work of Mellalieu and Hall (1983) and Benseman (1986) five factors are incorporated, and four in the work of Vaklieva-Bancheva et al. (2007), Guan and Philpott (2011) and Geary et al. (2010). Only one of the available models incorporated byproducts transport (Benseman (1986)). Given the interrelations of dairy production processes, it is important to include this element in the model. To obtain complete milk valorization, it is also important to include the whole product portfolio of producers, because only then a successful integral valorization can be obtained. Typically, only a few main milk products or a selected group of products (e.g. yoghurts) were incorporated in available models (e.g. Kerrigan and Norback (1986), Doganis and Sarimveis

(2007)). The complete product portfolio was included only in two of reviewed models (Guan and Philpott (2011) and Geary et al. (2010)).

Finally, one of the aspects indicated as the most important for valorization – seasonality of raw milk in terms of supply and composition – was incorporated only in two models (Mellalieu and Hall (1983) and Papadatos et al. (2002)). In Chapter 2, with the use of the developed DVM, we evaluated the impact of seasonal milk composition on valorization plans. We have shown that models in which seasonality of the composition of milk is not incorporated obtain different valorization plans, which are often not realistic and also less profitable. This outcome confirmed the conclusion of Geary et al. (2010) stating that including seasonality would improve the effectiveness of valorization models, making them a more useful, year-round, decision-support tool.

To summarize, the scientific contributions of the work presented in Chapter 2 are as follows: (1) list of factors necessary for successful integral valorization of milk, (2) a new comprehensive DVM based on linear programing, and (3) an assessment of the impact of the seasonality of raw milk composition on mid-term valorization plans.

Study 2: Whey valorization (Chapter 3)

Byproducts valorization is an important social and environmental aspect as the world population is constantly growing and thus more food is required. According to Food and Agriculture Organization of the United Nations (Gustavsson et al., 2011), up to 50% of food is wasted throughout the supply chain. The reuse of byproducts in the production of main products gives an opportunity to minimize food waste, especially in the processing stage of the supply chain, and thus creates more edible food for end customers. The dairy industry offers good possibilities for this. The conducted literature study presented in Chapter 3 has proven that considerable attention has been given to the valorization of byproducts, mainly from the biotechnological perspective (e.g. Gehring et al. (2011), Darine et al. (2010), Hollmann and Lindhauer (2005), Galanakis (2011), and Koutinas et al. (2009)). However, none of the studies available in the current literature focuses on the economic impact and opportunities that valorization of byproducts has for food processing companies. Therefore, an opportunity to contribute to literature emerged. We investigated this problem with the use of the whey byproduct as a case study. This byproduct was chosen due to its high nutritional content that creates large potential for valorization (González-Martínez et al., 2002; Panesar et al., 2007; Smithers, 2008). Furthermore, whey has high environmental impact as it is one of the most polluting byproducts of food industry (Cuartas-Uribe et al., 2009; González-Martínez et al., 2002; Gonzalez-Siso, 1996; Koutinas et al., 2009; Panesar et al., 2007; Smithers, 2008). And finally, whey is produced in high volumes, thus its valorization may have a strong impact (FAO, 2009; FAPRI, 2012; Russ and Meyer-Pittroff, 2004).

In the third chapter, we presented a new Integrated Dairy Valorization Model (IDVM; an extended version of the Dairy Valorization Model) that allows for integral valorization of main milk products as well as byproducts. Furthermore, we developed a three-step evaluation approach, in which outcomes of non-whey, stepwise, and integral valorization, conducted with the use of the IDVM, are compared. The comparison of non-whey and stepwise valorizations resulted in the evaluation of the added value of whey valorization; and the comparison of stepwise and integral valorizations allowed for providing recommendations on the possible merger of both valorization processes (whey and main products), which currently are conducted separately. By evaluating outcomes of multiple scenarios, we identified factors that are driving the effect of integral valorization. With extensive analyses, we showed that the valorization of byproducts is potentially very profitable for dairy processing companies. Finally, we demonstrated that the effect of integrating valorization of byproducts and main milk products strongly depends on the following four factors: (1) market demand and (2) sale prices of end products made from byproducts, (3) sale prices of main products using byproducts based inputs or producing byproducts, and (4) processing capacities for byproduct flows. Since none of the studies present in the literature aims at the evaluation of the economic effect of byproducts valorization on food processing companies, the findings presented in Chapter 3 provide different and new insights into byproducts valorization.

Study 3: Robustness evaluation (Chapter 4)

Production planning, which is one of the most significant activities carried out in the processing industry, is strongly affected by noisy, incomplete and inaccurate input data (Rahmani et al., 2013). The uncertainty of input parameters is one of the primary planning issues, since a small change in the input data could change the optimal solution significantly (Gharakhani et al., 2010). The robustness of solutions obtained with deterministic models is not known, as no uncertainty is incorporated in those models. Thus the optimality of valorization plans obtained with such models is open for discussion. In Chapter 4, we focused on the development of a framework for the evaluation of robustness of such valorization plans.

Considerable research has been devoted to improving the robustness of planning models. New models and methods that incorporate uncertainties have been developed, e.g.: stochastic programming (Kall and Mayer, 2011), fuzzy set theory (Wang and Fang, 2001), and robust optimization (Mulvey et al., 1995). These methodologies provide stable solutions in theory. Their applicability in practice to large scale problems is, however, limited because of the complexity of real-life problems. As a result, deterministic models of which solutions might not be robust, are still commonly used in practice to support planning processes (Verderame et al., 2010). None of the available studies focused on the robustness of solutions obtained with such deterministic models. The framework developed in Chapter 4 fills this gap by providing a new method for assessing the robustness of plans obtained with deterministic models.

The developed framework results in a multi-dimensional output because KPIs assess robustness from different angles, e.g. financial or volume differences. Furthermore, assessments can be made on different input- and time-related levels. As another contribution to literature, an extensive analysis of valorization plans indicated that the grouping approach of KPIs, the evaluation time level (month or year), the evaluation depth level (element or parameter), and chosen robustness bounds indicating maximum allowed deviations in plans, are aspects that considerably affect the overall robustness degree of valorization plans. It is therefore important to pay special attention to choices made with regard to those aspects.

Study 4: Benchmarking efficiency of processing units (Chapter 5)

The fifth chapter of this thesis is devoted to the development of a framework for efficiency measurement of processing units, as efficient operations will further contribute to the improvement of milk valorization. The framework was developed based on a case study of an express service provider (TNT Express). We evaluated the efficiency of depots, which are the main processing units of express service providers that transform inputs into outputs.

The development of the framework started with the identification of the most suitable method for performance measurement. Data Envelopment Analysis was selected as the best method for the efficiency assessment. To select inputs and outputs for the model, a specific selection process was developed that indicated the most relevant parameters for the evaluation of express depots. The efficiency scores of depots were internally benchmarked against each other and the outcomes were analyzed to obtain various insights such as: (1) potential savings in inputs that can be reached, (2) the worst performing units, (3) the role models (depots most efficiently converting inputs into outputs), (4) the critical factors affecting performance, and (5) relations between efficiency scores and various characteristics of depots. The framework developed in this study does not only assess the efficiencies of units, but also identifies various critical factors and relations that can contribute to the improvement of the performance of inefficient units. The presented framework can easily be generalized to other industries.

A large number of studies focuses on the evaluation of various types of warehouses (Chan and Qi, 2003; De Koster and Balk, 2008; Hamdan and Rogers, 2008; Kayakutlu and Buyukozkan, 2011; Ross and Droge, 2002; Ross and Droge, 2004; Schefczyk, 1993). However, to the best of our knowledge no research especially investigating distribution centers of express service providers was carried out. The outcomes presented in Chapter 5 provide a new framework for efficiency measurement and improvement of express depots; thus they enrich express companies' knowledge on their depots and provide guidelines on how to increase the performance level.

Overall contribution to academic literature

The scientific contribution of the research presented in this thesis is summarized and linked to specific scientific fields introduced in Chapter 1 (Figure 1.4 on page 13). The overview is presented in Figure 6.1. Foremost, we described and analyzed a complex dairy system, developed specific decision support tools to support production planning and performance evaluation and developed two performance measurement frameworks. Reviews of relevant literature assured the scientific relevance and theoretical correctness of the developed methods. Many discussions with experts conducted at all stages of each study assured the practical relevance and correctness of these methods. Moreover, discussions with relevant experts from industries, conducted at the last stage of each study proved the suitability of the developed methods for practical use. The applicability of the developed method is therefore the additional value of the discussed studies.

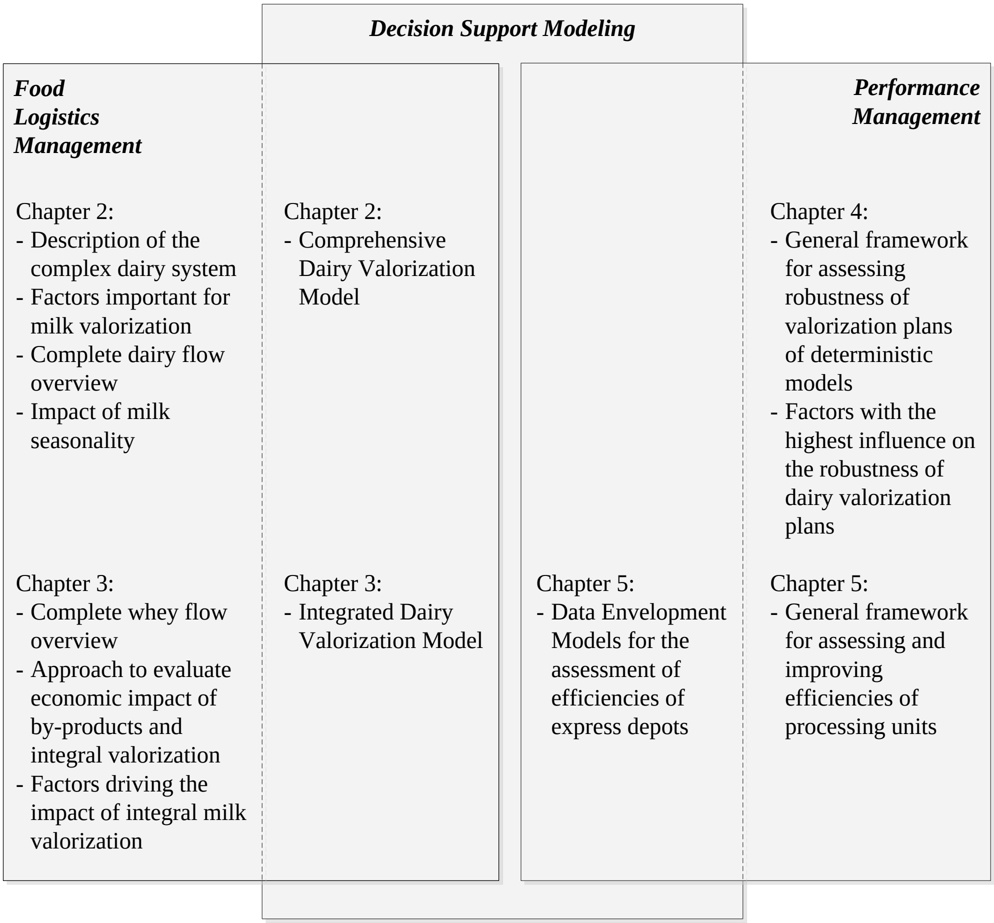


Figure 6.1 Scientific contribution of the research presented in this thesis per specific scientific field.

6.4 Limitations and further researcher

In this thesis, we developed a number of methods to contribute to the improvement of milk valorization. We have shown, in the previous paragraph that the developed methods are scientifically relevant and valid to be applied in practice; yet we can still distinguish a number of research limitations. Based on these limitations and on other relevant projects indicated by interviewed experts, directions for further research are indicated.

6.4.1 Limitations of this research

Three main research limitations that we had to work with during the process of the study are elaborated on below.

Data collection

The aim of the work presented in this thesis was to contribute to literature, but also to improve milk valorization in practice, and more in particular at FC. On the one hand, the practical application of all developed methodologies was a big advantage as it strengthened the relevance of the studies. On the other hand, it limited the progress of the work, mainly due to the time necessary for collecting and verifying large sets of data collected throughout the company. Because of the opportunity to closely investigate dairy processes and continuously discuss all issues with key stakeholders, new insights and information were constantly gathered through the course of the research. As a result, changes to the models in development or used data were continuously suggested and (depending on the relevance for studies) implemented. Although they were sometimes delaying the scientific development processes, in the end it is clear that they strengthened significantly the relevance of developed methodologies and resulting conclusions.

Case studies

The research presented in this thesis is based on case studies of two companies. Models discussed in Chapter 2 and Chapter 3, and the framework presented in Chapter 4, as well as the conclusions following from the analyses of the outputs are based on the study of FC. The framework for efficiency measurement presented in Chapter 5 is developed on the case study of TNT Express. The application of the methods developed in the first three studies to other dairy companies (and evaluations of obtained outputs) would confirm the validity of conclusions and possibly provide new insights. Note that FC is one of the largest world dairy companies that produces a complete range of dairy products and works with large supply, production and market capabilities. The conclusions may differ for smaller size companies. For instance, factors that affect the robustness of valorization plans could be different for smaller size dairy companies, as they produce smaller volumes of products and thus production might be less flexible. Furthermore, the impact of milk seasonality may be more severe for smaller size companies due to lower available capacities. Also dairy companies situated in other regions (e.g. New Zealand, which is another important milk producing region next to Europe) may be differently affected by milk seasonality, because of different supply patterns.

Furthermore, even though the framework developed in Chapter 5 was not based on a case study from the dairy industry, it is suitable for the evaluation and improvement of efficiencies of other types of processing units that transform inputs into outputs. However, the obtained conclusions on the critical factors affecting the performance, the relation between efficiency scores and regions, and the relation between efficiency scores and sizes of processing units, are case-specific and cannot be generalized. The application of the developed framework to a case study of a dairy company would provide additional insights, and thus further contribute to the improvement of milk valorization in the dairy industry.

Inventory management

One important aspect of the supply chain – inventory management – was excluded from this research. Information related to inventory decisions was, however, indirectly incorporated in valorization plans via input data on production requirements coming from FC's Operating Companies (OpCos). Even though this intermediate solution was sufficient to obtain realistic valorization plans at FC, an explicit inclusion of inventory management may make the model more applicable to other dairy companies. Also, by comparing results of the current DVM and a model that incorporates inventory options, the impact of inventory on the valorization of milk can be evaluated and recommendation on the inclusion of inventory options in the mid-term valorization model can be given.

Scope of the research: planning level

As mentioned in the first chapter of this thesis, the valorization of milk from a Logistics Management perspective can be focused on various elements of the supply chain and on various planning levels. The investigation of FC current practices and the literature study indicated that the largest potential for improving decisions support models concerned the mid-term planning level (1-1.5 year). Thus, in this research, most attention was given to the tactical production planning problem including supply, demand and transport. Nevertheless, the development of decision support models for the improvement of short-term (maximum 3 months in the future) and long term (5-10 years ahead) planning processes could also considerably contribute to the valorization of milk.

6.4.2 Directions for further research

New research opportunities are indicated based on discussed research limitations, and on some other remaining issues relevant for milk valorization and not extensively addressed in this thesis.

New case studies

To verify whether the conclusions from conducted studies would hold also when applied to, for instance, smaller dairy companies, further research is needed. Moreover, the application of the framework developed in Chapter 5 to a case company from the dairy industry would validate framework's applicability to the evaluation of processing units from this industry. Also, interesting relations can be revealed, for instance, (possibly) between size of production locations and efficiency scores.

Inventory management

As indicated in the previous section, inventory management was not incorporated in the current DVM nor in the IDVM. Instead, inventory decisions were indirectly incorporated via input data. A study that would extend the current (I)DVM with the inventory options, and the comparison of outputs of the current (I)DVM with the new developed version might result in interesting findings. Following this, the necessity of the explicit inclusion of inventory options in a mid-term dairy valorization model could be assessed. For instance, one could evaluate the impact of including inventory options on the ability of fulfilling contracted sales volumes, the availability of capacities or the profit. Furthermore, new inventory management approaches can be incorporated in the model and their impact on milk valorization can be assessed. Such results would indicate which inventory management approaches are most suitable for different product groups, and thus further improve milk valorization.

Valorization model incorporating data uncertainties

Based on results of Chapter 2 and Chapter 4, we concluded that valorization plans are strongly influenced by changes in input parameters related to raw milk supply and composition. Given the uncertainty ingrained in input data of those input parameters, but also in other input parameters, it would be interesting to develop a mid-term valorization model that directly incorporates these uncertainties. To the best of our knowledge, only one attempt to develop a stochastic production planning model for the dairy industry was made; the model of Guan and Philpott (2011). Unfortunately, this model does not base production recipes on the seasonal composition of milk, and also no re-utilization and transportation of byproducts is included. Therefore, an opportunity for a new stochastic comprehensive dairy valorization model emerges. There are also two other well-known methodologies to deal with uncertainty of input data: robust optimization (Ben-Tal and Nemirovski, 1998; Mulvey et al., 1995) and fuzzy set theory (Zimmermann, 2001). Each of the discussed methods has a different approach in dealing with uncertainty. The extension of the DVM with these methodologies, the comparison of results of all models (including the current DVM), and the evaluation of robustness of solutions with the framework presented in Chapter 4, would indicate the most suitable model to support mid-term valorization. Even though, in Chapter 4 we concluded that the robustness of FC's valorization plans is currently sufficiently high to achieve successful valorization of milk, the high impact of uncertain input parameters (fat, protein and milk supply) may affect the long term stability of these results.

Integration of other planning levels

In the introduction of this thesis, we indicated that three planning levels can be distinguished: strategic, tactical, and operational (Chopra and Meindl, 2007). The methods presented in this thesis are designed to support tactical valorization of milk. We can therefore state that there exists an opportunity for the development of decision support models that would support short-term (maximum 3 months in the future) and long term (5-10 years ahead) planning processes, and even allow for a synchronization of all three planning levels. The literature study presented in Chapter 2 indicated a limited number of models that concentrate on short-term planning (e.g. Lutke-Entrup et al. (2005), Doganis and Sarimveis (2008), Papadatos et al. (2002)), and only one model that concentrates on long-term planning (Papadatos et al. (2002)). This provides an opportunity for a new research.

Valorization in other industries

In this research, we focused on the valorization of raw milk - the main raw material of the dairy industry. We developed a number of methods to improve this process. Even though these methods were developed with a special focus on raw milk, the applicability of these methods to valorize raw materials in other food industries can be investigated. For instance, the approach on how to evaluate the effect of byproducts on the valorization of main products, presented in Chapter 3, can be used in other processing industries. The framework for robustness evaluation of valorization plans, presented in Chapter 4, can easily be applied to any other deterministic planning model. And finally, the framework for efficiency measurement of processing units, presented in Chapter 5, can also be used for evaluation of units from other industries. The application of models and frameworks to other industries would provide interesting findings on similarities and differences concerning the valorization of different raw materials.

Additional research opportunities

Other opportunities for further research are related to projects, which were indicated by FC experts as relevant for milk valorization (see Table 1.1 on page 6), but were not tackled in this thesis. Since valorization plans are strongly affected by changes in supply and composition of milk, a study that would focus on a development of **mid-term forecasting models** could improve the accuracy of input data, and thus the quality and robustness of valorization plans. Furthermore, input data related to demand and production are provided by individual OpCos, which as indicated in Chapter 1, have their own objectives that may not always lead to the best integral valorization of members´ milk. The development of **a game theory incentive model** to stimulate an integral valorization way of thinking among OpCos could contribute to higher accuracy of input data. Finally, given the high number of member farmers, different types of milk, and multiple dispersed factories, the **optimization of raw milk collection** could further improve valorization of milk. A study focusing on a division of supply area into new sub-areas, taking into account milk types and factories available in each sub-area could lead to lower transport costs and an even better allocation of milk to end products (e.g. high fat milk allocated to high fat products).

The opportunities for further research provided in this chapter do not exhaust the available possibilities of contributing to a better valorization of milk, not from an OR perspective, neither from other scientific fields’ perspectives. As much as the application of OR methods contributes to more efficient or even optimal use of milk, developments for instance in biotechnology may provide new technologies that will allow for better decomposition of milk, and thus more specific allocation of nutrients to end products.

6.5 Managerial insights and implications

Models and frameworks developed in this study provided many insights into the process of milk valorization and can be directly used by managers in practice to further improve this process. The proposed frameworks can also be used to improve the valorization of food resources in other industries. In the following sections, we discuss managerial insights and implications following from the conducted studies. The implications are the result of final sessions held with experts during which the outcomes of studies were discussed and different ways of using them to support decision making processes within the case companies were indicated.

Clear and comprehensive overview of the dairy system

The development of the DVM and the IDVM required close investigation of the whole dairy system, in particular the interrelated production processes, constraints, and specific characteristics. This resulted in a clear and comprehensive overview of the complete dairy system at a tactical level. Furthermore, in order to conduct the analyses input data were collected at FC. Prior to the collection process, clear definitions of required input data were not available and had to be developed. Also, the available dairy products were grouped into representative product groups. After the collection process, data were analyzed and one set of input data was prepared. Adding to the complexity, data were originating from multiple sources (OpCos) and many discrepancies were encountered (different definitions were used among different OpCos). In the end, all these steps led to a complete insight, and a unique and clearly defined set of input data necessary to conduct mid-term valorization of milk at FC.

The translation of the dairy system into the DVM allows for a simultaneous optimization of the whole system, and provides interesting insights into and understanding of dependencies ingrained in the system. In Chapter 2, we illustrated, by means of various analyses, how the developed DVM can be used to provide important managerial insights (e.g. impact of seasonal milk composition on the mid-term valorization of milk). Therefore, to successfully valorization raw materials companies should developed their own valorization model. To do that the following steps should be taken:

1) investigate the (dairy) system in order to identify key processes (e.g. production, transport), links between system elements (e.g. recipes, product – location combinations), and constraints of the system (e.g. processing capacities, market limits);
2) identify the objective(s) e.g. profit maximization;
3) based on the outcomes of the first step, prepare a schematic overview of the valorization model in which relevant parameters are included. All parameters necessary to represent relations and constraints of the system should be incorporated. For instance, production process requires parameter production rate, transport of milk requires parameter transport cost, recipes require a parameter representing fractions of input material used for the production of specific products;
4) formulate unique definitions of required input data and collect the data;
5) based on the outcomes of first three steps, formulate the model mathematically (indicate objective function and system constraints);
6) implement the model in an optimization software;

7) conduct numerous tests with limited set of data to verify whether all relations in the model are properly defined;
8) run the model to obtain the optimal valorization plan;
9) formulate and run various scenarios in order to answer pending managerial questions.

All steps should include the involvement of experts from the industry. Multiple discussions and interviews should be used to obtain the first insights and afterwards to verify the outcomes of each step.

The DVM presented in Chapter 2 was developed based on the case study of FC. Other dairy companies should first try to apply the DVM, because it includes all relevant dairy processes and products, instead of developing the valorization model from scratch.

Importance of byproducts valorization

One of the most interesting insights gained from this research, according to the involved managers, concerns the added value of integral valorization. We have shown that at FC post-processing of byproducts can result in considerable additional profits (in comparison to the profit made only on the main products). Furthermore, we have also shown that the added value of integrating valorization of whey-based and milk-based end products is small. This finding was contrary to the expectations of experts from FC, and thus provided a new insight. The added value of integration will be higher in case an increase in the following four factors occurs: market demand and sale prices of end products made from byproducts, sale prices of main products using byproducts based inputs or producing byproducts, or processing capacities for byproducts flows.

Even though the presented results indicate that both valorization processes can currently be conducted separately, since little value is added while integrating them, the impact of indicated four factors on those conclusions is considerable. Therefore, to assure that the possible future integration of both valorization processes occurs on time, dairy companies should investigate the possibility of changes in prices, demand and capacities of indicated products. For that purpose, a specific process should be defined and executed every year. In case strong developments in prices of end products related to byproducts occur, or possibilities for extending markets or capacities of whey-based products emerge, a reassessment of the effect of integral valorization is advised. Finally, the relation of cheeses and milk powders prices should be closely monitored. In a situation in which prices of milk powders considerably increase, the gain from integrating valorization processes becomes much higher.

It is expected that the presented insights and conclusions will also hold for other dairy companies than FC, especially for the ones that possess a similar portfolio of whey-based end products. Nevertheless, since input data play an important role in a decision making process, the application of the framework presented in this thesis to other dairy companies will confirm this statement. The developed framework should also be used to evaluate the effect of byproducts valorization in other food processing industries, since as shown in this study the added value of integration can be considerable (depending on the values of input parameters).

Factors critical for milk valorization

The development of the DVM also required identification of inputs and outputs that are relevant for mid-term valorization. The complete overview was presented in Chapter 2 (see Figure 2.1 on page 28). The importance of these inputs on the valorization of milk was investigated in Chapter 3 and Chapter 4. We have shown that the composition of milk has a strong impact on the valorization, because when it is neglected or wrongly forecasted it affects the robustness of valorization plans. In particular, we have shown that the fat and protein components of milk have the highest impact on the robustness degree. Milk supply volumes were indicated as the second most important input that affects the valorization of milk. Therefore, in order to obtain accurate and realistic valorization plans, more emphasis should be placed on the forecast accuracy of fat and protein components and supply volumes of milk. This was an interesting and important insight, because until now company experts were mostly focused on the improvement of the forecast accuracy of milk supply volumes and not of milk components.

The investigation of the effect of integral valorization on the overall valorization of milk revealed the importance of the following additional inputs: sale prices and demand of whey-based end products, sale prices of milk-based end products (especially cheese and milk powders) using or producing whey flows, and processing capacities of whey flows. Changes in values of those inputs can significantly affect the effect of integral valorization, and thus can lead to different conclusions regarding the integration of both processes. This information was previously not explicitly available within FC. However, even though the relation between the prices of cheese and of milk powders was known, it was not known that even small changes in price ratios of those two product groups may lead to different allocation of milk in case stepwise (current practice) or integral valorization of milk is applied. Consequently, the indicated inputs should also be closely monitored by FC.

Robustness of solutions of deterministic models

In Chapter 4, we focused on the development of a framework for the assessment of robustness of valorization plans obtained with deterministic models. Robustness of solutions is important in practice, because optimal solutions may quickly become suboptimal or even lead to unnecessary costs (e.g. related to ad hoc reallocation of milk). With the study presented in Chapter 4, we have shown how to evaluate the robustness of valorization plans obtained with a deterministic model. Until now no such framework was available, neither in the literature nor in practice. The developed framework is therefore a new managerial tool that can lead to better valorization of milk. The framework can also be used to assess the robustness of solutions of deterministic planning models in other industries. Additionally, critical factors affecting solutions can also be identified, as discussed in previous paragraph.

Furthermore, we have indicated that current valorization plans at FC are robust enough to conduct successful valorization. By investigating a broad range of input elements (e.g. prices and demand of particular products, production capacities of various locations), we indicated the elements that are, and the ones that are not, affecting the robustness of valorization plans. These new insights indicated how stable the mid-term valorization plans are and which elements should receive most managerial attention.

The study presented in Chapter 4 indicates to practitioners that the robustness of solutions is important, if even not more important than obtaining optimal plans. This is because in case robustness of solutions is low, the optimal plan indicated by a model will easily become suboptimal in practice. This aspect is often neglected. In case robustness of solutions is low, techniques that directly incorporate possible parameter uncertainties should be used so that the obtained valorization plans are more realistic. However, since the application of those techniques to practical problems can be intricate, the robustness of solutions obtained with deterministic models should first be assessed. This will provide information on the stability of solutions, and thus support decisions regarding the application of more advanced models.

Improvement of performance of processing units

In the last study, we focused on the development of a method that is most suitable for the efficiency measurement of processing units. We proposed a new method for efficiency measurement of express depots. In practice, many separate KPIs were used to evaluate the performance and they often led to contradictory conclusions. The model presented in Chapter 5 not only provided a unique efficiency outcome, but also indicated which part of the performance is attributed to a favorable external environment (e.g. low level of traffic congestion, small service area, high population’s income), and which to successful management practices (e.g. quality of training programs for employees, breakdown occurrences, percentage and quality of subcontracted fleet). For TNT Express, this was a new perspective on the performance measurement of their depots. The identification of the performance part attributed to the external environment made management aware that it is very likely that some of the processing units will not operate as efficiently as other units, no matter how good the practices of managers of those units will be.

Additionally, we used outputs of the model to provide new recommendations on how to improve the performance of inefficient depots. We indicated the possible input reduction in hired labor and in subcontracted fleet that TNT Express can achieve while still being able to obtain the same output levels. Before this model was developed, there was no clear method for estimating the potential savings of bringing inefficient depots up to an efficient standard. Furthermore, we identified depots that can be treated as role models in efficient use of certain inputs. Those depots should play the leading roles in the improvement process of inefficient units. Finally, we have indicated factors that increase or decrease the probability of a unit being efficient. Therefore, the appropriate input and output levels of these factors are critical for efficient operation and should get relatively more focus from management.

Following steps presented in this study, a DEA model for the dairy case should be developed. The model will identify factories that can more efficiently transform milk into end products. The post-analyses will indicate where savings can be made and how to improve the processes of the inefficient units. Replication of processes of units indicated as role models will reveal different successful management practices that should be implemented by inefficient units. Benchmark shares will indicate which efficient units should be treated as role model for which inefficient units. The application of the framework presented in Chapter 5 will increase processing efficiency of assessed units, and thus will further contribute to a better valorization of milk.

To conclude

The overall managerial implication that follows from the presented studies is that in order to valorize milk or other food resources to the maximum an integrated point of view should be chosen. Also OR techniques should be used, since the complexity of many processing industries makes the application of practical rules of thumb insufficient and often inadequate. However, even in case production systems are fully represented by optimization models, it is still very difficult to understand all occurring relations. That is why it is important to uncover the critical factors that are affecting complex planning processes. Any steps taken towards the improvement of the accuracy of those elements should result in more accurate planning, and thus improve the implementation process of the obtained solutions. Also, awareness of the robustness of plans will improve the overall planning, as alternative solutions can be prepared in case input values turn out to deviate from the forecasted ones.

Therefore, the model and frameworks developed in this thesis provide new insights into complex production systems. The findings provide new perspective on the valorization of milk.

6.6 Final remarks

In this thesis, we presented a number of decision support tools that are suitable for the improvement of valorization processes, especially in the dairy industry. We believe the developed methods will lead to considerable gains at food processing companies. Furthermore, we trust the insights the Milk Valorization & Allocation department has gained during this 4-years long research have contributed to the improvement of the milk valorization process and have indicated directions for further improvements. Finally, we believe the presented research creates new links between the worlds of science and practice.

Summary
Samenvatting
References
About the author
Completed training and supervision plan

Summary

The research presented in this thesis concerns decision problems in practice that require structured, precise, scientific studies to provide strong, reliable answers. An opportunity to contribute to both practice and science emerged in 2008 when two large, Dutch dairy companies merged, creating FrieslandCampina (FC), which was the fourth largest dairy company in the world at that time. In 2009, a new Milk Valorization & Allocation (MVA) department was created at the corporate level to optimally utilize raw milk (the main raw material) in all business units. The main goal of this research was the development and application of decision support models to help MVA attain its mission of "getting more out of milk."

The dairy processing industry is a specific and challenging research field. This is related to the fact that the main raw material (raw milk) is transformed into thousands of end products via highly interrelated production processes. The production processes are affected by uncertainties related to supply, processing capacities, and demand. Gradual abolition of the European quota system and weather conditions are two causes for uncertain supply. Processing capacities are affected by unexpected machines breakdowns, and demand by a highly competitive market and the highly diversified portfolio of end products. This illustrates the complexity ingrained in a dairy system. Attaining high profitability requires a central, integral planning process that facilitates the optimal allocation of raw milk to a large range of products. Optimal allocation of raw milk is achieved when it is successfully allocated to the most profitable end products and all important constraints are taken into account. This process is defined as *milk valorization*.

Objectives, questions and methodology

The overall objective of this research is to contribute to the improvement of milk valorization in the dairy industry. We approached the problem of milk valorization from a Logistics Management perspective. We focused on decisions supporting the optimal flow of raw materials to end products, from farmers to consumer markets. With the use of Operations Research (OR) techniques, we developed quantitative models and frameworks to improve the mid-term milk valorization process.

The main problem the company faced was the lack of suitable tools to support mid-term valorization. Therefore, developing a dairy valorization model at the mid-term planning level was the first step to improve valorization. The model was further developed in subsequent studies to answer the most important questions related to milk valorization that FC identified. The directions for development were identified based upon an extensive literature review, and many interviews and discussions with relevant FC employees. The potential added value for FC, data availability, and the contribution to literature were the three main aspects taken into account during these discussions. The optimality and comprehensiveness of

valorization plans and efficient implementation of these plans are needed for successful, integral, milk valorization. We focused on both the development of an appropriate valorization model (Part I) and of performance evaluation tools (Part II). We defined four specific research objectives:

Part I

1) *Development of a comprehensive Dairy Valorization Model*
2) *Evaluation of the effect of byproducts valorization and of integral valorization on the overall valorization of milk*

Part II

3) *Evaluation and improvement of robustness of valorization plans obtained with deterministic models*
4) *Development of a framework for efficiency measurement of processing units*

A separate chapter is devoted to each research objective. We used a combination of quantitative and qualitative methodologies. Literature studies were carried out to identify the gaps, formulate the research questions, investigate the most suitable OR methods for the problems, gather and verify collected data, and define scenarios to test the hypotheses. We conducted many open and semi-structured interviews with experts. Each research question was supported with explanatory case studies of FC (Chapters 1–3) and TNT Express (Chapter 4). The outcomes of conducted studies are provided in the following section.

Main findings and conclusions

1) Dairy Valorization Model

Chapter 2 presents the Dairy Valorization Model (DVM). The model creates optimal mid-term plans for the allocation of milk and production of end products, and considers all relevant constraints. We posed the following research question: *Which elements should be included in the model to properly represent the complete dairy system and allow for efficient milk valorization?*

The following important elements were included in the DVM: recipes based on raw milk composition; seasonality of raw milk composition and supply; a complete dairy product portfolio; byproduct utilization; network of supply regions and production locations; byproduct and raw milk transportation; and changes in sale prices. Including all relevant elements assures DVM comprehensiveness. This important aspect achieves truly integral valorization of milk. Furthermore, the developed DVM also fosters understanding of complex, underlying production processes. This aspect is also important, because the production of dairy items is highly interrelated and it is not trivial to fully understand links between all products without an appropriate tool and analyses.

We also show that the seasonal composition of raw milk (dry matter, fat, and protein content) plays an important role in the valorization process. It considerably affects decisions regarding milk allocation to end products, volumes of end products, and company profit. This result was important because the majority of models in the literature based the recipes on milk volumes, so neglected the seasonality of milk components.

Based on our findings, we conclude that a comprehensive milk valorization model that incorporates the indicated elements is necessary to successfully valorize milk. It is particularly important to base the production processes (recipes) on the components in raw milk, rather than just raw milk volumes.

2) Whey valorization

The DVM developed in the first study focuses on the valorization of main milk products (milk as the main ingredient). The production of those products, however, results in additional large volumes of byproducts. At the moment this research was conducted, the valorization of main milk products and byproducts were conducted separately. This led us to the second research question: *What is the added value of integrating byproducts valorization into the main valorization process and does it affect the production of main milk products?* None of the studies in the literature answered this question.

In Chapter 3, we develop a new Integral Dairy Valorization model (IDVM) to allow for an integral milk valorization (simultaneous valorization of whey byproducts and main milk products). We also develop a three-step evaluation approach to compare results of stepwise valorization (in which whey valorization only follows after main milk products valorization) and integral valorization. With the IDVM, the evaluation approach, and outcomes analysis, we show several results. The explicit valorization of whey flows leads to significant economic gains for FC. The effect of integrating both valorization processes is small at FC. If the demand for, and sale prices of, whey-based products, sale prices of milk powders or processing capacity for whey increases, the gain from the integration can be considerably larger. Incorporating information on the value of processing whey in the valorization of main milk products negatively affects cheese production. This means that currently whey products are not profitable enough to drive the production of milk products that are the source of the whey byproduct.

We conclude that currently the integration of valorization of main milk products and valorization of whey flows does not result in additional gains. However, in case strong developments in prices of end products related to byproducts occur, and possibilities for extending markets or capacities of whey-based products emerge, the added value can considerably increase.

3) Robustness evaluation

The developed DVM is a linear programming model. This on the one hand facilitates the analyses process, but on the other hand neglects uncertainty ingrained in the input data. As a result, the model may produce non-robust solutions. Robustness is defined as: *the degree to which selected critical performance measures remain within a predefined robustness range, for different realistic scenarios of input data.* Robustness is important, since initially optimal plans can easily become suboptimal or even very costly if realization of input data is different from forecasted values. Chapter 4 focuses on evaluating the robustness of valorization plans obtained with our deterministic model. We also answer the third research question: *How can we assess the robustness of valorization plans obtained with deterministic models?*

We developed a five-step framework comprised of the following: (1) definition of Key Performance Indicators (KPIs), (2) selection of relevant input parameters, (3) definition of scenarios, (4) evaluation of robustness, and (5) extraction of conclusions. The output from Step 4 of the framework is multidimensional. In order to arrive at the final robustness degree, a number of decisions must be made *a priori*: acceptable KPIs limits (robustness bounds); evaluation time (month or year); evaluation depth (parameter or element); and the grouping approach of KPIs. The study shows that different conclusions regarding valorization plans robustness are obtained, depending on the selection of these aspects.

In the case study, FC found the overall robustness degree of valorization plans obtained with the DVM to be sufficiently high for successful milk valorization. The calculated robustness degrees identified the parameters with the greatest effect on robustness. Composition and supply of milk were the most influential parameters.

Therefore, it is not always necessary to implement complex valorization models that directly incorporate input parameter uncertainties. The developed framework can easily be applied in practice to indicate the robustness degree of valorization plans of deterministic models. Furthermore, by focusing on improving forecast inaccuracies of the most influential parameters, the robustness degree can be increased.

4) Benchmarking efficiencies

In addition to improving milk valorization by developing a comprehensive valorization model (in other words, selection of the most profitable products), more gains can be achieved by improving the efficiency of all processing units. To achieve the fourth objective of this thesis, we answered the following research question: *How can the performance of processing units be measured and improved?* Since little relevant information was available at FC, the framework was developed and tested as the case study of an express service provider (TNT Express).

In the first step, we investigated suitable methods currently used in literature for performance measurement. Based on this, we concluded that Data Envelopment Analysis (DEA) is most suitable and comprehensive, as it includes various KPIs and expresses performance level in one single value. To construct the models, we investigated which factors were most relevant for measuring efficiency of express depots. Two DEA models were developed. They showed which units were operating inefficiently. The first model treats all factors similarly, and the second model distinguishes between factors that are uncontrollable and controllable by management. This indicates parts of efficiencies that are the result of either successful management practices or the inherited external environment. The results of the second DEA model were used to obtain information on how the performance of inefficient units can be improved. We identified: inefficient units; the parts of efficiency levels (of inefficient units) that result from either management practices or a favorable external environment; potential consumed input resource reductions that allow for the same output levels; and the role models that can be treated as master units in efficient use of certain inputs and thus should play leading roles in setting benchmarks.

The findings confirmed the suitability of the DEA method for assessing performance. Results of various DEA outcome analyses can improve the performance of inefficient units. The developed framework can easily be applied to other industries. When applied to the dairy industry, it can increase the processing efficiency of factories, and thus further contribute to better milk valorization.

Scientific contribution

We developed a number of decision-support models with OR techniques to improve decision making on milk valorization. The research contributes to the overall field of Decision Support Modeling and focuses on the efficient use of food resources. Each presented study also contributes to specific parts of Food Logistics Management and Performance Management. Chapter 6 shows the link between the scientific contribution of the research and specific scientific fields (see Figure 6.1 on page 144). We describe and analyze a complex dairy system, develop specific decision support tools to support production planning and develop two performance measurement frameworks.

Managerial insights and implications

Models and frameworks developed in this study provide many new insights into the milk valorization process and can be directly used by managers to further improve this process. The proposed frameworks can also be used to improve resource valorization in other food industries. We conclude that to successfully valorize raw materials, companies should develop their own valorization model following the development approach presented in Chapter 2; have a comprehensible overview of the complete system; and have access to necessary input data. Furthermore, as the FC case study shows, integrating main product and byproduct valorization processes might be profitable. The added value, however, depends on the input data related to market and production capacities of byproducts and related to them main products. To ensure that possible future integration of both valorizations processes occurs correctly, companies should investigate the possibility of changes in input data. Moreover, we also show that the robustness of solutions obtained with a deterministic valorization model can be sufficiently high to obtain reliable plans (Chapter 4). This means that it is not always necessary to implement complex modeling techniques (such as stochastic programming). This study has indicated to practitioners that the robustness of solutions is important, if even not more important than obtaining optimal plans. To ensure accurate solutions, apart from focusing on factors affecting the added value of integral valorization, companies should also focus on improving forecast accuracies of parameters affecting the robustness degree of valorization plans. The robustness degree should also be regularly assessed with the framework developed in Chapter 4. Finally, to further improve valorization of raw materials, managers should also focus on performance levels of processing units.

Following the steps presented in Chapter 5, companies can develop a DEA model to identify inefficient factories and provide new insights to improve the performance.

Opportunities for further research

New research opportunities are possible, based on the discussed research limitations and other remaining issues relevant for milk valorization that were not extensively addressed in this thesis. The main research opportunities are: incorporation of inventory management into the current (I)DVM; development of a (stochastic) valorization model incorporating data uncertainties to further mitigate the impact of uncertain parameters; development of milk (component) forecasting models to improve input-data accuracy; development of a game theory model to stimulate integral valorization way of thinking among business units; and investigation of new case studies to verify whether the conclusions from the conducted studies also hold for other dairy companies, and whether the developed methods are also suitable to improve valorization in other food industries.

These directions do not exhaust the available possibilities of contributing to better valorization from either an OR perspective or those of other scientific fields. For example, developments in, biotechnology may provide new technologies for better decomposition of milk, and thus more specific allocation of nutrients to end products.

Conclusion

Based on the conducted research, we conclude that in order to properly valorize milk or other food resources to its maximum an integral point of view should be chosen. OR techniques should be used to do this because the complexity of many processing industries makes applying practical rules of thumb insufficient and often inadequate. The models and frameworks developed in this thesis provide new insights into complex production systems. They provide a new perspective on milk valorization. We showed that analyses of results obtained with the developed methods can answer many managerial questions, and thus support the decision making process within a company. This improves overall raw material valorization, creates more value for companies, and leads to more sustainable dairy chains.

Samenvatting

Nadat twee Nederlandse zuivelbedrijven fuseerden tot FrieslandCampina (FC) ontstond in 2008 het op drie na grootste zuivelconcern ter wereld. Vrijwel direct na de fusie besloot het management van FC om de afdeling Melk Valorisatie & Allocatie (MVA) op te richten. De belangrijkste taakstelling van MVA was het optimaal benutten van de belangrijkste grondstof voor de zuivelindustrie, namelijk rauwe melk, in alle business units van FC. Het voornaamste doel van het beschreven onderzoek in deze dissertatie was het ontwikkelen en toepassen van beslissingsondersteunende modellen voor MVA om hen te ondersteunen in het bereiken van hun missie, namelijk "getting more out of milk".

De zuivelindustrie biedt een specifiek en uitdagend onderzoeksveld. De algemene perceptie op rauwe melk wordt menigmaal ten onrechte gegeneraliseerd door de uitspraak "melk is wit". Echter, de hoogwaardige voedingskundige en functionele eigenschappen van melkbestanddelen hebben tot een grote verscheidenheid aan verwerkingsprocessen geleid. Hieruit is een sterk divergerende productiestructuur ontstaan waarin duizenden eindproducten worden geproduceerd. De onderling verweven productieprocessen worden in hoge mate beïnvloed door (seizoensgebonden) variatie en onzekerheden met betrekking tot de melkbestanddelen en levering van rauwe melk, de beschikbaarheid van productiecapaciteit en de vraag naar eindproducten. Onzekerheid in de aanvoer wordt bijvoorbeeld veroorzaakt door de afschaffing van het Europese melkquotasysteem en weersomstandigheden. Productiecapaciteiten variëren door verstoringen in het productieproces en de vraag naar eindproducten fluctueert door een hoog competitieve markt gecombineerd met de grote diversiteit aan eindproducten. Om, ondanks deze hoge mate van complexiteit, toch winstgevendheid te realiseren, is een centraal en integraal planningsproces nodig dat de rauwe melk optimaal toewijst aan de meest winstgevende eindproducten, natuurlijk onder de voorwaarden dat aan alle belangrijke beperkingen wordt voldaan. Dit toewijzingsproces wordt ook wel *melkvalorisatie* genoemd.

Doelstelling, onderzoeksvragen en methodologie

De algemene doelstelling van dit onderzoek is een bijdrage te leveren aan de verbetering van melkvalorisatie in de zuivelindustrie. Het probleem van melkvalorisatie wordt vanuit een logistiek- managementperspectief benaderd. Het onderzoek concentreert zich op beslissingsondersteuning voor de optimale toewijzing en doorstroming van grondstoffen richting eindproducten in een sterk divergerende productiestructuur van boeren tot consumentenmarkten. Met behulp van de Operations Research (OR) zijn kwantitatieve modellen en raamwerken ontwikkeld om het melkvalorisatieproces op middellange termijn te verbeteren.

In eerste instantie is een algemeen melkvalorisatiemodel ontwikkeld voor de middellange termijnplanning. Dit model is in de daaropvolgende studies verder verfijnd op

basis van een uitgebreid literatuuronderzoek, vele interviews en gesprekken met experts van FC. Hierbij stonden voortdurend de potentiële toegevoegde waarde voor FC, de beschikbaarheid van gegevens en de bijdrage aan de literatuur centraal. Een succesvolle melkvalorisatie in de praktijk hangt enerzijds af van het bereiken van een optimaal en integraal valorisatieplan, waarin alle relevante aspecten zijn meegenomen; anderzijds van een efficiënte implementatie van het plan resulterend in een goede prestatie. Als gevolg hiervan is het onderzoek in twee delen opgesplitst, i.e. de ontwikkeling van een doelmatig valorisatiemodel (Deel I) en de ontwikkeling van instrumenten voor prestatiebeoordeling (Deel II). Vier specifieke onderzoeksdoelstellingen zijn gedefinieerd, die elk in een apart hoofdstuk worden besproken:

Deel I

1) *Ontwikkeling van een Melk Valorisatie Model waarin alle relevante elementen zijn opgenomen*
2) *Evaluatie van het effect van de valorisatie van bijproducten en integrale valorisatie op de totale valorisatie van melk*

Deel II

3) *Evaluatie en verbetering van de robuustheid van valorisatieplannen met behulp van deterministische modellen*
4) *Ontwikkeling van een raamwerk om de efficiëntie van verwerkingseenheden te meten*

Er is een combinatie van kwalitatieve- en kwantitatieve methodieken gehanteerd. Literatuurstudies zijn uitgevoerd om hiaten op te sporen, de onderzoeksvragen te formuleren, geschikte OR methoden te vinden, het verzamelen en verifiëren van gegevens alsmede het definiëren van scenario's om de hypothesen te toetsen. Veel open en semi-gestructureerde interviews met experts zijn gevoerd. Elke onderzoeksvraag is ondersteund met case studies bij FC (Hoofdstukken 1-3) en TNT Express (Hoofdstuk 4).

Belangrijkste bevindingen en conclusies

1) Melk Valorisatie Model

In Hoofdstuk 2 is het Melk Valorisatie Model (DVM) beschreven. Het model genereert optimale middellange termijnplanningen voor de toewijzing van melk aan eindproducten waarbij rekening wordt gehouden met alle relevante beperkingen. De achterliggende onderzoeksvraag was: *Welke aspecten zijn modelmatig van belang om het zuivel proces zodanig te beschrijven dat efficiënte melkvalorisatie-plannen gegenereerd kunnen worden?*

De volgende aspecten zijn als belangrijk geïdentificeerd en in het DVM gemodelleerd: recepturen gebaseerd op de samenstelling van rauwe melk, seizoensgebondenheid variatie in samenstelling en levering van rauwe melk, het volledige product portfolio, benutting van bijproducten, netwerk van aanvoerregio's en productielocaties, het transport van rauwe melk en bijproducten alsmede de veranderingen in verkoopprijzen. Het modelleren van alle voorgaande aspecten blijkt van groot belang voor de integrale valorisatie van melk. Voorts werd tijdens het proces ook duidelijk dat het ontwikkelde DVM het begrip bevordert van de complexe samenhang van onderliggende productieprocessen en producten.

In Hoofdstuk 2 tonen we ook aan dat de seizoensgebonden samenstelling van rauwe melk (dat is het droge stof-, vet- en eiwitgehalte) een grote invloed heeft op de valorisatie van melk, i.e. op beslissingen met betrekking tot de toewijzing van melk aan eindproducten, de geproduceerde volumes aan eindproducten alsmede de winst van het bedrijf. Dit terwijl de gangbare modellen in de literatuur deze seizoensinvloeden op melksamenstelling negeren en zich uitsluitend richten op volumes rauwe melk.

2) Wei valorisatie

De productie van eindproducten leidt ook tot grote hoeveelheden bijproducten in het hele proces, in het bijzonder wei. Toen we met dit onderzoek begonnen, werd de valorisatie van de belangrijkste zuivelproducten en bijproducten bij FC afzonderlijk uitgevoerd. Dit leidde tot de tweede onderzoeksvraag: *Wat is de toegevoegde waarde van een integra.al valorisatieproces voor eind- en bijproducten tezamen en heeft een dergelijke aanpak invloed op de productie van de voornaamste eindproducten?* In de literatuur zijn geen studies bekend die deze vraag beantwoorden.

In Hoofdstuk 3 is een nieuw Integraal Melk Valorisatie Model (IDVM) ontwikkeld waarin de belangrijkste eindproducten gelijktijdig met wei als bijproduct worden gevaloriseerd. Om de resultaten van gefaseerde valorisatie (primair de voornaamste eindproducten valoriseren en vervolgens wei) met een integrale valorisatie-aanpak (alles gelijktijdig valoriseren) te kunnen vergelijken, ontwikkelden we ook een stapsgewijze (hiërarchische) evaluatie-aanpak. We tonen aan dat: expliciete valorisatie van wei-stromen tot aanzienlijke verhoging van de winst bij FC leidt; het effect van de integratie van twee valorisatieprocessen op dit moment gering is voor FC; als de vraag en verkoopprijzen van wei producten, de verkoopprijzen van melkpoeders of de verwerkingscapaciteit van wei toenemen, het voordeel van een integrale aanpak aanzienlijk groter kan zijn; de waarde van wei-verwerking in de valorisatie van belangrijke eindproducten betrekken, zal de kaasproductie nadelig beïnvloeden. Dit als geheel betekent dat wei-producten momenteel onvoldoende winstgevend zijn om invloed te hebben op de productie van de voornaamste eindproducten.

3) Robuustheid

Het ontwikkelde DVM is een deterministisch lineair programmeringsmodel. Onzekerheden met betrekking tot de invoergegevens kunnen daardoor echter tot niet-robuuste oplossingen leiden. Robuustheid is gedefinieerd als: *de mate waarin kritische prestatie-indicatoren, bij verschillende realistische scenario's van invoergegevens, binnen een vooraf vastgesteld bereik vallen*. De robuustheid van de gegenereerde oplossing is van groot belang omdat initieel gegenereerde planningen suboptimaal of zelfs zeer kostbaar kunnen worden als de realisatie van stochastische invoergegevens afwijkt van de voorspelling. Hoofdstuk 4 richt zich op de evaluatie van de robuustheid van valorisatieplanningen die gegenereerd zijn met een deterministisch model. We beantwoordden de derde onderzoeksvraag: *Hoe kunnen we de robuustheid van valorisatieplanningen beoordelen als de resultaten met deterministische modellen zijn verkregen?*

We ontwikkelden een raamwerk in vijf stappen: (1) definieer de kritische prestatie-indicatoren (KPI's), (2) selecteer relevante invoerparameters, (3) definieer scenario's, (4) evalueer de robuustheid, en (5) kom tot conclusies. Het resultaat van stap 4 is multidimensionaal. Om uiteindelijk tot een robuustheidsgraad te komen moeten vooraf een aantal beslissingen worden genomen: de aanvaardbare grenzen voor de KPI's (robuustheidsbereik); de evaluatieperiode (maand of jaar); evaluatieniveau; en de groepering van KPI's. De studie toont aan dat, afhankelijk van de gemaakte keuzes, de robuustheid van valorisatieplanningen tot verschillende conclusies zal leiden.

In de case study beoordeelde FC de overkoepelende robuustheidsgraad van de gegenereerde planningen voldoende hoog voor effectieve melkvalorisatie via het DVM. Via het model zijn de belangrijkste parameters geïdentificeerd met de hoogste impact op de robuustheid, namelijk de melksamenstelling en de melkaanvoer. Het onderzoek heeft aangetoond dat het niet altijd noodzakelijk is om complexe valorisatiemodellen te ontwikkelen waarin stochastische invoer-parameters direct zijn opgenomen. De berekende graad van robuustheid betekent ook dat identificatie van parameters met het grootste effect op de robuustheid, mogelijk is. Door de betrouwbaarheid van de prognoses voor de meest invloedrijke parameters te verbeteren kan de robuustheid verder worden verhoogd.

4) Benchmarking van verwerkingseenheden

In aanvulling op een verbeterde verwaarding van melk met behulp van het ontwikkelde valorisatie model, kan de winst ook worden verhoogd door de efficiëntie van verwerkingseenheden te verbeteren. Om de vierde doelstelling uit dit proefschrift te bereiken, beantwoordden we de volgende onderzoeksvraag: *Hoe kunnen de prestaties van de verwerkingseenheden worden gemeten en verbeterd?* Aangezien weinig relevante informatie beschikbaar was bij FC, werd een raamwerk ontwikkeld dat in een case studie getest werd bij een Europese marktleider op het gebied van wereldwijde koeriers- en expressdiensten voor de zakelijke markt (TNT Express).

In eerste instantie werd een literatuuronderzoek naar methoden voor prestatiebeoordeling uitgevoerd. We concludeerden dat Data Envelopment Analysis (DEA) het meest geschikt was temeer de methodiek uitgaat van diverse KPI's en het prestatieniveau vervolgens in een enkele waarde wordt uitgedrukt. Om modellen te ontwikkelen, zijn de belangrijkste factoren van de express depots geanalyseerd. Vervolgens zijn twee DEA-modellen ontwikkeld die de efficiency van depots aangeven. Het eerste model behandelt alle factoren identiek. Het tweede model maakt een strikt onderscheid tussen factoren die niet of juist wel via management beïnvloedbaar zijn. De resultaten van het tweede DEA-model zijn gebruikt als informatiebron om inefficiënte verwerkingseenheden te verbeteren. We identificeerden: inefficiënte eenheden; het aandeel van gerealiseerde efficiëntieniveaus (van inefficiënte eenheden) dat een gevolg is van managementactiviteiten of van gunstige externe omstandigheden; mogelijke reducties van "input" niveaus realiseerbaar bij gelijkblijvende "output" niveaus; en eenheden die specifieke inputs het meest efficiënt gebruiken en daardoor als benchmark gebruikt kunnen worden voor andere eenheden.

Deze bevindingen bevestigen de geschiktheid van DEA voor het beoordelen en verbeteren van prestaties van verwerkingseenheden. Het ontwikkelde model kan in de zuivelindustrie ingezet worden om de efficiëntie van productie-eenheden te vergelijken en daarmee bijdragen aan een betere valorisatie van melk.

Wetenschappelijke bijdrage

Met behulp van de Operations Research (OR) zijn een aantal beslissingsondersteunende modellen ontwikkeld om besluitvorming over melkvalorisatie te verbeteren. Het onderzoek draagt in brede zin bij aan beslissingsondersteunend modelleren en richt zich in het bijzonder op het efficiënt gebruik van grondstoffen. Voorts draagt elke studie op onderdelen bij aan de theorie omtrent Logistiek Management van Voedselproducten en Prestatiemanagement. Hoofdstuk 6 toont het verband aan tussen de wetenschappelijke bijdrage van het onderzoek en de specifieke wetenschapsgebieden (zie Figure 6.1 op pagina 144). Meer specifiek, we beschrijven en analyseren een complex melksysteem, ontwikkelen specifieke beslissingsondersteunende hulpmiddelen om besluitvorming op het gebied van de productieplanning te ondersteunen en ontwikkelen twee raamwerken voor prestatiemeting.

Management inzichten en implicaties

De ontwikkelde modellen en raamwerken bieden nieuwe inzichten in het melkvalorisatieproces, maar kunnen ook als basis gebruikt worden om valorisatie van grondstoffen in andere industrieën te verbeteren. Voor effectieve verwaarding van grondstoffen moeten bedrijven hun eigen valorisatiemodel ontwikkelen. In Hoofdstuk 2 wordt een aanpak beschreven voor het ontwikkelen van dergelijke modellen. Hiertoe is een gedegen overzicht van het complete systeem noodzakelijk alsmede toegang tot de benodigde invoergegevens. De case studie bij FC toont aan dat het integreren van hoofd- en bijproducten in valorisatieprocessen winstgevend kan zijn; de toegevoegde waarde is echter afhankelijk van marktgegevens en productiecapaciteit van bijproducten en daaraan gerelateerde hoofdproducten. Om ervoor te zorgen dat een toekomstige integratie van beide valorisatieprocessen correct plaatsvindt dienen bedrijven mogelijke veranderingen van invoergegevens te onderzoeken. Voorts tonen we in Hoofdstuk 4 aan dat de robuustheid van de oplossingen die met een deterministisch valorisatiemodel verkregen zijn, voldoende hoog is om betrouwbare planningen te genereren. Dit betekent dat het niet altijd noodzakelijk is om complexe, stochastische modelleertechnieken te hanteren. Deze studie heeft voor FC uitgewezen dat de robuustheid van de oplossingen belangrijk is, zo niet van groter belang is dan het genereren van optimale planningen. Om de robuustheid en de kwaliteit van valorisatieplanningen te verbeteren, dienen bedrijven de betrouwbaarheid van de prognoses voor de meest invloedrijke parameters te verbeteren. Ook moet de robuustheidsgraad regelmatig beoordeeld worden met het ontwikkelde raamwerk in Hoofdstuk 4. Ten slotte dienen managers zich ook te richten op de prestatieniveaus van verwerkingseenheden. Met behulp van de stapsgewijze aanpak in Hoofdstuk 5 kunnen bedrijven een DEA-model ontwikkelen om inefficiënte fabrieken te identificeren en nieuwe inzichten verwerven voor het verbeteren van prestaties.

Mogelijkheden voor verder onderzoek

Alhoewel belangrijke stappen gezet zijn, zijn er ook voldoende mogelijkheden voor vervolgonderzoek. De belangrijkste opties zijn: integratie van voorraadbeheer in het huidige DVM; het ontwikkelen van een stochastisch valorisatiemodel waarmee de invloed van onzekerheid in parameterwaarden op de gerealiseerde oplossingen, verder beperkt kan worden; ontwikkeling van specifieke voorspelmodellen voor de bestanddelen van rauwe melk waarmee de nauwkeurigheid van de invoergegevens verbetert; de ontwikkeling van een model uit de speltheorie met als doel om de integrale valorisatie van melk over verschillende business units te stimuleren; en aanvullende case studies uitvoeren om na te gaan of de conclusies van de uitgevoerde onderzoeken ook voor andere zuivelondernemingen gelden en/of de ontwikkelde methoden ook geschikt zijn voor de valorisatie van productstromen in andere branches van de voedingsmiddelenindustrie.

Conclusie

Op basis van het uitgevoerde onderzoek concluderen we dat goed en maximaal valoriseren van rauwe melk een integrale aanpak vereist. Hiertoe moeten modellen en technieken uit de OR gebruikt worden omdat het toepassen van praktische vuistregels veelal ontoereikend is om invulling te geven aan de complexiteit van de verwerkende industrie. De modellen en raamwerken die in dit proefschrift ontwikkeld zijn, bieden nieuwe en aanvullende inzichten in complexe productiesystemen. Ze voorzien in een nieuw perspectief ten aanzien van melkvalorisatie. We toonden aan dat de analyse van de resultaten die verkregen zijn met de ontwikkelde methoden veel vragen vanuit management perspectief kunnen beantwoorden en dus besluitvormingsprocessen binnen een bedrijf ondersteunen. De valorisatie van grondstoffen wordt daarmee verbeterd, het creëert toegevoegde waarde voor bedrijven en leidt uiteindelijk tot duurzamere zuivelketens.

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About the author

Agata Banaszewska was born on August 7, 1984 in Białystok (Poland). In 2003 she started bachelor studies, at the faculty of Information Technology and Econometrics, Warsaw University of Life Sciences (WULS). In 2006 she obtained her bachelor degree and continued with a master program Statistics and Econometrics at WULS. In 2007, within the confines of a Double Degree program, she started a second master program at Wageningen University (WUR) in the Netherlands (faculty: Management, Economics and Consumer Studies, specialization: Operations Research and Logistics). In 2009, she graduated from both master programs. Her master thesis was awarded with the WUF-KLV Thesis Prize as the best master thesis of 2008/2009 of WUR.

After graduation, Agata was enrolled as a doctoral student at Wageningen University, as part of the Operations Research and Logistics group. Her doctoral project is related to the use of Operations Research tools to improve the tactical allocation and production planning processes of the large international dairy company FrieslandCampina. As a result Agata was working both at WUR and at FrieslandCampina. She acted as a bridge between the science and practice; she interacted with people from diverse backgrounds in order to contribute to the scientific developments and to solve relevant practical problems. As a part of her doctoral program she attended courses at WUR, at the Dutch Network on Mathematics of Operations Research (LNMB), a Doctoral MIT-Zaragoza Summer School at Zaragoza Logistic Center (Spain), and a number of scientific conferences (9th Wageningen International Conference on Chain and Network Management organized by WUR, 37th conference on The Mathematics of Operations Research organized by LNBM, ORP3 conference organized by the Association of European Operational Research Societies).

Completed Training and Supervision Plan

Agata Banaszewska
Wageningen School of Social Sciences (WASS)

Name of the course	Department / Institute	Year	ECTS[1]
I. General part			
Scientific writing	Wageningen Graduate Schools	2009	1.8
PhD competence assessment	Wageningen Graduate Schools	2010	0.3
Techniques for writing and presenting a scientific paper	Wageningen Graduate Schools	2012	1.2
II. Mansholt-specific part			
Mansholt introduction course	Mansholt Graduate School	2009	1,5
Mansholt multidisciplinary seminar	Mansholt Graduate School	2012	1
"Measuring true efficiency levels. The case of TNT Express depots"	WICaNeM[2] conference, Netherlands	2010	1
"A Comprehensive Dairy Valorization Model"	LNMB[3] conference, Netherlands	2012	1
"A Comprehensive Dairy Valorization Model"	ORP3[4] conference, Austria	2012	1
III. Discipline-specific part			
Writing the research proposal	Department of Operations Research and Logistics, WUR	2010	4
Combinatorial optimization 2b (CO2b)	LNMB, Netherlands	2010	4
OR-Games (ORG)	LNMB, Netherlands	2010	4
Introduction to stochastic processes (ISP)	LNMB, Netherlands	2011	4

Continued on the next page

[1]*One ETCS is equivalent to 28 hours of course work*
[2]*WICaNeM = Wageningen International Conference on Chain and Network Management*
[3]*LNMB = Landelijk Netwerk Mathematische Besliskunde*
[4]*ORP3 = EURO peripatetic conference designed for young Operations Research researchers and practitioners*

Name of the course	Department / Institute	Year	ECTS[1]
Using laboratory experiments to build better operations management models	Zaragoza Logistics Center, Spain	2012	0.85
Pricing and revenue management	Zaragoza Logistics Center, Spain	2012	0.85
Advanced topics in inventory management	Zaragoza Logistics Center, Spain	2012	0.85
Operations management models with supplier and customer incentives	Zaragoza Logistics Center, Spain	2012	0.85
Retail operations	Zaragoza Logistics Center, Spain	2012	0.85
IV. Teaching and supervising activities			
Supervising students	Department of Operations Research and Logistics, WUR	2012, 2013	4
Total			33.05

[1]*One ETCS is equivalent to 28 hours of course work*

Print
GVO printers & designers B.V.

Cover design
Katarzyna Westrych