FOOD INDUSTRY SUPPLY CHAIN PLANNING WITH PRODUCT QUALITY INDICATORS

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DECLARATION

I hereby certify that all material in this thesis is my own work. Any quotation from, or description of the work of others is acknowledged by reference to the sources, whether published or unpublished.

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Abstract

Quantitative supply chain modelling has contributed substantially to a number of fields, such as the automotive industry, logistics and computer hardware. The inherent methods and optimisation techniques could also be explored in relation to the food industry in order to offer potential benefits.

One of the major issues of the food industry is to overcome supply seasonality and on-shelf demand. On the shelf demand is the consumer's in store demand which could also be seasonal. Objective of this work is to add flexibility to seasonal products (i.e. soup) in order to meet the on-shelf demand. In order to achieve this, a preparation process is introduced and integrated into the manufacturing system. This process increases the shelf-life of raw materials before starting the production process. This process, however, affects the quality of fresh raw materials and requires energy. Therefore, a supply chain model is developed, which is based on the link between the quality of the raw material and the processing conditions, which have an effect on the process' energy consumption and on the overall product quality.

It is challenging to quantify the quality by looking at the processing conditions (degrees of freedom) and by linking it with energy in order to control and optimise the quality and energy consumption for each product. The degrees of freedom are defined differently for each process and state. Therefore, the developed model could be applied to all states and processes in order to generate an optimum solution. Moreover, based on the developed model, we have determined key factors in the whole chain, which are most likely to affect the product quality and consequently overall demand. There are two main quality indicator classes to be optimised, which are both considered in the model: static and time dependent indicators. Also, this work considers three different preparation processes – the air-dry, freeze-dry and freezing process – in order to increase the shelf-life of fresh raw materials and to add flexibility to them.

A model based on the interrelationship between the quality and the processing conditions has been developed. This new methodology simplifies and enables the model to find the optimum processing conditions in order to obtain optimum quality across all quality indicators, whilst ensuring minimum energy consumption. This model is later integrated into the supply chain system, where it generates optimum solutions, which are then fed into the supply chain model. The supply chain model optimises the quality in terms of customer satisfaction, energy consumption and wastage of the system linked to environmental issues, and cost, so that the final products are more economical. In this system, both the manufacturing and inventory systems are optimised. This model is later implemented with a real world industrial case study (provided by the industrial collaborator). Two case studies are considered (soya milk and soup) and interestingly enough only one of them (soup) corresponds with this model. The advantage of this model is that it compares the two systems and then establishes which system generates an optimum end product.

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Firstly I would link to thank my supervisor Professor Nilay Shah at the Centre for process engineering who has given me professional guidance throughout my PhD. Also he has been very helpful on my personal issues.

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I would like to thank my sponsor Unilever for their financial support. Also I would like to thank them for giving me the opportunity to apply and test my model in the real world industrial case.

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

The competition in the industrial world to gain market share is becoming more and more fierce. Improvements to product quality, customer satisfaction and the final product price are all factors which could provide producers with an edge in the market. In the FMCG (Fast Moving Consumer Goods) sector, the product improvement process is based on fundamental research and development, which is a key factor for technology development. Technology development uses product innovation in order to improve existing products or to create new products and services. Process innovation, on the other hand, aims to reduce the cost of production. Supply chain management is a research area, which develops model-based techniques, and which finds the bottlenecks and optimises all steps from supply to distribution.

Many organisations have started to appreciate the criticality of creating an integrated relationship with suppliers and the customers. Process industry companies and researchers have tended to have a company-centric view of the supply chain, and studies with a broader viewpoint are less common. Considering the more extended view, Shah (2005) states that it is beneficial to consider company nodes and to share information with all of the participants in the supply chain. This is now a major area of study for many industries.

1.1. Supply chain and food processing review

Since the 1950s, operations research practitioners and logistics experts have given extra thought to the term supply chain. The design, planning and control of the networks for business processes in order to improve competitiveness have been a common theme for operational research. Supply chain management has grown in popularity over time, especially amongst industrial companies, such as the petrochemical industry and pharmaceutical companies. Companies react to increasingly competitive markets and globalisation trends with an integrated management of their supply chains. The integration of food processing and food engineering with supply chain management is a complex issue, but it also offers advantages to companies, such as profitability and customer satisfaction.

1.1.1. Supply chain management review

Supply chain management is a series of logistical internal and external activities for companies in order to increase efficiency, by sharing information between entities, and by gaining customer satisfaction with the lowest possible costing (Shah, 2005). In very simple language, Blackwell (1997), in his book entitled *From Mind to Market*, says "*supply chain management is all about having the right product in the right place, at the right price, at the right time and in the right condition.*"

Studies on the supply chain indicate the importance of integrated relationships between suppliers and customers. The objective of supply chain management is to connect the supplier to the customer in the most efficient way. There is a particular topic, which needs to be taken into consideration in order to achieve this objective, namely supply chain planning, which covers the decisions and plans made for manufacturing systems. Supply chain strategy covers the long-term network optimisation for warehousing, location and allocation, distribution centres and facilities, which basically specifies where to make and make/buy decisions. Demand management aims to manage the upper and lower boundaries of a manufacturing site in order to deliver the best value to the costumer at the lowest possible cost. Manufacturing generates the production design and schedule with the lowest waste, energy usage and cost, as well as producing a high-quality product. Distribution aims to find the best and cheapest way for distributing a product from the manufacturing site. Customer service is the relationship management between the company and its customers. And finally, financial management accounts for cost, profit, revenue and all of the financial activities (Fig 1.1).

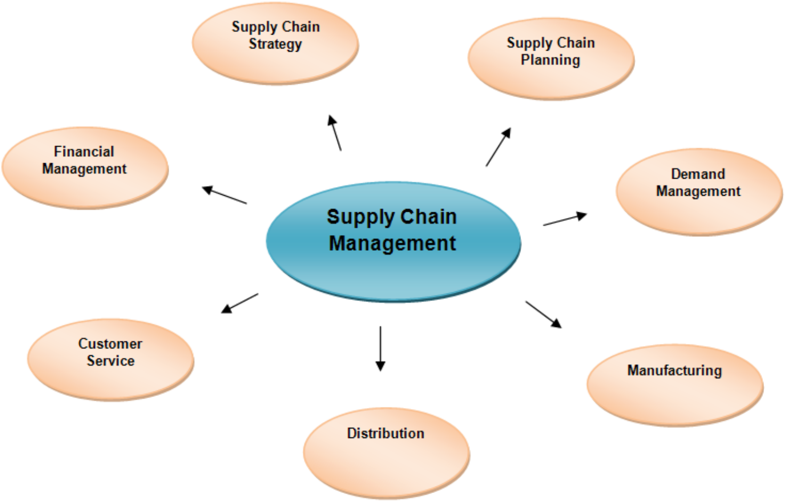


Figure 1-1 Supply chain management

The manufacturing components of supply chains in many industries consist of two main lines: production and distribution. Production starts with raw material, manufacturing, and packaging. The product is then stored, before being distributed to retailers and/or distribution centres. Over time, new information is fed back, which forces each node to adapt its operations in accordance with the most up-to-date information in order to increase the efficiency of the node and therefore the system as a whole. For instance, information on consumer demand is fed back from the distribution and logistics systems department to the production and manufacturing systems department, in order to control the production rates and the quantity of the product (Fig 1.2).

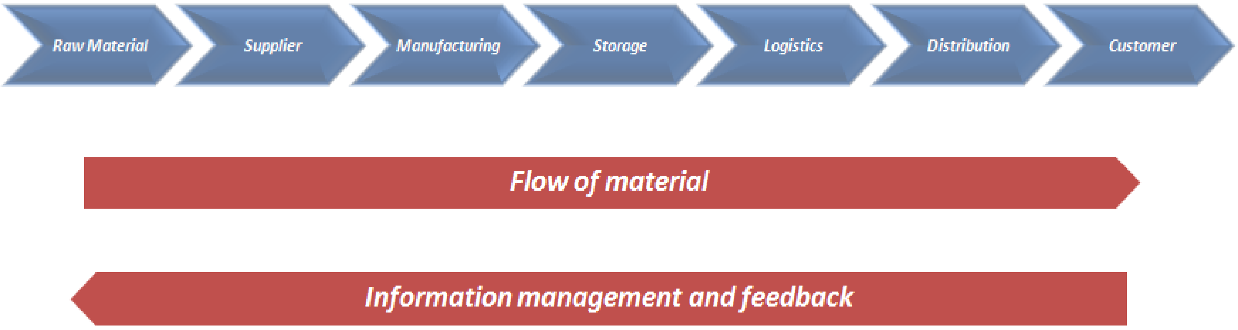


Figure 1-2 Material and information flow in a supply chain model

1.1.2. Planning and scheduling review

Planning and scheduling are an important aspect of supply chain management. This is simply the regular decision-making aspect of the system. The decision-making process features in two different levels: the strategic and the operational level. The strategic level refers to long-term planning and design, and the major tasks associated with this level are the supply chain network design, the plant design, and development management. The operational level decides what, when, where, and how to produce. There are two tasks here: planning and scheduling. Planning tasks plan the manufacturing system, and the scheduling activity determines the ingredients, the demand, the timing, the inventory, and the distribution. A simultaneously strategic and operational planning approach is very difficult to achieve. It is even more difficult in an industrial world and within large companies. But when a new site or plant is established/ a new structure is embedded especially in large companies, the combination of operational planning with strategic planning could lead to greater financial savings. This is because instead of forecasting some of the parameters and variables, such as energy usage and demand, the actual value is fed back into the system from the operational level to the strategic level. Therefore, more accurate results are generated on how, where and when to produce. It also identifies a more suitable long-term plan, which could result in financial savings from cost reductions. As a result, the simultaneously strategic and operational planning approach is very attractive to large organisations, despite it being difficult (Kallrath 2002).

Typically, there are three time horizons: long, mid, and short-term. Scheduling has a short-term horizon, usually a one-day or weeklong window, and it forecasts customer demand and the required raw material usage. Regarding the forecasts, the scheduling exercise determines the production procedure, as well as the detailed allocation of manufacturing resources over time. Planning on the other hand, requires a longer time horizon, and uses information obtained over time. This then updates the model. Overall, planning and scheduling deal with the allocation of resources over time, as well as the generation of plans to ensure the right level of product quantity and quality at the right location.

The objectives of planning and scheduling are low costs, fast responses and a high level of flexibility in products, not to mention profitability. Due to the recent recession, an increase in flexibility in terms of supply, the product itself and the customers plays a crucial role. This is, because flexible suppliers could assist a company in achieving flexibility in terms of the availability of raw materials and it could reduce shortages and waste of raw material. Product flexibility could attract customers with different tastes, and a flexibility in customer satisfaction could allow a company to expose its products more easily.

1.1.3. Food supply chain review

Quality control and the food supply chain have not been widely studied, especially in the industrial world. Until 2002, there was no specific structured approach to food products and process quality modelling (Costa *et al.*, 2002). The reason for this is that managing a food supply chain for specific products and process characteristics, such as quality, is complicated, especially if the process characteristics limit the possibility of integrating food engineering considerations into the supply chain management. These limitations and barriers have been investigated by Van Donk *et al.* (2008). The report argues that the combination of food characteristics and the use of shared resources results in limitations in terms of integration. Uncertainties and complex business conditions, on the other hand, are parameters, which increase the possibility of integration.

In order to model the food supply chain, food characteristics must be included successfully. One of the most important food characteristics is product quality (e.g. Smith and Sparks 2004). In 2008, Trienekens and Zuurbier stated that an integrative view on logistics and product quality is one of the keys to supply chain management for the food industry. This has been labelled as quality-controlled logistics by Van der Vorst *et al.* (2007). This means that products with different quality levels could follow different logistical distribution channels and attract different customers with different quality demands.

Research by Rong *et al.* in 2010 is relevant in this respect. They have developed an MILP model for planning food production and distribution with a focus on quality control. The approach combines decision-making on logical issues, such as production volumes and transportation flows, with decisions on storage and transportation temperature. This model has become a tool for supporting production and distribution systems in the food industry. However, it only considers a single product in the production and distribution network and is still fairly large and complex. The key objective of this model is to keep the transportation and storage costs as low as possible and to keep the quality degradation low in parallel by varying the temperature. Also, in order to keep the final product quality within an acceptable range, they have added a wastage constraint with a boundary for minimum and maximum quality in their model. The quality model can, however, only be used to calculate certain quality indicators, such as the colour intensity and nutrient content. We have studied this paper carefully and have extended it in this thesis. Rong *et al.* control the quality of the product by using a kinetic model at each stage and process. In this thesis, on the other hand, we have developed a model to not only control, but to also optimise the quality and energy consumed by the product at each stage and process. Also, our model has been implemented into the supply chain system in order to minimise overall costs. The model developed in this thesis can be used as a tool for products subject to seasonality and on-shelf demand.

As mentioned before, research reported in the literature has paid some attention to food supply chain management. Most of these reports concern the logistics and inventory systems of the food supply chain and the transportation of food products. This thesis introduces a newly developed methodology for controlling, measuring, analysing and increasing product quality in the manufacturing system in order to meet consumer expectations and to relate the quality to supply chain operations in a quantitative way, which could in turn optimise profits.

1.1.4. Food processing types and quality indicators

Food engineering is a field, which introduces the process of food production, and which measures and analyses quality changes in food products during this process. In this sub-section, a number of potential process types and quality indicators for this project are introduced.

i) Food processing

Removing water from raw foods is a way of increasing the shelf-life of food ingredients and of retaining a number of other quality indicators, as well as reducing the cost. Drying, freeze concentration, evaporation and reverse osmosis are a few ways of removing water from the product.

Thermal processing: thermal processing consists of heating food containers in pressurised steam at a constant temperature for a given period of time. During the process, the timing, temperature, and pressure is set in a way to achieve a sufficient bacterial inactivation in each container. The bacterial inactivation is temperature-dependent, and the temperature at each point in the container changes at different rates. The inactivation therefore occurs at a different rate in different locations of the same container.

Freezing: Food freezing is a reduction in temperature until ice crystals are formed in the product structure. Food freezing is used for food preservation and is as economical as canning in the food industry. The accuracy of the freezing times for various products in the process is an important requirement for the design of commercial food freezing systems.

Drying: This is a food dehydration process with the objective of removing water from the product. The mathematical model in the drying process includes the mass transfer of moisture, air and aroma components. The degradation of quality factors, such as vitamins, during the processing is a function of the moisture content, as well as time and temperature (Saguy *et al.* 1980).

Uncertainty in food processing

Overcoming uncertain factors, such as the processing time, temperature and demand, is a very important issue, especially in regards to the food processing system. These are all factors that could affect the system. Action must be taken on the following factors in order to reduce uncertainty:

- Timing and quality of product
- Balancing the production rate with the demand rate
- Balancing the supply rate with production
- Planning for the collection of failed products

Advantages of air-dried and freeze-dried material compared to other process types

Drying is the simultaneous process of both heat and mass transfer, where the drying itself leads to a diffusion and convection process. The drying process encapsulates the original flavour and maintains the nutritional value. Air/freeze dry reduces weight, transportation costs, packaging costs and storage space. These processes also secure a good level of control in terms of process duration and product quality. This is a very important factor in terms of avoiding spoilage of raw material, and consequently waste production (Singh and Heldman 2009).

ii) Quality indicator

The quality of the product is disturbed after going through the drying process. Despite all the advantages the drying process brings, it does also affect the quality of the product. Drying causes physical, nutritional, microbial and structural changes in the material. In this subsection, the product quality and quality indicators are introduced. In terms of the product quality, two terms can be introduced here.

- *Intrinsic:* This term consists of physical properties, such as the flavour, texture, appearance, shelf-life, and the nutritional value. These factors can be measured directly in the production line.

- *Extrinsic:* This is the modification of product properties and influences the acceptance of the product by the consumer. It includes factors, such as packaging. However, it does not have a direct influence on the physical properties.

Together, intrinsic and extrinsic factors determine the purchasing behaviour (Jongen and Meerdink 1998).

Quality attributes

Quality attributes can be divided into three classes. There are quantitative attributes, which could include be the finished product yield of vegetables or meat. Hidden attributes are quality attributes, which are not visible, such as vitamin content, nutritional value and toxic substances. Sensory attributes are quality attributes, which are visible. They include, for example, the shape, consistency, texture, colour and gloss of the product.

Quality modification

- Some qualities are modified by biochemical reactions, e.g.: enzyme reaction, protein denaturation, Maillard reaction, lipid oxidation, vitamin oxidation/ inactivation. These are most likely to occur in the presence of excess heat and during the drying process.
- Others are modified by microbiological reactions: product modification by microbiological reactions, growth of micro-organisms, and the destruction of micro-organisms, which again would occur during the drying process.
- Aroma loss is caused mainly by evaporation and occasionally by oxidation.
- Mechanical phenomena and phase changes cause crystallisation, glass transition, collapse due to water elimination and thermo-hydric effects, such as shrinkage, formation of cracks, holes and folds.

Quality indicators

So far, the quality attributes have been classified and modified. Now, the quality indicators of interest to this project are introduced. There are two types of quality indicators: static and time-dependent indicators. Static indicators are quality indicators for the material, which change every time there is a process. For instance, the shape of a potato changes only after the cooking process. Time dependent indicators, on the other hand, are quality indicators, which have a rate of change over time. The rate of change can vary after each process. For instance, the colour intensity of the food product changes over time, and it could change faster after each process. The quality indicators that are of interest to the project are as follows:

Static indicators:

- Shelf-life is affected by the expiry date of the material.
- Shrinkage (which includes volume, shape and size); this is caused by moisture/ water loss during the drying process.
- Cracking, which is affected by temperature changes and the distribution of stress levels.

Time-dependent indicators

- Texture, temperature changes, crystallisation of water particles, weight changes and water or moisture loss.
- Colour intensity is affected by the concentration and measured and absorbed by wavelength.

- Vitamin content – vitamins, such as ascorbic acid, thiamine and riboflavin, must be maintained in the product. In order to maintain the vitamin content, the critical temperature must be found. Also, the duration of the process in the case of freezing must be kept to a minimum. This is a time and temperature-affected indicator.
- Nutrient content, including beta-carotene, carotenoids, lycopene, thiosulphiates. These changes are caused by evaporation and sometimes oxidation, which in drying is due to temperature increases and in freezing the driving force is the temperature difference.
- Microbial content; this is affected by the drying process and excess of heat.

In food engineering, drying is a popular process, due to all of its advantages, such as weight, storage space and cost reduction, as well as an increase in the product's shelf-life. However, this process disrupts the quality of the product. During the sterilisation process, for instance, some of the indicators of product quality are disrupted. The key quality indicators affected by sterilisation are:

- Reduction in the quality of the product, changes in the texture, and softening of the material.
- Increase of enzyme reactions, which lead to potentially unsafe products.
- Reduction in vitamins, such as vitamin C, thiamine, and folate content.

Also, some of the dried materials undergoing retort or sterilization processes have the potential to explode. For this class, a few options could be considered. One option could be half drying the raw materials or adding a step to rehydrate the dried materials before usage. However, rehydration is costly and takes time and half drying the materials would lead to a lower shelf-life compared to the dried materials.

Sterilisation not only affects the product in terms of quality, but also from an economical point of view. For example, the heat used for the sterilisation process affects energy consumption and the carbon footprint.

After reviewing the supply chain management and food engineering areas, a decision has been made to integrate food engineering analyses into the supply chain in order to control the quality and cost of products.

1.2. Food supply chain problems

Food supply chain management is a new but fast growing sector of supply chain management, both from an industrial and scientific point of view. Food supply chain management has been paid relatively little attention in literature. The reason being that the integration of food engineering into supply chain management is a complex task. Also, it is complicated to manage the food supply chain by specific product and process characteristics, such as quality.

Food engineering is a field, which combines science, microbiology and engineering education for food and related industries. Foods undergo changes after each process. These changes could be physical, chemical, enzymatic, or microbiological. Food engineering is a field which analyses, measures and quantifies these changes. Food engineering studies mostly concentrate on the quality aspect of the production process. Quality optimisation has been a huge concern for the food processing sector, as an increase in quality leads to an increase in cost, energy consumption and processing time. As a result, this thesis shows how to overcome these problems by combining food engineering, processing, and supply chain management. Supply chain models are quantitative models, which focus on the optimisation of cost, energy and time. The challenge for food supply chains is to build a model, which can predict quality and use it in a quantitative way, together with cost and other criteria.

Supply chain management is an area of research, which develops techniques to optimise all of the steps from the supplier to distribution. Supply chain management has proven hugely successful in various industries, such as pharmaceuticals, oil and gas and customer goods. Some of the studies focusing on supply chain management are Almansoori and Shah (2006), Stefansson *et al.* (2006), Dunnett *et al.* (2007), Dunnett *et al.* (2008), Slade *et al.* (2009), Almansoori and Shah (2009), Slade *et al.* (2009), Yu *et al.* (2012), Ganesh and Ghadially Zoher (2013), Abdallah (2013) and Brun *et al.* (2013). The successful implementation in these industries implies that supply chain management could help the food industry to improve performance against a range of metrics.

The supply chain design considered in this thesis is as follows (Fig 1.3):

The plan of the model is to design a successful supply chain for a typical food product. The first step is to develop a product specification according to consumer requirements (the supply chain industry strategy). Next, performance measures will be taken into account. In this report, three classes will be considered: quality, flexibility and cost. Quality is a major performance measure in terms of food engineering. Cost and energy usage are the performance measures in regards to the supply chain management. Flexibility is included in the model by making it multi-optional, multi-supplier, multi-customer and multi-objective. The next step is to use data from literature to analyse the design. After running a simulation on the model, design alternatives are then identified. Then, the model is run using real industrial data. The evaluation and validation of the model is based on the results it generates with the given data and compared with the literature results. The validated model shows that the design has generated an acceptable and feasible result and therefore it has improved the cycle. If the result is unacceptable, on the other hand, the model returns to the identification of design alternatives and the experiment is run again.

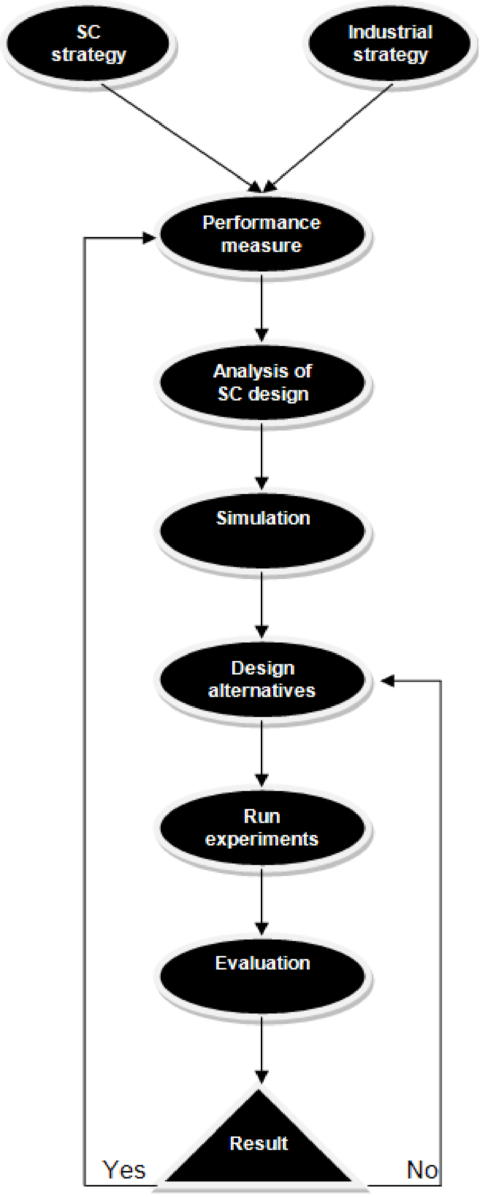


Figure 1-3 Supply Chain Design

1.3. Project motivation

Supply chain management refers to the business process of designing or configuring product (or service) supply lines in order to meet on-shelf consumer requirements whilst minimising waste in every regard: natural resources, energy, space, nutritional value, labour and cost. However, a global optimisation of a geographically distributed supply chain taking all of these aspects into account is too complex for currently available tools and techniques. Despite all of the difficulties, supply chain management has been widely used in different industries, such as the pharmaceutical industry, as this technique has been proven to increase the efficiency of the process operation in regards to processing time, energy usage and running costs.

Supply chain management and modelling has contributed substantially to different fields, such as pharmaceuticals and consumer goods. In this thesis, these methods are used and implemented in the food industry in order to introduce possible advantages. As part of this project, we plan to apply a multi-scale supply chain optimisation method for the food industry in order to minimise energy and water usage, transport costs and raw material wastage, as well as to increase product quality and to maximise company profits.

The technical objectives of this project are as follows:

- Development of multi-scale models by taking into account the appropriate level of detail
- Capturing key processing and logistics details
- Developing quantitative methods in order to link network structures and parameters to multiple criteria
- Development of multi-scale, hierarchical solution algorithms in order to optimise developed models
- Application of modelling and optimisation techniques to real-world examples from the food sector (provided by the industrial sponsor)

The scope of this thesis is to overcome on-shelf demand and to satisfy the consumer on a quantitative and qualitative level, whilst ensuring minimal energy consumption, waste and cost.

In order to achieve this, a model has been developed to capture all of the technical objectives discussed above. The model quantifies the quality and optimises the quality, energy consumption, inventory time, wastage and the total cost for each product. In this work, we have studied and considered a seasonal product (soup) as an example. This product suffers from the seasonality of its raw materials and on-shelf demand. Four different soup products are considered (e.g. potato, green peas, carrots and onion soup,) where all undergo a preparation process in order to increase the shelf life of the fresh raw materials. Later, this is implemented using a real-world industrial case study in order to test the industrial implications of this model.

1.4. Thesis outline

The thesis is divided into six further chapters, which address previous literature in regards to supply chain applications, a developed supply chain and food/quality model, solution methods and algorithms for quality and supply chain models, real life industrial case studies, as well as conclusions and recommendations for potential further work.

In **Chapter 2**, various literature articles on supply chain and food supply chain research are reviewed. Also, modelling approaches, various methods of decision-making and solution methods are discussed.

In **Chapter 3,** different types of quality indicators are described and studied in order to identify the most efficient indicator set. In this chapter, we present the input data to the model from experimental data. We also describe general methods of quality measurement across all indicators and the energy consumption for the different processes. In some cases, these methods could be used as input data for the model.

Chapter 4 presents a generated model and methodology for quality control in the food supply chain model, as well as an energy consumption optimisation model.

In **Chapter 5,** the models are integrated into the supply chain system in order to study all of the processes and the inventory system, as well as the manufacturing system. A general direct approach in the supply chain system has been used. The concepts of mixed integer linear programming, global optimisation and models with quality indicators are all employed in the model.

Chapter 6 presents a realistic evaluation of the industrial case studies provided by Unilever in regards to two different products. For each case study, the problem is first solved in terms of quality and energy optimisation, and it is then integrated into the supply chain system.

Chapter 7 presents some concluding remarks on the quality and seasonality of food products and the mathematical approaches used, whilst also recommending possible future research.

Chapter 2

Literature review

The proposed framework covers three major areas, namely supply chain modelling, planning and scheduling, and the optimisation of the food process. All of these sections together generate a large modelling and optimisation problem, with different quantitative and mathematical models. Traditional solution algorithms and methods are used for problems as such, with a large number of variables and constraints. Hierarchical and/or decomposition procedures are a way to simplify and reduce a large amount of problems into a smaller number of sub-problems in order to achieve faster and more cost-effective results. This solution method relaxes the original problem and reduces the information to the size of the model solved in each step.

Decomposition methods are solution methods, which can be applied to such problems. This family of methods relaxes the problem by decomposing the variables. The results for this model have to be feasible. A number of constraints relevant to the problem are therefore set in order to force the solution into a feasible region.

In this chapter, a comprehensive review of relevant existing research, works and studies is discussed and presented.

2.1. Supply chain modelling approaches

Supply chain management is a research area which develops new techniques in order to make changes to an existing product portfolio to match consumer expectations. This research area optimises all of the steps from supplier to distribution. In order to achieve such an optimised system, the two main areas to study and model are decision-making and managerial systems.

1. Planning and scheduling is a key decision-making process and is used routinely by processing industries. Planning and scheduling has been established in order to identify the right quantity and quality as per customer expectation and to plan the supply and demand of a particular product. It assists in designing plans and allocates resources over time. A time-based model is built in order to address these decisions.
2. The managerial system, on the other hand, is a process, which manages these decisions and solves the models. Some managerial issues may be solved by applying simple mathematical programming. However, there are a number of problems, such as location/allocation, inventory control, production planning, transportation mode selection, and supplier selection, which cannot be solved by simple mathematical programming tools. In order to solve these problems, a complex model is built, which covers the problem objective with all its constraints. This model is often solved by using a number of methodologies, namely hierarchical and decomposition methods.

2.1.1. Modelling planning and scheduling problems

In order to model planning and scheduling problems, two main factors, namely time and process representation need to be taken into account.

i) Time: discrete or continuous

Discrete time modelling divides the time horizon into N equally spaced intervals, where the tasks start and finish at a given time. Since the duration of all intervals is the same, the duration must match the largest common factor. A discrete time representation is very flexible and capable of accounting for many scheduling features and different planning layouts, however, it also has disadvantages, such as an approximate time domain and a high number of variables and constraints. The continuous time model, on the other hand, divides the time horizon into unequal durations and unknown intervals. Continuous time models do not face the problems associated with the discrete time model. In fact, they demonstrate a low number of variables and constraints. However, the constraints are more complex and it is therefore difficult, time-consuming and expensive to solve. Due to the unknown number of intervals, it is likely that the continuous time model can yield a sub-optimal solution (Fig 2.1).

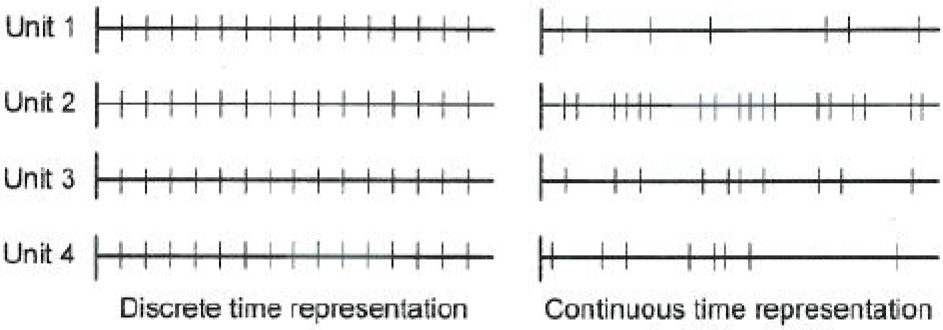


Figure 2-1 Different time grids used in the planning and scheduling models

ii) Process representation

There are several possible ways in which the problem could be presented, including sequential representation (sequential process) and network representation (e.g. StateTaskNetwork, ResourceTaskNetwork).

Sequential representation is suitable for simple production processes. In a sequential process, the products follow the same sequence of production stages with a possibility of skipping some of the stages. During each stage, there are one or more processing units, where the processes have a linear production structure without splitting or merging materials. The operations are performed with a single input from the last stage and a single output to the next stage. Stefansson *et al.* (2005) has tackled the planning and scheduling problem by implementing a discrete time and sequential process. Stefansson *et al.* (2005) focus on single plant production planning and scheduling for a multistage, multi-product secondary pharmaceutical production facility. The objective of the paper is to determine the campaign plan and to schedule the customer orders in order to meet the requested delivery date. They propose a planning and scheduling approach based on a discrete time and sequential process for a continuous and dynamic decision process with the assumption that all of the data is given. A hierarchical structure has been used, where each level optimises a part of the model in order to support the relevant decisions. The model has then been tested using industrial data and has resulted in a quality solution. This work has further been studied by Stefansson et al. (2006) in order to eliminate all infeasible solutions. The integration strategies are implemented with hard constraints, bounds, shaping methods and penalty functions in order to obtain near optimal solutions. The integrated strategy also restricts the solution space and therefore eliminates infeasible solutions.

The other representation method is the network representation, which is divided into two classes. The state task network (STN) has two types of nodes, namely state and task nodes. States represent the feedstock, the intermediates and the final product and task nodes represent process production activities. Kondili, Pantelides and Sargent (1993a) have studied a short-term scheduling problem in multi-product/ multipurpose batch chemical plants. The problem has been formulated with an MILP based on discrete time. They have introduced STN representation and have used it instead of sequence-based representation. This is because the old representation introduces ambiguities into the system (Fig 2.2).

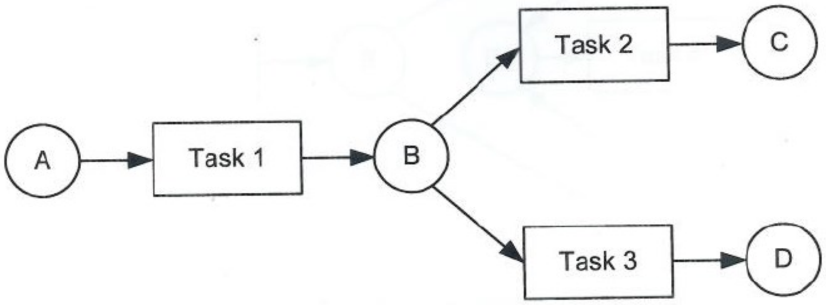


Figure 2-2 An example of State Task Network (STN) representation. The boxes represent the operations and the circles represent the feedstock, the intermediate and the final products.

Pantelides (1994) has later argued against the STN representation, and has stated that the problem with STN is the limitation around the modelling of plant operations, as it is assumed that tasks are always processing actively, which in turn would change the material's state. In his work, he formulates the problem based on discrete time and a resource task network (RTN) representation (Fig 2.3). RTN is similar to STN, where other resources and their interactions with the tasks are also included. Both RTN and STN representations are suitable for complex processing networks, but RTN has an advantage over STN in terms of capturing additional problem features. Despite the RTN's advantage and the problems associated with the STN as illustrated by Pantelides (1994), Balasubramanian and Grossmann (2004) insist on using STN representation in their work. The reason being that STN is more suitable for multipurpose plants, as it does not use task precedence relations, which can become complicated. It is also suitable for complicated material flow, where it can use different kinds of intermediate material storage.

Balasubramanian and Grossmann (2004) deal with the uncertainty problem of scheduling under demand by representing a multi-product batch plant through STN. They formulate the model as a discrete time STN with several time intervals for each period. The objective of the model is to identify the schedule, which maximises the expected profit. This is a multi-stage problem, but, in order to minimise the complexity, the multi stage model is divided into several two-stage models. A comparison of the results for the two approaches shows that the difference is only a few per cent. Therefore, by considering the time consumption and complexity of the multi-stage model, as well as the computational effort, the two-stage model generates a relatively satisfactory result.

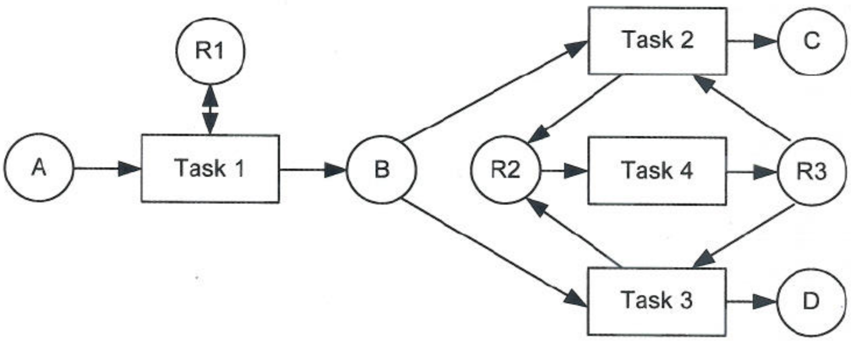


Figure 2-3 An example of a Resource Task Network (RTN) representation. The boxes represent the operations and the circles represent the resources, equipment, feedstock, the intermediate and the final products.

As mentioned before, the discrete time representation has a number of disadvantages, such as a high number of binary variables and constraints. Some researchers therefore prefer to deal with continuous time models. Some studies using continuous time models are Dogan and Grossmann (2006), who deal with the simultaneous planning and scheduling problem in continuous multiproduct plants. Zhu and Majozi (2001) also use a continuous time MILP formulation in their work. Mendez *et al.* (2001) propose a MILP continuous time approach with a sequential process representation for short-term scheduling problems. Ierapertrirou and Floudas (1998) formulate their model in continuous time for short-term scheduling and multipurpose batch processes. Shaik and Floudas (2007) model a short-term scheduling problem in continuous time and RTN representation. They also evaluate the performance of the proposed model along with other continuous time models. A comparison of this model with the STN based model of Ierapertrirou and Floudas (1998) shows an improved LP relaxation. Furthermore, although the RTN has more continuous variables and constraints, it solves faster. Castro *et al.* (2001) formulate the short-term scheduling of multipurpose plants in RTN continuous time. All of them use the continuous time model, as it contains a low number of variables and constraints, which leads to a more efficient solution. However, continuous time models are complex, difficult and expensive to handle. As a result, the question still remains as to which method is more suitable.

Maravelias and Grossmann (2006) have studied the relation between discrete and continuous time models. The continuous time model of Maravelias and Grossmann (2003) and the discrete time model of Shah *et al.* (1993) are also looked at in this paper. It is demonstrated that by imposing two restrictions – a fixed time grid and a fixed processing time - into the Maravelias and Grossmann (2003) continuous time model, the model can be reduced to a discrete time model similar to Shah *et al.* (1993) with some additional variables. Maravelias (2005) exploits the above observation and proposes a mixed time representation. In this model, the time grid is fixed, but the task processing times are variable. This model combines the advantages of both the continuous and the discrete time model. However, this method must be improved for real-world and industrial applications, and has so far not been proven to be accurate. Ivanov (2010) solves the scheduling supply chain problem for transportation and operations with a high level of complexity by combining both continuous and discrete processes. The generated model is represented as an optimal programme control problem, together with mathematical programming in a dynamic process for operations control. This model plays an important role in regards to the stability and adaptability of operational and transportation issues. The dimensionality of the operation-based problem is relieved by distributing model elements between an operations research model with static aspects and a control model with dynamic aspects. They are both integrated into the discrete and continuous processes.

A piece of work on the optimal short-term scheduling for general multipurpose batch plants with a number of operational characteristics, such as sequence-dependent changeovers, temporary storage, lots blending and material flows traceability, is reported by Moniz *et al.* (2013). An MILP with a discrete time formulation based on an STN is proposed. The reason for using an STN in this work is that the STN model is more effective than the RTN according to computational tests. However, some other works using the RTN representation, namely Castro *et al.* (2008), solve the scheduling supply chain problems for the pharmaceutical industry by using a periodic RTN formulation. Wassick and Ferrio (2011) propose an extension of the RTN formula. Sundaramoorthy and Maravelias have developed a scheduling framework (2011) in order to address the structure of network and sequential representations. Moniz *et al.* (2012) use a sequential approach for a non-regular multipurpose-batch plant scheduling problem. They apply RTN representation to this problem, as it appears to generate a more accurate result.

Sundaramoothy and Maravelias (2011) compare discrete and continuous time models in terms of the computational performance and scheduling approaches for batch process networks. They have run the two models for more than 100 problem instances and 800 optimisation runs covering five different process networks, various objective functions, different scheduling horizons and a wide range of features (fixed and variable processing times, utility, holding and backlog costs, intermediate shipments and setups). They show that the computational requirements of discrete time models increase moderately with the incorporation of these features, which is not the case in continuous models.

2.1.2. Modelling classification

Mathematical models of the entire supply chain include interacting strategic and operational decisions. These models are not consistent with managerial decision processes, due to the computational complexity of the models. Mathematical programming is most common in regards to formulating planning and scheduling problems within the process industry. Combinatorial problems, however, are very difficult to solve and it is essential to develop modelling strategies, mathematical formulations and solution methods. In order to find solutions for real-world planning and scheduling problems in an effective manner, simplification, approximation or aggregation strategies are necessary (Grunow *et al.* 2002).

The first step of modelling is to establish the scope of the model. The scope could be one of the following: competitive strategies, tactical plans, and operational routines. Based on the scope and the problem, the model can use different frameworks. Depending on the framework, the supply chain model falls into three different classes of mathematical structure: deterministic, stochastic and hybrid structures. The deterministic model is the simplest model, as it does not take uncertainty into account and all of the parameters in the model are assumed to be fixed and known with certainty. Stochastic models, on the other hand, refer to more complicated problems, as the model includes uncertainty factors. Stochastic models contain random elements, such as customer demand, lead-time, and production fluctuation. Dynamic programming approaches, probability-based approaches, and scenario-based approaches are the three approaches used for optimising uncertainties and therefore deal with stochastic problems.

The hybrid model is a combination of both the deterministic and the stochastic model and is usually based on inventory theory and simulation. The hybrid model simplifies the modelling problems by reducing the problem size, such as the size of the mathematical formulation, by using mathematical programming together with non-analytical methods. In order to solve a large and complex model, the hierarchical method is used. A hierarchical method simplifies large and complex models by reducing them in size and complexity. Here, the hierarchical method simplifies the problem by decomposing it into a number of smaller and simpler problems. These smaller and simpler problems are easier and more cost-effective to solve. Moreover, commercial solvers, such as CPLEX and XPRESS, are used to solve the mathematical problems in the model. Commercial solvers assist the model builder in regards to solving large and complex problems. Larbi *et al.* (2012) present a case study on an Algerian supply chain company. They include suppliers, manufacturers, distribution centres and client demands to the distribution centres. The model is based on optimising the cost and time in regards to the execution of the orders. Notable constraints regarding the work are the production capacity and balanced stock with the aim of achieving the shortest possible time between orders and delivery and minimum costs throughout the whole system. They use CPLEX to solve this problem. A number of other studies, which use CPLEX are Sousa *et al.* (2011), Suwanapal (2010), D'Amours and Ronnqvist (2012) and Susarla (2012).

i) Deterministic model

The deterministic model can be a steady state or a multi-period one. In steady state models, time is described by a discrete set of time periods, where the overall duration adds up to the total time horizon. Multi-period models contain variables and parameters, which change over time and where there is an inventory, which is carried over between time periods.

Supply chain planning problems are described by:

- A set of locations defining the nodes, supplier, manufacturing plants, storage and customers.
- A product portfolio: raw materials, the intermediate and final products
- A specific time horizon and product recipes
- Sets of distribution channels
- A financial structure, pricing of the product and costing.

Some of the studies and examples on these problems based on deterministic models are summarised here.

Cohen and Lee (1988) describe a framework model for linking decisions and performance through the raw material, production, and distribution supply chain. The goal is to predict the impact of alternative manufacturing and supply chain strategies on the performance at three levels: the cost of products, services, and the flexibility of the production and distribution system. This work has been further studied by Cohen and Moon (1991) in order to test the impact of the supply chain optimisation on the scale, as well as on the complexity (operational cost for the number of products being processed) and the weight (production, transportation, and allocation cost) of each cost factor in regards to the design and utilisation patterns of the supply chain system.

Jackson and Grossmann (2003) have developed a multi-period, non-linear programming model for the production planning, transportation, and sales of several multi-production plants, which are located at different sites and are distributed to different geographical markets. This work is concerned with a global supply chain optimisation problem. The output of the model is a decision on how much of each product is produced by each site, as well as how much of the demand will be fulfilled and how the distribution networks to end customers will be organised.

Chen *et al.* (2003) have studied the problem of fair profit distribution in a multi-product, multi-stage, and multi-period system. Ishii *et al.* (1998) also use a deterministic model, and the goal of their paper is to calculate the base stock level and lead times in a finite time horizon for an integrated supply chain. Another deterministic model presented by Guillen *et al.* (2006) aims to optimise the multilevel supply chain process with integrated financial decisions. Sousa *et al.* (2011) use a deterministic model in order to solve a global supply chain planning problem for pharmaceutical industries. In this work, they tackle a dynamic allocation and planning problem in order to optimise the production system and distribution. This is a large problem, which cannot be solved in a realistic time scale. The model has therefore been divided into two algorithms. Both problems have been divided into independent sub-problems in order to simplify the optimisation model and to increase the solution speed. Similar papers using deterministic models for supply chains are Corsano and Montagna (2011), Tako and Robinson (2012) and Brandenburg *et al.* (2014).

ii) Stochastic models

Despite the advantages of deterministic models, such as their simplicity, deterministic models do not present the most suitable solution in the face of uncertain events. Also, deterministic models leave out uncertain parameters in the model, which leads to over-optimistic solutions and the missing of possible strategic opportunities. In order to produce robust plans and designs, uncertain factors, such as demand forecasts and technological aspects, must be taken into account. Two types of solution methods could be used to tackle stochastic models, namely optimal control theory and dynamic programming. Optimal control theory states that there needs to be an optimal decision process for the tailing problem at each state, anywhere in the time horizon, regardless of how the state has been achieved. Dynamic programming has been used to create a framework for this problem. The first step is to work on the last stage of the tail sub-problem, which contains the smallest portion of the time horizon. The next step is to work backwards and to take the last but one stage of the tail sub-problem, bearing in mind that the sub-problem increases exponentially as we move backwards. Each step in the process uses the solution of the pervious step. The problem is that the number of sub-problems increases exponentially; therefore, the number of state and control variables increases, which results in a dimensionality problem (Sahinidis (2004) and Guillen *et al.* (2006a)). Grossmann (2012) uses stochastic modelling for an enterprise-wide optimisation. This model optimises supply, manufacturing and distribution activities, reduces the costs, as well as maximises the profit and responsiveness. The mathematical model is based on MILP and MINLP methods leading to a real-time optimisation for planning and scheduling.

Uncertainty

There are three different approaches in terms of planning optimisation with uncertainty.

1) *Stochastic dynamic programming approach*

The framework of dynamic programming has been described above, and in order to overcome the dimensionality problem, simulation-based optimisation can be used to calculate the tail problem. Dapklus and Bowe (1984) apply stochastic dynamic programming in a case study for generating new electrical technology, where uncertainty affects the solution. The uncertainty relates to the commercialisation date for new technologies and a possible loss of service of existing nuclear capacity. Cheng *et al.* (2004) deal with uncertainty in regards to the demand forecast. In order to address the expected net profit and downside risks, they define the capacity planning and inventory control problem as a multi-objective Markov decision (optimal control). Tong *et al.* (2014) use the stochastic programming approach to optimise and design operations in regards to integrating hydrocarbon bio-fuels and petroleum into the supply chain. Also, Stritto et al. (2013) present a supply chain network design for the diffusion of a new product. Bozorgi-Amiri *et al.* (2013) develop a multi-objective robust stochastic programming model for disaster relief logistics with uncertainty.

2) *Probability-based approach*

The probability-based approach is a mathematical approach, where the expected value of the objective function is provided by integrating the probability space. The uncertainty of the model then becomes one of its variances. This is a mathematical formulation in order to add constraints to the model and to plan for optimising a model with uncertainty. Applequist *et al.* (2000) use this approach in their model for supply chain design and for the management of the optimisation problem, taking into account the investment risk on a financial basis. The objective function of the model is the trade-off between risk and return and allowing the results to be compared with other alternative financial investments.

3) *Scenario-based approach*

The scenario-based approach is an alternative and more popular mathematical approach compared to the probability-based approach. The uncertainty of this approach is modelled as a multi-layer scenario tree in a multi-stage stochastic programme, and the optimisation problem is the schedule that hedges against the scenario tree. In the scenario-based approach, a scenario tree is produced, which grows exponentially over time and throughout the stages. A finite number of scenarios is used in this approach and, due to the large number of scenarios, MILP is usually used to solve the problem iteratively. Liu and Sahinidis (1996) tackle two-stage stochastic planning problems for process planning with uncertainty. The uncertainty factors considered in the work refer to economical parameters (forecast sales and demands), and the objective is to maximise the net present value. MILP has been used to solve the problem iteratively due to a large and finite number of scenarios. Iyer and Grossmann (1998) extend this work to a multi-period planning model with multiple scenarios in each period. Both works use MILP. Ahmed *et al.* (2003), on the other hand, uses LP in his work. This paper uses a scenario-tree approach in order to tackle a capacity expansion problem in an uncertain environment with uncertain economic factors, such as demand and cost. LP and the heuristic scheme can be used to reformulate and produce good quality solutions. Arbatzis *et al.* (2013) tackles an uncertain demand problem in fuel wood supply by using a scenario-based approach and by building a conceptual model. MILP and a Lagrangean relaxation algorithm are utilised to solve this.

iii) Hybrid model

A hybrid model is the combination of both the deterministic and the stochastic model and includes elements from both models. Moreover, hybrid methods can be used to simplify the problem by reducing the problem size (e.g. the size of the mathematical formulation). The hybrid solution method uses a combination of both non-analytical methods and mathematical programming in order to reduce the problem size. The Lagrangean decomposition method is a way to achieve this. The Lagrangean decomposition method reduces the problem size by decomposing the original problem into several smaller sub-problems.

Karmarlar and Patel (1977) use a decomposition approach in order to solve a single product, single period, multiple location inventory problem with stochastic demands and transportation. This method works perfectly in terms of small problems, but it is not suitable for solving larger problems. In order to overcome this disadvantage in terms of numerical solutions, the problem has to be formulated as an LP with column generation. As mentioned before, hybrid models can be used to solve larger models. Gupta and Maranas (1999) use a hybrid solution method in order to reduce the problem size. In their lot-sizing problem, they deal with multiple products at multiple sites and in multiple time periods. A Lagrangean decomposition method is used to simplify the problem by decomposing multiple products into several independent product groups.

Lee and Kim (2002) propose a hybrid approach by combining analytical and simulation models in their work, and to tackle an integrated production distribution problem. The models incorporates various types of uncertainties, including unexpected delays, queuing and breakdowns. Knowing the operation time is one of the major constraints of the analytical model. The operation time in the analytical model cannot represent the dynamic behaviour of the consumption of the real operation time, which makes it another uncertain factor. The operation time is therefore considered to be a dynamic factor and is adjusted by the result generated by a simulation model, which includes the production distribution characteristics. This iterative hybrid analytic-simulation procedure generates a better optimal production distribution plan. Gambhir *et al.* (2013) uses a hybrid modelling approach to develop a scenario for China's carbon dioxide emissions up until 2050.

2.2. Solution algorithms

In the previous section, different supply chain modelling approaches are discussed and classified. Some studies are presented in regards to deterministic and stochastic models for certain and uncertain cases. This part introduces the mathematical models available and relevant to solving these models and problems.

The world of supply chain management covers various types of managerial issues. Some of them can be solved with analytical tools, such as mathematical programming. To name a few: inter-organisational conflicts, joint production planning, dynamic demand forecasting, profit sharing, team-oriented performance measures, customer relationship management, information sharing, real-time communication, inventory ownership, channel power shift, and technical compatibility.

However, other issues, such as location/allocation, inventory control, production planning, transportation mode selection and supplier selection, are more complicated. In order to tackle such problems, a supply chain model should be built and solved by using solution methods, such as hierarchal methods (Min and Zhou 2002).

2.2.1. Mathematical programming techniques

Mathematical programming is a technique for developing and solving optimisation models. There are a vast number of different mathematical programming techniques with different applications. Mathematical programming (MP) is used for optimising objective functions and it is broadly used in the process industry in order to optimise various objective functions. Some of the mathematical programming techniques include:

Linear programming (LP) refers to high-level planning programming and the following must apply in order for LP methods to be suitable:

- There must be a constant return to scale
- The level of the activity and the use of resources by an activity must be proportional.
- The total use of resources by the number of activities is the sum of the individual activity usage (Williams 2008).

A vast number of practical problems can be modelled using integer variables and linear constraints. If the model is solely based on integer variables, then it would be modelled using integer programming. This class of programming has 0, 1 variables and the model can be applied to yes or no decision problems. However, for more realistic industrial problems, integer and continuous variables are used, which would require a mixed integer linear programming (MILP) modelling approach.

In some cases, one or more of the LP conditions do not apply. For instance, under the first condition, rather than during a constant return to scale, variable returns are present. This would cause a non-linearity of the problem and it would be modelled by non-linear programming (NLP). NLP is best used for solving a production process in the presence of non-linear factors. Mixed integer non-linear programming (MINLP) is an alternative method to NLP and may include non-convexity. MINLP may have multiple local optima, therefore making it difficult for the model to identify the global optimum. This model is again best used in production processes with non-linear factors, where integer and continuous variables and results are required. MINLP/NLP can be converted to MILP/LP before solving, to make it simpler and more cost-effective. But this conversion can decrease the accuracy of the results and could lead to an approximate result.

MILP is the most popular method in terms of supply chain planning for industrial problems, as it considers both continuous and integer variables in the model, which is essential in regards to industrial problems. But most importantly, it is also a simpler problem to tackle, compared to MINLP (Williams 2008).

LP and MILP techniques could be used in regards to some of the capacity allocation and production planning problems. A good example of this is Vercellis (1999), where a capacitated master production planning and capacity allocation problem for a multi-plant manufacturing system is dealt with in two serial stages for each plant. The proposed solution suggests two iterative heuristic procedures, which are formulated as mixed {0,1} LP problems. The model is tested on a real-world case study and leads to a successful result. The multi-site planning problems are similar to multi-level capacitated lot-sizing problems. Chen and Lin (2008) employ an LP technique for the hierarchical multi-site production chain planning framework with master production scheduling and supply network planning problems. In this paper, three different planning decisions are being discussed, resulting in production and transportation costs being major factors in regards to the total cost of the system's allocation problems. NLP and MINLP are used in the presence of non-linear factors. Ferrer-Nadal *et al.* (2008) use MINLP for a batch scheduling problem. Doganis *et al.* (2005) also use MINLP in order to forecast demands for short-life food products. NLP is also used by Elmaraghy and Majety (2007) in regards to integrated supply chain design problems. Liu *et al.* (2013) use MILP to solve a multi-objective optimisation problem in order to optimise production, distribution and capacity planning of global supply chains in the procurement industry. Yue *et al.* (2013) design a case study using MILP and MINLP for sustainable product systems and supply chains in order to optimise based on functional units.

Other mathematical techniques include quadratic programming (QP) and mixed integer quadratic programming (MIQP). QP and MIQP are used in quadratic functions with several variables subject to linear constraints. Some works on these models are as follows: Abdel-Malek and Areeratchakul (2006) tackle the multiproduct newsvendor problem with a QP approach. Yang *et al.* (2009) use the same approach to solve a neural network model. In a case study by Osorio *et al.* (2006), MIQP is implemented in order to solve a mean-variance post-tax optimisation model. Keshvari and Kuosmanen (2014) tackle a stochastic non-convexity problem by using QP mathematical programming and non-parametric regression.

In real and industrial cases, the problems and models generally give rise to larger MILP models, which require the development of effective solution algorithms to be solved in realistic time scales. Therefore, in order to reduce the problem size, a traditional solution method should be used, e.g. a hierarchical solution approach and/or a decomposition procedure.

2.2.2. Solution method, hierarchical

Supply chain models are usually large and complex. They can be simplified by applying a hierarchical decomposition method. This reduces the problem size or converts the problem into a series of smaller sub-problems. It is important to retain the main functional objective of the problem. Dotolo *et al.* (2005) propose a three-level hierarchical method for supply chain network design and planning. The stage selection is based on transportation connection and information flow. The first level evaluates the performance of the candidate entities, whilst the second level solves the multi-criteria integer linear optimisation problem. The last level validates the results generated in the first two levels. Iyer and Grossmann (1998) solve large MILPs by using a hierarchical method. The model has been divided into two levels, where the first level solves the design problem by substituting binary time-dependent variables with time invariant sets concerning the choice of the process to be developed. This substitution causes a reduction in the number of binary variables and is therefore easier to solve. The second level is exactly like the first level, but it contains extra constraints without substitution and fewer binary variables. It is therefore faster to solve. In the case of infeasibility, integer cuts are added to the first level and the process is repeated. Bok *et al.* (2000) use this bi-level model in their work. In the first level, the model is solved with a low number of variables in terms of delivery to the customers without relevant information on production plans. In the second level, the delivery plan is fixed and sub-problems are defined by the solution of the previous level. Again, in the case of infeasibility, integer cuts are added to the first level in order to eliminate the solution, and the whole process is repeated. Despite all of the advantages of the hierarchical decomposition method, there are also some disadvantages. Although the problem has been simplified, several constraints have been added in order to form these sub-problems. The added constraints increase the solving time and affect the accuracy of the results.

Tezaur *et al.* (2001) solve a large scale problem iteratively, by presenting a decomposition method with Lagrange multipliers. Jackson and Grossmann (2003) introduce a number of temporal and spatial two-solution techniques based on the Lagrangean decomposition method in order to solve the non-linear multisite production planning and distribution model. In terms of the solution method, it should be emphasised that both the MILP and especially the MINLP approach are time-consuming. A hierarchical Lagrangean approach can overcome the shortcomings of the MILP and MINLP approach to a certain extent, however, it is hard to determine, which constraints should be relaxed and decomposed (Gupta & Maranas, 1999). Kiraly *et al.* (2013) uses MILP to achieve energy self-sufficiency by integrating renewables into the company's supply network. Shi *et al.* (2014) tackle a large-scale production scheduling system by integrating MILP into a discrete time model and by generating computational tests in order to demonstrate the efficiency of the method.

Supply chain system hierarchy

In order to solve the supply chain model in a hierarchical decomposition method, a closed-loop reactive supply chain optimisation has been built (Fig 2.4). This system has been divided into five optimisation modelling system types, namely manufacturing, inventory, logistics, tactical supply chain network optimisation and strategic supply chain network optimisation systems.

Data acquisition: This is the starting data used in the model. The data could be certain or uncertain.

Planning and forecasting: Demand forecasting should use uncertainty in regards to constructing multiple demand scenarios to be optimised by the supply chain model. Demand forecasting, planning and order entry forecasting are all required for the distribution, production, and for the inventory systems. There are several ways of forecasting, namely:

Time series: searches for patterns in historical data and finds the best fit for the data measured by forecast variance.

Data mining: most common in retailing companies. It finds a pattern through automatic or semi-automatic exploration and analysis of a large amount of data.

Regression and econometrics: product demands are calculated through casual relationships or explanatory factors, which link independent variables to demand forecasts.

The difference between time series and regression is that time series find the best fitted pattern for the result, but that regression analyses how the value of a certain variable (dependent variable) changes, when any one of the independent variables changes.

In the supply chain decision database, decisions are made based on the data given. These decisions are fed back to the planning and forecasting step. A regression is a run to find the best fit for a linear quality model. The result of the regression will be fed back to the planning and scheduling step in order to update the data and, as a result, generates a more accurate outcome.

Manufacturing system: this system models the production, reengineering, and quality of the product.

Logistics system: models the distribution and transportation of the product.

Inventory system: hedges against the uncertainties of supply and demand.

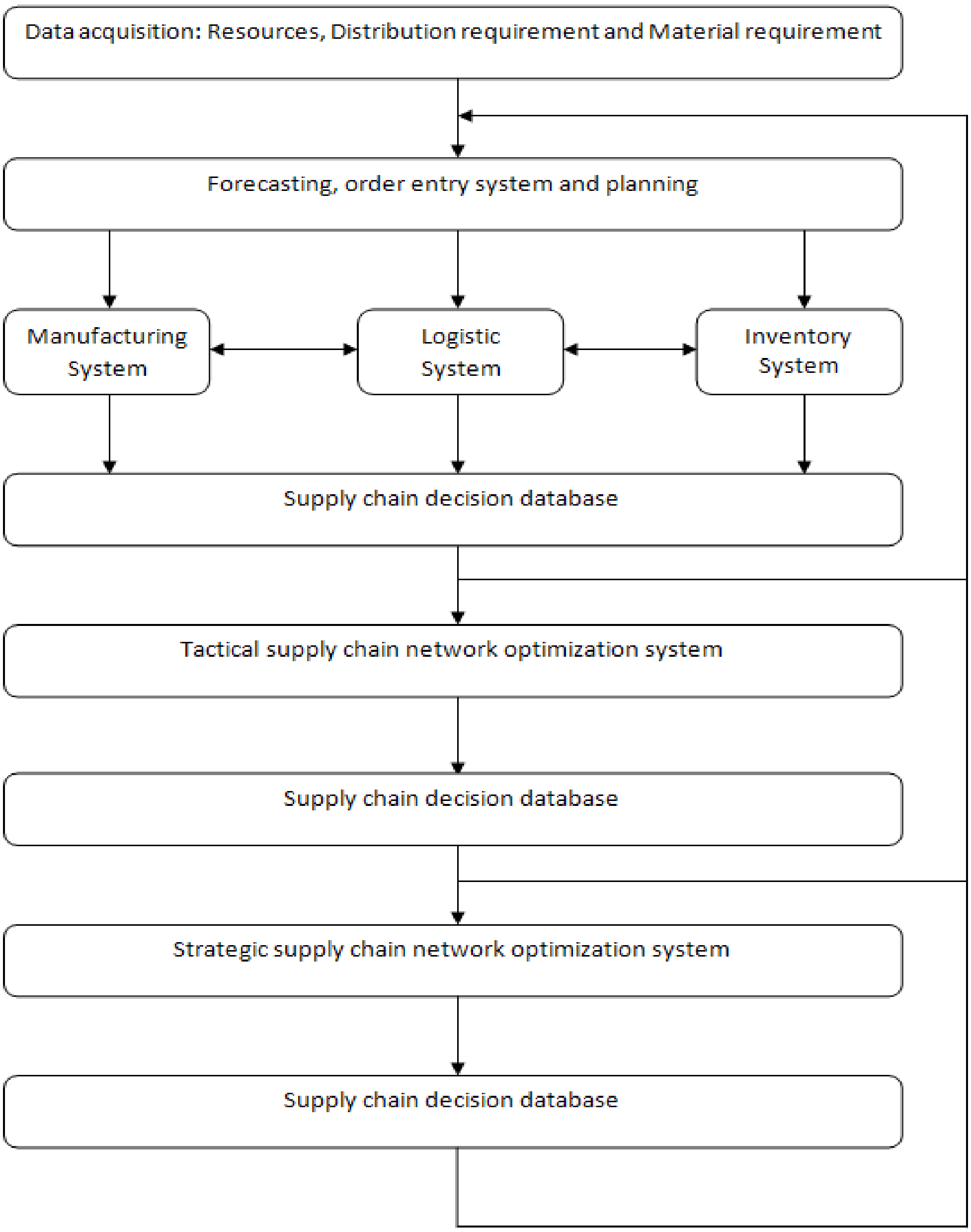


Figure 2-4 Supply chain system hierarchy

2.3. Planning and scheduling for food supply chains

Planning and scheduling for products in the food industry should receive greater attention. Firstly for health and environmental reasons, but also to ensure customer satisfaction in every aspect. All these factors, however, are controlled by manufacturing and inventory systems. During the process, the quality of the product must be controlled in order to reach an acceptable level. The costs must be evaluated and minimised as far as possible. The waste and energy usage should be controlled throughout the model (in order to be environmentally friendly, as well as to minimise cost), and the final product must have a microbial content at a healthy level in order to avoid health issues. The environment can add uncertainties to the manufacturing model. These uncertainties refer to seasonality, unexpected raw materials and harvest issues.

As mentioned above, Rong *et al.* (2011) have undertaken a study into food industry production and distribution planning. This is relevant to this thesis and this work has expanded on the concept. Rong's model only considers one single fresh raw material and one final product. In order to satisfy customers, they quantify and control the quality through zero and first order kinetic models. Since the shelf-life of the fresh materials is low, freezers have been integrated in the inventory and distribution system in order to lower the material temperature and to increase the shelf-life of the product. This is a costly and energetic task. The kinetic models are integrated in the supply chain modelling for the production and distribution planning and MILP is used for this model.

For this thesis, on the other hand, we have developed an innovative model to control and optimise both the quality and energy consumption of the product for each state and process. Rong's model only allows for a limited number of quality indicators to be considered in the model (i.e. colour intensity and nutrient content). This is extended in our work, so that we can control, measure and optimise the vast number of required quality indicators. As mentioned above, Rong's model only uses one fresh raw material in their model, whereas this work provides an opportunity to increase the shelf life of the raw materials before the manufacturing process by adding a preparation process to the system (drying and/or freezing) and by allowing multiple raw materials. The model we developed also uses MILP and, like Rong's model, also uses a direct approach and hierarchical solution methods. The model developed in this thesis can be used as a tool for products subject to seasonality issues.

In the fast moving customer good (FMCG) sector, there is always an increasing trend towards product variety and shorter replenishment cycle times. The industry constantly seeks a better co-ordination of production and distribution activities. Ahmuada and Villalobos (2011) use a block planning approach in order to establish cyclical production patterns. Two transportation modes are considered for delivering the final goods from plants to the distribution centres, which are both full truckloads and partial truckloads. In this paper, an MILP model is considered in order to minimise the overall production and transportation costs. In order to address the problem, rigid and flexible block planning approaches with different degrees of flexibility in regards to the scheduling of the production lots are compared. Through comprehensive numerical experiments it is demonstrated that this approach can generate production blocks of variable size and flexible timing, which allows for an assignment of the output from the corresponding production lots to the various demand elements at minimum cost. The flexible block planning approach promises considerable cost savings compared to the rigid block planning often found in practice. A key factor with considerable impact on the computational effort is the introduction of daily time periods and the use of Heaviside variables, which are needed in order to trace the completion date of the production lots. The work integrates production and distribution planning, which is significantly appealing in the FMCG industry. The results demonstrate that such an integration can lead to considerable cost savings. In the case of large diversified networks, the distribution of the final goods involves a considerable number of transportation links. It is therefore more appropriate to determine a separate distribution plan based on the given production schedule. The MILP framework provides flexibility in regards to the integration and application of certain features. However, this is not the case for conventional lot sizing and scheduling models explored in academic literature. With various products to produce and minimise the changeover time, as well as to prevent quality losses, block planning represents an efficient way to support decision-makers in practice.

Supply and demand planning of food products is a challenging task, as it requires many variables to be considered. Food products and their ingredients are very seasonal. Furthermore, supply and demand are highly volatile and very much dependent on the quality and price of the product. The challenge in the planning and scheduling of food products is to quantify the quality and to feed back the information, including all of the constraints relating to health issues, environmental issues and customer satisfaction, and to overcome the seasonality problem by controlling the shelf-life of the ingredients and the final product.

Rajaram and Karmarlar (2004) analyse the planning and scheduling of a multi-product batch operation in the food processing industry. The paper addresses the problem with the timing and duration of product campaigns in order to minimise average setup, quality and inventory holding costs over a horizon. The supply chain is based on a multiproduct, single stage, single equipment batch-process scheme. The work assumes that multiple batches of the same product are run sequentially in campaigns in order to minimise set-up and quality costs. This is a deterministic model and so it considers the static version of the problem over an infinite horizon. The results of this model are feasible, but they are not necessarily finite cyclic solutions. Therefore, a number of conditions are set for the model. A single product problem is solved to set the lower bounds in terms of the costs for multiproduct problems. They are used to test the heuristics developed for this problem. Later, the paper modifies the formulation to incorporate fixed cycles, which might be necessary due to factors such as product obsolescence, perishability and customer contracts. This is done to allow for the disposal of excess stock, so that finite cycles are always feasible, even though they might not be optimal. Some bounds and heuristic solution procedures are developed for this case. This method is tested using data provided by a leading food-processing company. They suggest that this method could potentially reduce total annual costs by about 7.7%, which translates to an annual saving of around $7 million.

Most food products are subject to seasonality problems. Seasonality problems arise, when sales vary significantly during the different seasons. In order to satisfy demand, the manufacturer must make a special provision to integrate the acquisition of raw materials and to work with an effective manufacturing and inventory schedule. Planning and scheduling packaging in manufacturing systems is one of the ways to overcome seasonal demands. Claassen and Beek (1993) have developed and implemented a pilot decision support system for bottleneck packaging facilities for large dairy companies to assist with the planning and scheduling of packaging systems in the food industry. They divide the problem into two levels: tactical and operational levels. The feasible daily production level as recorded in the order book is determined as part of the tactical level, which is solved by MILP. At the operational control level, the problem is divided into two sub-problems. Heuristics have been used to solve these. Buxey (1993) recommends an aggregate planning procedure with many algorithms in order to produce good quality solutions. 20 Australian factories with seasonal demand are sampled and empirical research for the production planning is considered. The problem is divided into two levels, strategic and tactical, in order to bypass the aggregate planning step. The problem is then resolved at the master production schedule level. This work suggests that there is a link between, business strategy, seasonal distortion and the tactical remedies available. The aggregate planning procedure is very theoretical, even though empirical data from real industrial factories has been used. There is a gap between theory and practice, which makes these problem-solving methods less attractive to industries, to the point where they are being ignored completely.

There are further studies on food supply chains, which are summarised in the tables 2.1 to 2.7. In these models, the types of raw materials are classified into perishable or non-perishable materials. Figure 2.5 shows the scope and the modelling approaches considered in these papers.

The main objective is presented in tables 2.1, 2.4 and 2.7. The planning and decision variables are displayed in tables 2.2 and 2.5, and the mathematical modelling approaches can be seen in tables 2.3 and 2.6. In the food industry, two types of products are considered, namely non-perishable products in tables 2.1 to 2.3, and fresh products in tables 2.4 to 2.6.

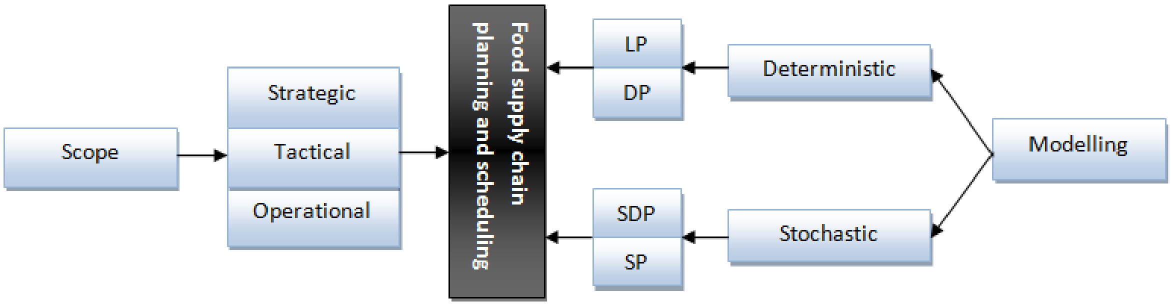


Figure 2-5 Food supply chain modelling, LP: linear programming, DP: dynamic programming, SDP: stochastic dynamic programming and SP: stochastic programming

Model	Main objective of the paper
Yu and Nagurney (2013)	A case study on the cantaloupe market in order to investigate the computational framework within a model for cost minimisation and disposal of food spoilage
Hubner *et al.* 2013	To develop a holistic operations planning framework for grocery retailing.
Dora *et al.* 2013	A food quality management system to review the strategies and feasibility for European foods
Trokamani (2005)	Evaluates the prospective technology options using SP with the aim of maximising utility to the farmer (exponential utility maximising objective)
Kobzar *et al.* (2005)	Develop an RP model for capturing joint stochastic distributions (parametric and non-parametric) using a mean–variance objective function
Apaiah and Hendrix (2005)	Design a supply chain network for growing, harvesting, transporting and processing a pea-based product using an MIP that minimises the total cost
Jiao *et al.* (2005)	Develop a harvest schedule for sugar cane farms using an LP model, which maximises the sugar content in crops for harvest season
Biswas and Paul (2007)	Plan seasonal crops within a year by using a fuzzy programme with the objective of increasing the utilisation of the land, labour, production and profits
Visagie (2004)	Determines farm planning strategies (crop and livestock) with an MIP that maximises the profits earned, given the level of risk selected
Jones *et al.* (2003)	Design a plan for making decisions for a two-period SP problem for a corn seed producer with variable yield with the objective of reducing costs
Recio *et al.* (2003)	Develop a farm plan that includes scheduling field tasks and analysing investments with the objective of minimising costs using an MIP model
Vitoriano *et al.* (2003)	Prepare a plan for cropping tasks with an LP, satisfying precedence and time window constraints with the objective of minimising costs
Higgins (2002)	Schedules the roster for the harvest of a sugar cane region using MIP with the objective of reducing costs in regards to transportation and within the processing plant
Maatman *et al.* (2002)	Develop an SP model for planning the production and consumption of a farmer for a given rainfall, with the objective of minimising shortages
Gigler *et al.* (2002)	Design a DP model for planning the decisions of multi-echelons agri-chains, to satisfy demand at the minimum total chain cost

Glen and Tipper (2001)	Plan the introduction of improved cultivation systems using an MIP model for semi-subsistence farmers with the purpose of increasing the discounted return
Lien and Hardaker (2001)	Analyse farmers' responses to different types of subsidies in whole-farming, and their attitude towards risk through an SP with a utility maximising objective
Ekman (2000)	Determines the best combination of equipment and crop mix with the objective of maximising revenue using an SP model
Schilizzi and Kingwell (1999)	Estimate the impact of price and yield uncertainty on the introduction of crops using SP, with the objective of maximising the expected utility for farmers
Raju and Kumar (1999)	Plan irrigation and production tasks with an LP model in order to find the best compromise between net benefits, agricultural production and employed labour
Higgins (1999)	Schedule harvesting and replanting operations with an LP model, considering the available processing capacity with the objective of maximising net revenue
Abdulkadri and Ajibefun (1998)	Generate crop plan alternatives, which are close to the optimal decisions for farmers with different objectives and using an LP model
Sumanatra and Ramirez (1997)	Develop a plan for multi-crop water allocation and intra-seasonal stochastic irrigation scheduling using DP and SDP models in order to maximise revenue
Lazzari and Mazzetto (1996)	Develop a model for selecting and scheduling the machinery for a multi-crop farm using search techniques in order to minimise the cost
Torkamani and Hardaker (1996)	Design a utility efficient non-linear SP model used for analysing the economic efficiency of farmers with several utility maximising functions
Burton *et al.* (1996)	Determine the production policy of double cropping and crop rotations with a MOTAD objective (maximising revenue and minimising low returns)
Nevo *et al.* (1994)	Design a crop plan with an expert system and an LP model with the objective of maximising profits
Duffy and Taylor (1993)	Analyse long-term farm planning decisions under the provision of the 1990 farm bill using an SDP model with the objective of maximising the expected present value
Kaiser *et al.* (1993)	Determine the potential impact of climate change by using an SP model, which maximises revenue in different simulated scenarios
Dobbins *et al.* (1992)	Develop an LP model for planning the production, harvest, storage and marketing of crops and livestock, with the objective of maximising revenue
Adesina and Sanders (1991)	Design an SP model, which is then applied to sequential decision-making under weather uncertainty for selecting cereal technologies, which maximise profit
Nanseki and Morooka (1991)	Evaluate the economic performance of farmers using an SP model with three risk preferences (max utility, max probability and chance constraint)
Alocilja and Ritchie (1990)	Develop a simulation tool for maximising profit and minimising yield risk by planning the sowing date, fertiliser treatment and plant population
Turvey and Baker (1990)	Determine the relation of farm programmes to a farmer's hedging decisions with futures and options by using an SP with a utility maximising objective
Bin Deris and Ohta (1990)	Develop a production system, which minimises machine demand in a two-stage cost minimising application using LP and DP
Perry *et al.* (1989)	Design a multi-period MIP model in order to identify the participation in government programmes and crop mixes with the objective of maximising the net present value
Clarke (1989)	Determine a cropping pattern, which maximises the return from farms, applied to a farm in Bangladesh using an LP model
Kaiser and Apland (1989)	Determine production and marketing plans for two crops using an SP model with the objective of maximising profit and reducing profit deviation
Lambert and McCarl (1989)	Develop a discrete SP for selecting from marketing alternatives with the objective of maximising revenue
Turvey *et al.* (1988)	Design an RP model for providing useful alternatives to the variance–covariance quadratic programming method
Tan and Fong (1988)	Determine cropping decisions for perennial crops, with the objective of maximising revenue with MOTAD and by using an LP model
Glen (1986)	Designs a plan for integrated crop and beef production with an internal feed production, using an LP model for maximising revenue
El-Nazer and McCarl (1986)	Develop an LP model to design and determine the optimal long-run rotation of crops with the objective of maximising revenue whilst being risk averse
Butterworth (1985)	Develops an MIP model for a whole farm plan with crop, livestock and labour decisions with the objective of maximising revenue
Stoecker *et al.* (1985)	Design of an application for LP and DP models for determining production, irrigation, drilling and water distribution decisions in order to maximise revenue

Table 2-1 Studies on food supply chains for non-perishable products

In the studies, three types of scope are considered, namely strategic (S), tactical (T) and operational (O) types of scope. The models in the papers are either deterministic or stochastic, and the mathematical modelling approaches include linear programming (LP), dynamic programming (DP), mixed integer programming (MIP), stochastic programming (SP) and stochastic dynamic programming.

Model	**Planning scope**				**Decision variables**				
	S	**T**	**O**	**DM**	**P**	**H**	**D**	**I**	**Other decisions considered**
Trokamani (2005)	X	X		Advisor	X				Labour and financial
Kobzar *et al.* (2005)		X		Planner	X				Risk reduction
Apaiah and Hendrix (2005)	X	X		SC	X	X	X		Production at plant
Jiao *et al.* (2005)		X		Planner		X			
Biswas and Paul (2007)		X		Advisor	X				
Visagie (2004)	X	X		Farmer	X				Livestock planning
Jones *et al.* (2003)		X		Planner	X				
Recio *et al.* (2003)		X	X	Advisor	X				Scheduling of activities
Vitoriano *et al.* (2003)	X	X		Planner	X				Modeling approach
Higgins (2002)			X	Planner		X			Reduce variability at plant
Maatman *et al.* (2002)		X		Advisor	X			X	Consumption and purchase
Gigler *et al.* (2002)		X		SC	X	X	X	X	
Glen and Tipper (2001)	X	X		Advisor	X				Selection fallow system
Lien and Hardaker (2001)		X		Planner	X				Subsidies, labour
Ekman (2000)	X			Farmer	X				Equipment investment and tilling schedule
Schilizzi and Kingwell (1999)		X		Advisor	X				Crop rotations
Raju and Kumar (1999)		X		Advisor	X				Planning of irrigation, labour
Higgins (1999)		X	X	Planner		X			Replanting decisions
Abdulkadri and Ajibefun (1998)		X		Farmer	X				Generate alternative plans
Sumanatra and Ramirez (1997)		X	X	Advisor	X				Irrigation scheduling
Lazzari and Mazzetto (1996)	X			Advisor					Equipment sizing/scheduling
Torkamani and Hardaker (1996)		X		Planner	X				Utility functions
Burton *et al.* (1996)	X	X		Advisor	X				Crop rotations and labour
Nevo *et al.* (1994)		X		Farmer	X				
Duffy and Taylor (1993)	X	X		Planner	X				Participation in programme
Kaiser *et al.* (1993)	X	X		Farmer	X	X			Tilling schedule

Dobbins *et al.* (1992)		X	X	Advisor	X			X	Activities schedule
Adesina and Sanders (1991)		X		Advisor	X				Purchasing and consumption
Nanseki and Morooka (1991)		X		Planner	X				Labour requirements
Alocilja and Ritchie (1990)		X		Advisor	X				Sowing date and fertiliser use
Turvey and Baker (1990)	X	X		Planner	X				Financial and hedging
Bin Deris and Ohta (1990)			X	Advisor	X				Scheduling of machines
Perry *et al.* (1989)	X	X		Farmer	X				Programme participation
Clarke (1989)		X		Advisor	X				Crop selection and rotation
Kaiser and Apland (1989)		X		Farmer	X	X		X	Tillage and marketing
Lambert and McCarl (1989)		X		Advisor			X	X	Utility function
Turvey *et al.* (1988)		X		Advisor	X				
Tan and Fong (1988)	X			Planner	X				Assign crops to soil type
Glen (1986)		X		Advisor	X			X	Livestock decisions
El-Nazer and McCarl (1986)	X			Advisor	X				Design of crop rotations
Butterworth (1985)		X		Advisor	X				Livestock an labour
Stoecker *et al.* (1985)	X	X		Farmer	X				Irrigation and aquifer
Amorim *et al.* (2011)		X		Advisor				X	
Romsdal (2014)		X		Advisor				X	
Yan *et al.* (2010)		X		Advisor				X	
Rong *et al.* (2009)			X	Advisor	X			X	

Table 2-2 Planning scope and decision variables for non-perishable products

Here, the DM is the decision maker for which the model is designed, P is the production variable and the decisions, H refers to harvesting variables and decisions, D represents the distribution variables and decisions, and I refers to the inventory variables and decisions.

Model	**Modelling approach**					
	LP	**SP**	**DP**	**SDP**	**MIP**	**Other aspects**
Trokamani (2005)		X				Non-linear SP
Kobzar *et al.* (2005)	X					Risk programming
Apaiah and Hendrix (2005)	X					
Jiao *et al.* (2005)	X					Regression analysis
Biswas and Paul (2007)					X	Fuzzy goal programming
Visagie (2004)						Risk programming
Yan *et al.* (2011)					X	

Jones *et al.* (2003)		X			X	
Recio *et al.* (2003)					X	Decision support systems
Vitoriano *et al.* (2003)	X				X	
Higgins (2002)						Taboo search
Maatman *et al.* (2002)		X				
Wang *et al.* (2010)					X	Non-linear
Gigler *et al.* (2002)			X			
Rong *et al.* (2011)	X				X	
Glen and Tipper (2001)	X				X	
Lien and Hardaker (2001)		X				Time series
Ekman (2000)		X				
Schilizzi and Kingwell (1999)		X				
Raju and Kumar (1999)	X					MCDM and constraint prog.
Higgins (1999)	X					
Abdulkadri and Ajibefun (1998)	X					Modelling to generate alternatives
Sumanatra and Ramirez (1997)			X	X		
Lazzari and Mazzetto (1996)						Search methods
Torkamani and Hardaker (1996)		X				
Burton *et al.* (1996)	X					
Bosona and Gebresenbet (2011)					X	
Nevo *et al.* (1994)	X					Expert systems
Duffy and Taylor (1993)				X		Time series
Kaiser *et al.* (1993)		X				Simulation and time series
Dobbins *et al.* (1992)	X					
Adesina and Sanders (1991)		X				
Ahumada and Villalobos (2011)					X	
Nanseki and Morooka (1991)		X				
Alocilja and Ritchie (1990)						Simulation
Turvey and Baker (1990)		X				Utility functions
Bin Deris and Ohta (1990)	X		X			
Perry *et al.* (1989)					X	

Clarke (1989)	X				
Kaiser and Apland (1989)		X			Time series and regression
Lambert and McCarl (1989)		X			Time series and regression
Rong and Grunow (2010)				X	
Turvey *et al.* (1988)	X				Risk programming
Tan and Fong (1988)	X				Multiple objectives and MOTAD
Glen (1986)	X		X		
El-Nazer and McCarl (1986)	X				MOTAD
Butterworth (1985)					
Stoecker *et al.* (1985)	X		X		
You *et al.* (2011)				X	

Table 2-3 Mathematical modelling approaches for non-perishable products

The table below describes existing studies on fresh products, as well as the modelling approaches and planning and decision-making processes.

Model	**Main objective of the paper**
Liu *et al.* (2013)	Critical criteria when implementing electronic chain traceability in a fish in the food supply chain
Ferrer *et al.* (2008)	Determine a plan for the optimal scheduling of the harvest of wine grapes using an LP model with the objective of minimising operational and grape quality costs
Widodo *et al.* (2006)	Design of a DP model to integrate production, harvest and storage of perishable items with growth and loss functions for maximising the satisfied demand
Caixeta-Filho (2006)	Development of an LP, which links chemical, biological and logistics constraints to the quality of the fruit for harvesting, with an objective of maximising revenue
Kazaz (2004)	Designs a two-stage SP in order to determine the olive trees to contract in the season for an oil producer with an uncertain yield and demand, in order to maximise revenue
Allen and Schuster (2004)	Determine the optimal rate of harvesting and capital investment (capacity) using a non-linear programme, to reduce losses due to weather and overcapacity
Rantala (2004)	Designs a production–distribution model for the supply chain of seedlings with the objective of minimising costs
Itoh *et al.* (2003)	Design a model for crop planning with uncertain values, described with fuzziness and randomness, with the objective of maximising the minimum value of revenue
Caixeta-Filho *et al.* (2002)	Develop an LP model for maximising the expected gross revenue of a greenhouse by designing an appropriate marketing and planting plan
Berge Ten *et al.* (2000)	Develop a whole-farm model to compare between different farming technologies before starting empirical work. Includes economic and environmental goals.
Darby-Dowman *et al.* (2000)	Design of an SP model for determining the optimal planting plans for vegetable crop with the help of weather scenarios, with a revenue maximising objective
Romero (2000)	Determine an efficient cropping pattern by considering the risk of the producers with a multi-objective (max revenue, min variability) model
Pandey *et al.* (2013)	Work on a case study to test the supply chain re-engineering for the fresh produce industry
Leutscher *et al.* (1999)	Design of a production model with tactical and operational decisions with the objective of increasing profitability
Stokes *et al.* (1997)	Develop optimal production and marketing decisions for a nursery producing ornamental plants using SDP with a revenue maximising objective
Aleotti *et al.* (1997)	Develop an SP model, which optimises revenue by changing the capacity of food preservation facilities and by considering the uncertainties in the crop market
Miller *et al.* (1997)	Determine a plan for production and harvesting of a packing plant with an LP and fuzzy programmes with the objective of minimising costs
Hamer (1994)	Determines a planting and harvesting plan for fresh crops using an LP model with the objective of maximising profits

Purcell *et al.* (1993)	Develop an RP decision model for landscape land production, with the objective of maximising returns for a given level of risk aversion
van Berlo (1993)	Determines sowing, harvesting and production plans using an LP model with the objective of minimising costs across the logistical chain
Annevelink (1992)	Determines a plan for the location of pot-plants inside a greenhouse with the objective of minimising costs using heuristics and genetic algorithms
Saedt *et al.* (1991)	Develop a plan for a pot-plant greenhouse with two models, one LP for future plans and one MIP for transition plans, with the aim of maximising revenue

Table 2-4 Studies on the food supply chain for fresh products

Model	Planning scope					Decision variables				
	S	T	O	SL	DM	P	H	D	I	Other decisions considered
Ferrer *et al.* (2008)		X	X	X	Planner		X			Labour and routing
Widodo *et al.* (2006)		X	X	X	SC	X			X	
Caixeta-Filho (2006)		X			Planner		X			
Kazaz (2004)		X		X	Planner	X	X			Purchases from other sources
Allen and Schuster (2004)	X				Planner	X	X			Capacity planning
Rantala (2004)	X	X			SC	X		X	X	Open/closed facilities
Itoh *et al.* (2003)		X			Farmer	X				
Caixeta-Filho *et al.* (2002)		X	X		Farmer	X	X			
Berge ten *et al.* (2000)	X	X			Advisor	X				Technology selection
Darby-Dowman *et al.* (2000)		X			Farmer	X	X			Capacity decisions
Romero (2000)		X			Planner	X				
Leutscher *et al.* (1999)		X	X		Farmer	X				Operational policies
Stokes *et al.* (1997)		X			Farmer	X				Selling or retaining
Rijpkema *et al.* (2013)	X				Advisor				X	
Aleotti *et al.* (1997)	X	X			Farmer		X	X	X	Preservation technology
Miller *et al.* (1997)			X		Planner		X		X	
Hamer (1994)		X			Farmer	X				Variety selection
Purcell *et al.* (1993)		X			Advisor	X				
Tsao (2013)	X				Advisor	X			X	
van Berlo (1993)	X	X			Farmer	X	X		X	Processing schedule
Annevelink (1992)			X		Farmer	X				Spatial location
Saedt *et al.* (1991)		X	X		Farmer					Transition planning

Table 2-5 Planning scope and decision variables for fresh products

Model	**Modelling approach**					
	LP	**SP**	**DP**	**SDP**	**MIP**	**Other aspects**
Yu *et al.* (2013)	X				X	

Pauls-Worm *et al.* (2013)					X	
Ferrer *et al.* (2008)	X				X	Relaxation heuristic
Widodo *et al.* (2006)			X			Growth and loss functions
Caixeta-Filho (2006)	X					
Kazaz (2004)		X				Non-linear optimisation
Allen and Schuster (2004)						Non-linear optimisation
Rantala (2004)	X				X	
Itoh *et al.* (2003)	X					Fuzzy programming
Caixeta-Filho *et al.* (2002)	X					
Berge Ten *et al.* (2000)	X					Multi-objective programming
Darby-Dowman *et al.* (2000)		X				
Romero (2000)	X					Risk programming
Leutscher *et al.* (1999)	X					Simulation and regression
Stokes *et al.* (1997)				X		
Aleotti *et al.* (1997)		X			X	
Miller *et al.* (1997)	X					Fuzzy programming
Hamer (1994)	X					Decision support system
Rong *et al.* (2011)					X	
Purcell *et al.* (1993)	X					Risk programming
van Berlo (1993)	X					Goal programming
Annevelink (1992)	X					Genetic algorithm
Saedt *et al.* (1991)	X					

Table 2-6 Mathematical modelling approaches for fresh products

Other studies on food supply chains are listed below in table 2.7.

Model	**Main objective of the paper**
Yu *et al.* 2013	Develop a network-based food supply chain model under oligopolistic competition and perishability, with a focus on fresh produce.
Tolossa *et al.* (2013)	Review the integration of supply chain management and industrial cluster
Schepers and van Kooten (2006)	Plan the value chain of fresh fruits (producer, trader and retailer) using system dynamics with the objective of maximising total revenue
Higgins and Laredo (2006)	Develop an IP model for harvesting and transporting crops, together with the rationalisation of railroads with the objective of minimising overall costs
Higgins *et al.* (2004)	Develop a framework for integrating harvesting and transportation decisions into the Australian sugar value chain in order to minimise costs
Higgins (1999)	Schedule harvest dates and crop cycles, considering transportation and capacity restrictions and using an IP model, which maximises the net revenue

Tijskens and Polderdijk (1996)	Develop a model for estimating the quality of harvested products affected by temperature, chilling injury, and different levels of initial quality
Porteus (1993b)	Plan the use of new technologies, demand management, and sensitivity analyses in order to improve the performance of a cranberry packing plan
Porteus (1993a)	Develop a tactical plan for capacity and staffing decisions in order to improve the efficiency of a cranberry packing plant using queuing models

Table 2-7 Other studies on the food supply chain

2.4. Comments

As discussed before, the main issue in terms of food supply chains is seasonality. Overcoming this issue requires a high level of energy consumption, which significantly affects the quality of the raw material and therefore the final product. In studying different case studies, papers and existing literature, we have found that there are works on measuring and controlling the quality using a kinetic model. Furthermore, in order to optimise energy, cost minimisation models have been used. In this thesis, we have quantified the quality by using degrees of freedom and by linking it to energy consumption in order to optimise both the energy and the quality of the product. Furthermore, by adding a process to the manufacturing system, we overcome the seasonality issue. These are later integrated into the whole supply chain system for the purpose of inventory optimisation and cost minimisation.

Different modelling approaches and studies have been presented in this chapter. In conclusion, continuous time models do not suffer from problems such as a high number of variables and constraints, but the complexity of the constraints makes this model less attractive. The model by Maravelias (2005), on the other hand, which mixes both the discrete and the continuous time model together, does not appear to generate results in real industrial environments and requires further improvement. The discrete time model, however, is very flexible and capable of accounting for many scheduling features and different planning layouts. Even though it contains a high number of variables and constraints, it is a simpler model to solve. The sequential process representation is suitable for simple production processes. However, this is not a very popular representation, as there appears to be a lack of accuracy in terms of the results. The discrete time model is suitable for our model, as it offers many advantages and benefits.

Although RTN representation has advantages in regards to capturing additional problems when compared to STN representation, STN is preferable to RTN in this case, as it is more simple. STN is suitable for complicated material flows, where the system may use different kinds of intermediate material storage. The supply chain model is classified into two models: the deterministic and the stochastic model. Deterministic models are useful in the absence of uncertainty, unlike stochastic models, where uncertainty plays an important role. There are various methods and approaches to simplify models and to tackle uncertainty in stochastic models. Deterministic models, however, are much simpler models and are often used for supply chain planning problems, such as location and allocation, product portfolio, time horizon and product recipes, distribution problems, the financial structure, the pricing of a product and costing. Since deterministic models can model a wide range of supply chain planning problems, and because of their simplicity, they are preferable to stochastic models. However, in the presence of uncertainty, stochastic modelling must be taken into account. In this thesis, we have developed and used constrains in order to decrease the number of uncertainties. We have also added a process to the manufacturing system in order to increase the shelf life of the product and to overcome the seasonality issue. By fixing the seasonality results, uncertainties can be made certain. As a result, a deterministic model will be used here, as it is a popular modelling method in the absence of uncertainty.

In order to solve the supply chain model, a wide range of mathematical programming methods are being considered. MILP is the most popular and relevant mathematical technique to use. Most problems in regards to task allocation and equipment assignments involving discrete decisions, where integer variables are required, use MILP. Furthermore, since MILP considers both integer and continuous variables, and due to its simplicity compared with MINLP, it is a popular mathematical programming method in the industrial world. Supply chain models are usually complicated, difficult and time consuming. A hierarchical decomposition method is therefore introduced. Although a hierarchical decomposition method simplifies the problem, it also increases the solving time and affects the accuracy of the results, due to additional constraints. The hierarchical Lagrangean approach is a solution method used in the MILP. An MILP is time consuming and lacks in flexibility, but a hierarchical Lagrangean procedure overcomes these problems in some sense. The difficulty in terms of this approach, however, is to choose the right constraints, which need to be relaxed and decomposed (Gupta & Maranas, 1999). In this thesis, we linearise the non-linearities and use both integer and continuous linear constraints. MILP is therefore the most suitable mathematical model in this case. And finally, a hierarchical decomposition method is used to solve this problem.

In the next chapter, quality degradation and energy usage in different processes throughout the food manufacturing system are studied. Also, product characteristics and quality indicators are introduced and it is demonstrated how they change during the different processes. In chapter 3, real experimental datasets are used to illustrate these as characteristics, as well as some mathematical equations in order to measure them.

Chapter 3

Quality degradation and energy usage for processes in the food manufacturing system

In the fast moving customer goods (FMCG) sector, the three key factors to focus on are health issues, environmental issues and overall customer satisfaction. In order to control these factors, two elements are being considered: quality control and energy consumption.

Quality control is a very important issue in regards to customer satisfaction, health and waste production. Energy consumption, on the other hand, is a key factor in terms of environmental issues and it affects the cost of the final product, which in turn directly affects the price of the product.

There are a number of existing mathematical methods, which measure quality and energy consumption, as well as various studies, which have been performed in terms of the quality degradation of products and raw materials after every process. This chapter describes the quality degradation and energy consumption of each process, using mathematical models and experimental data.

This chapter contains a database, which can be used for estimating quality degradation across various quality indicators, as well as the energy consumed for various raw materials during the different processes. The database is applicable to food products, and especially products with seasonality problems, such as soup products. The survey is based on published materials and information communicated directly to the author by the industrial collaborator. The survey in this chapter is all from the publications. On the other hand, in the chapter 4 and 5 part of the data and chapter 6 most of the date are shared from the industrial collaborator.

3.1 Introduction

There is an increasing concern about on-shelf products within the food industry. This is because food products are subject to seasonality, where the supply and demand have to match in order to meet on-shelf demand. Another important concern for the food industry is uncertainty in terms of food processing. It is very important to overcome uncertain factors, such as processing time, temperature and demand, especially in regards to food processing systems. Action must be taken in regards to the following factors in order to reduce uncertainty:

- Timing and quality of the product
- Balancing the production rate with the demand rate
- Balancing the supply rate with production
- Planning for the collection of failed products

A number of different raw materials are required for manufacturing food products, and each of them has a different shelf-life. The shelf-life for fresh raw materials needs to increase in order to overcome the seasonality problem in terms of supply, which would in turn help to fulfil the demand. In order to increase the shelf-life of raw materials, the removing or freezing of the inherent water could be a possible solution. In addition to increasing the shelf-life, this process is also beneficial in terms of retaining a number of quality indicators within the food product amongst other things. Drying, freeze concentration, evaporation and reverse osmosis are a few ways of removing water from food material.

A preparation process is considered in this thesis as part of the food manufacturing system in order to freeze or dry the raw material. During this process, quality and energy are being measured in order to meet the company's performance criteria. The shelf-life of the raw material changes as follows for the different preparation processes:

Drying: Findings by researchers at Brigham Young University (Norseth, 1986) show that storing dried materials at room temperature or below keeps them nutritious and edible for a long time. The shelf-life of most raw materials (when dried) is estimated to be over 20 months. However, there is a small decline in taste and quality of the raw materials. The shelf-life during the storage of raw materials is extremely dependent on the following factors:

Temperature: Excessive temperature could damage the stored raw materials. As the temperature increases, proteins break down and some vitamins are being destroyed. Also, such an excessive temperature could affect the colour, flavour and aroma of some products. In order to enhance its shelf-life, food should be stored at room temperature or below.

Moisture: Excessive moisture can result in the creation of an environment, in which microorganisms may grow, and where chemical reactions could take place, which could result in the deterioration or spoilage of the product.

Oxygen: The oxygen in the air has an effect on fats, food colours, vitamins, flavours and other food constituents. It can cause conditions which will enhance the growth of microorganisms.

Light: The exposure of foods to light results in the deterioration of specific food constituents, such as fats, proteins, and vitamins, resulting in discoloration, off-flavours, and vitamin loss.

Freezing: In the case of freezing, however, temperature does play a very important role. Table 5.1 demonstrates the importance of temperature. Lower temperatures result in a higher shelf-life. For instance, in the case of peppers, the shelf-life reduces from three weeks to two weeks when the temperature increases from 7.2 to 10°C (Laboza, 1982).

Temperature	Shelf-life (days)
-15	132
-24	345
-35	386
-70	561

Table 3-1 Relationship between temperature and shelf life for green peppers (Labuza, 1982)

Advantages of the drying and freezing process

Freezing is the act of crystallisation of water in a material, which, in addition to increasing the shelf-life, also retains the nutrient content, shape and texture of the material. Drying, on the other hand, is a simultaneous process of both heat and mass transfer, which enables a convection process. The drying process encapsulates the original flavour and maintains the nutritional value.

Two types of drying are being considered: air and freeze drying. The drying process reduces the weight, transportation cost, packaging cost and storage space. It is also relatively easy to control the duration of the process and the quality of the product. This is a very important factor in order to avoid spoilage of raw material, and therefore waste production (Heldman *et al.* 2009). Having mentioned the advantages of the drying and freezing process, it also has disadvantages, such as a quality degradation of the product and an excessive energy usage, which has to be added to the system in order to carry out the process. In this chapter, a survey is being undertaken in terms of the experimental data and the mathematical models for quality degradation across different indicators, as well as the energy usage for each process.

	Shelf-life (days)*			
Temperature	Green peas	Spinach	Green beans	Okra
-5	24	8	21	40
-10	56	20	50	98
-15	132	55	122	249
-20	325	153	311	660

* Shelf-life is based on 50% vitamin C loss

Table 3-2 Relationship between temperature and shelf life for different materials (Giannakourou and Taoukis, 2003)

The scope is to present a survey, which is based on a number of publications, together with input from relevant parties. In the next section, mathematical models and data across the indicators for quality degradation of the material are presented. Later, mathematical models and data in regards to energy consumption are being presented for the different processes throughout the manufacturing system.

3.2. Quality indicators and degradation

As discussed before, despite all of the advantages offered by the preparation process, it also disturbs the quality of the product. There are physical, nutritional and microbial quality disturbances. As discussed in chapter 1, there are two classes of quality indicators, namely static (shrinkage and cracking) and time dependent (texture, colour intensity, vitamin content, nutrient content and microbial content). The next subsection demonstrates how these quality indicators are modelled. In the absence of experimental data, these models can be used to calculate the input data and parameters for each quality indicator for our model.

3.2.1. Mathematical models for quality degradation

Existing literature refers to many mathematical models, which measure the quality indicators presented here. The mathematical models, together with literature data and experimental data, are listed in this section. Regression models and analyses are run on the data in regards to the quality models.

Time dependent quality indicators:

This class of quality indicators has a rate of change over time, which can vary after each process. This means that these types of quality indicators are affected by the process and also change over time. This class of quality indicators is modelled in two different ways. The first model measures and controls the following indicators: nutrient content, microbial content, vitamin C and colour intensity.

The typical correlation takes the following form

$$q = f(T, X) \tag{3.1}$$

q: is the quality measured for a time-dependent indicator,

T: process temperature

X: is the variable set associated with the drying process, e.g. moisture content or thickness of the material or the drying process parameter.

More fundamental approaches using various kinetic models to measure changes in the quality indicators of the model are generally described by zero-, first-, second-, or pseudo first- order reactions (Villota and Hawkes, 2007):

Zero order reaction: $A \rightarrow p$

$$-\frac{dq_A}{dt} = k \tag{3.2}$$

First order reaction: $A \rightarrow p$

$$-\frac{dq_A}{dt} = kq_A \tag{3.3}$$

Second order reaction: $A + B \rightarrow p$

$$-\frac{dq_A}{dt} = kq_A^2 = kq_A q_B \tag{3.4}$$

Pseudo first order reaction: $A + B \rightarrow p$

$$-\frac{dq_A}{dt} = k' q_A^2 = kq_A q_{B_0} \tag{3.5}$$

q_A refers to the quality of a certain indicator, e.g. the nutrient or microbial content A at any time *t*, q_B is the quality/concentration of the other species B, such as oxygen in an oxidation reaction at any time, q_{B_0} is the initial concentration of the other reactant species *B*. *k* and *k'* are the reaction rate constants and P is a product of a reaction. The temperature-dependent reaction rate is provided by an Arrhenius equation:

$$k = k_0 \exp\left(-\frac{E_a}{RT}\right) \tag{3.6}$$

Where k is a rate constant and k_0 is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant and T is the temperature.

The quality level of a product at a certain location in the production process based on an initial quality (q_0) and subsequent storage periods *i=1,...,m* with the time interval t_i and the degradation rate k_i (depending on temperature T_i), can be described by:

$$q = q_0 - \sum_{i=1}^{m} k_i t_i \tag{3.7}$$

for zero-order reaction and

$$q = q_0 . \exp\left(-\sum_{i=1}^{m} k_i t_i\right) \tag{3.8}$$

for first-order reactions, which are formed by integrating the previous equations as a substitute for the rate of quality degradation (k) in the zero-order and first-order reactions:

$$q = q_0 - \sum_{i=1}^{m} k_0 t_i . \exp\left[-\frac{E_a}{RT_i}\right] \tag{3.9}$$

$$q = q_0 . \exp\left(-\sum_{i=1}^{m} k_0 t_i . \exp\left[-\frac{E_a}{RT_i}\right]\right) \tag{3.10}$$

Figure 3.1 illustrates the expected quality changes in zero-order and first-order reactions over time. A good example of this is shown in figure 3.2, which reflects the experimental data of the nutrient content changes for potatoes during the drying process (Kaminski and Tomczak, 2000).

Tables 3.3 and 3.4 show the kinetic models used for the different products in order to measure the quality degradation for the nutrient content and the colour intensity at different operating parameters.

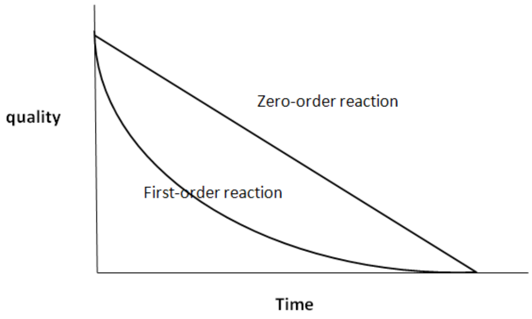


Figure 3-1 Quality degradation of food products going through zero or first-order reactions

Nutrient	Material	Drying Method	Operating Parameter	Kinetic Model	References
Ascorbic acid	Sweet potato	Hot air drying	Drying temp: 30-60°C	First order	Orikasa *et al.* (2010)
	Pineapple slices	Hot air drying	Pre-treatment conditions: Sucrose conc: 40-60%	First order	Karim & Adebowale (2009)
	Red pepper	Cross-flow hot air drying	Drying temp: 50-70°C Air-velocity:0.2-1.2 m/s	First order	Di Scala & Crapiste (2008)
	Potato	Tunnel hot air drying	Drying temp: 30-60°C	First order	McMInn& Magee (1997a)
ß-carotene	Carrot, pumpkin	Osmotic dehydration	Sucrose conc: 20-65%	First order	Di Scala & Crapiste (2008)
Carotenoids	Red pepper	Cross-flow hot air drying	Drying temp:50-70°C Air-velociry:0.2-1.2 m/s		
Lycopene	Tomato pulp	Spray drying	Air inlet temp:110-130°C Atomising agent flow rate: 500- 700 L / h	First order	Goula *et al.* (2006)
Polyphenols	Cocoa bean	Hot air drying	Drying temp: 40-60°C Air-RH: 50-80%	Pseudo-first order	Kyi *et al.* (2005)
Selenium	Cabbage	Hot air drying	Drying temp: 60-100°C	First order	Mo *et al.* (2006)
Thiosulphinate	Onion	Hot air drying	Drying temp: 50-75°C	Second order	Kaymak-Ertekin & Gedik (2005)
Volatile compounds	Apple	Hot air drying Freeze drying	Drying temp: 30-70°C -	First order	Krokida & Philippopoulos (2006)

Table 3-3 quality degradation reaction type used for different materials in different temperature, depending on nutrient content (Devahastin & Niamnuy 2010)

Material	Drying method	Operating parameter	Kinetic model	Reference
Basil	Microwave drying	Microwave output power: 180-900	Zero and First order	Demirhan & Ozbek (2009)
Okra	Microwave drying	Microwave output power: 180-900	Zero and First order	Dadali et al (2007a)
Spinach	Microwave drying	Microwave output power: 180-900	Zero and First order	Dadali et al (2007b)
Onion	Hot air drying	Drying temp: 50-75°C	Zero order	Kaymak-Ertekin & Gedik (2005)
Grape juice and leather	Hot air drying	Drying temp: 40-90°C, Wet bulb temp: 27-33°C	Zero order	Maskan et al (2002)
Apple, banana, potato, carrot	Hot air drying, vacuum drying, microwave drying, freeze drying, osmotic drying	-	First order	Krokida et al (2001)
Apple, banana	Osmotic dehydration	Solute type: sucrose, glucose	First order	Krokida et al (2000b)
Avocado, prune, strawberry	Hot air drying	Drying temp: 50-70°C	First order	Tsami & Katsioti (2000)
Apple, banana, potato, carrot	Hot air drying, vacuum drying	Drying temp: 50-90°C	First order	Krokida & Maroulis (1998)
Hazelnut	Forced air-circulation drying	Drying temp: 30-80°C	Zero order	Lopez et al (1997)
Potato	Tunnel hot air drying	Drying temp: 30-60°C	Zero order	McMinn & Magee (1997a)
Apple	Hot air drying, vacuum drying	Drying temp: 40-90°C	Zero order	Voegel-Turenne et al (1997)

Table 3-4 quality degradation reaction type used for different materials in different temperature, depending on colour intensity (Devahastin & Niamnuy 2010)

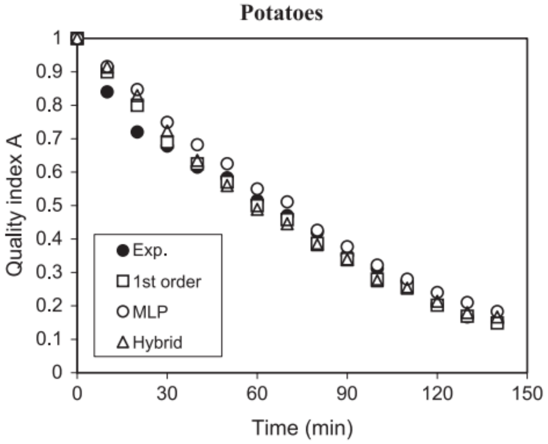


Figure 3-2 Nutrient content change of potatoes during the drying process (Kaminski and Tomczak, 2000)

The second class model measures and controls the texture of the material. Texture changes can be fitted into a first-order kinetic model (e.g. Nisha *et al.* 2006). But it has been reported in some vegetables, such as potatoes and carrots, that an initial tissue softening followed by tissue hardening appears after undergoing the drying process (Krokida *et al,.* 2000; Moyano *et al.,* 2007). Therefore, the following mechanism is being proposed:

$$R(raw\ tissue) \overset{k_1}{\to} S(soft\ tissue) \overset{k_2}{\to} H(hard\ tissue) \qquad (3.11)$$

k_1, k_2 are the rate of disappearance of raw tissue and soft tissue (appearance of hard tissue), respectively. It is being assumed that changes in the tissue stages follow first-order kinetics, and that there is only one type of raw material at the beginning of the drying process.

$$q = 1 - \frac{Kk_1}{k_2 - k_1}\left[e^{-k_1 t} - e^{-k_2 t}\right] \tag{3.12}$$

Here, q refers to quality in the form of texture. It is therefore a dimensionless maximum force (the ratio of the maximum force at any time t to the maximum force at $t=0$) and K is a constant.

In the case of negligible tissue hardening, $k_2 = 0$:

$$q = 1 - K\left[1 - e^{-k_1 t}\right] \tag{3.13}$$

for *K=1*

$$q = e^{-k_1 t} \tag{3.14}$$

The temperature dependency of the reaction rate constants and other model parameters is provided by the Arrhenius equation (equation, 6)

The experimental data for the texture change in potatoes after the drying process at different temperatures and with different processing times is shown in figure 3.3.

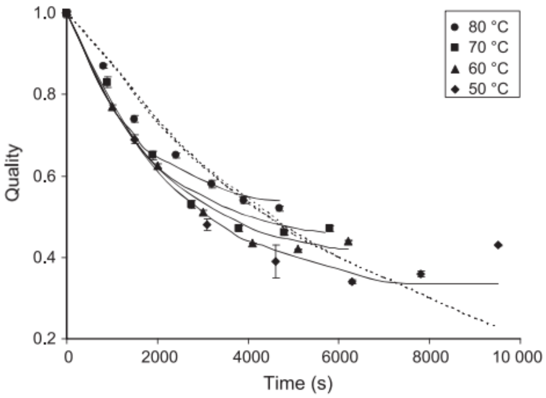
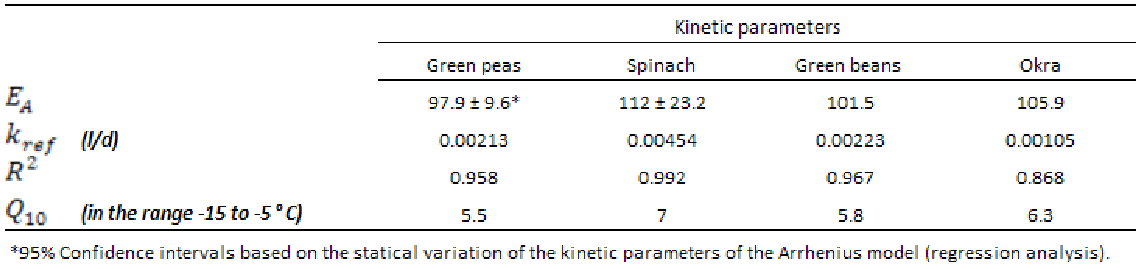


Figure 3-3 Texture change in potatoes during the drying process (Troncoso and Pedreschi 2007)

Table 3.5 shows the kinetic parameters and how the different temperatures can affect the shelf-life of frozen green vegetables. Some examples on how the vitamin C and nutrient content can change over time for frozen green vegetables can be seen in figure 3.4.



		Kinetic parameters			
		Green peas	Spinach	Green beans	Okra
E_A		97.9 ± 9.6*	112 ± 23.2	101.5	105.9
k_{ref}	*(l/d)*	0.00213	0.00454	0.00223	0.00105
R^2		0.958	0.992	0.967	0.868
Q_{10}	*(in the range -15 to -5 °C)*	5.5	7	5.8	6.3

*95% Confidence intervals based on the statical variation of the kinetic parameters of the Arrhenius model (regression analysis).

Table 3-5 Kinetic parameters and shelf-life in days for frozen green vegetables (Giannakourou *et al.* 2003),

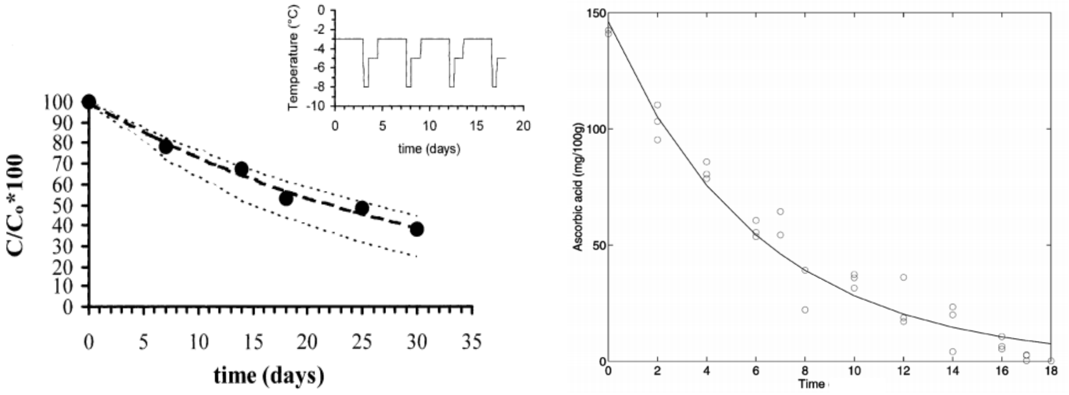


Figure 3-4 Left, Vitamin C change of frozen green peas (Giannakourou *et al.* 2003). Right, nutrient content degradation for frozen green vegetables (Martins *et al.* 2006),

Static quality indicators:

The main static quality indicator is shrinkage. Shrinkage is a deformation in the surface, shape, volume and size of a product. This type of quality indicator for the material changes abruptly, every time there is a process. The correlation takes the following form:

$$\frac{q}{q_0} = f\left(\frac{X}{X_0}\right) \tag{3.15}$$

Here, q is the quality of the material in the form of shrinkage at any time, and q_0 is the quality prior to the drying process. X is the moisture content of the material at any time t and X_0 is the initial moisture content of the material. Linear and non-linear models exist for this indicator,. In the case of linear models, there is a study on potatoes by McMinn and Magee (1997b) and Khraisheh *et al.* (1997), and by Simal *et al.* (1996) on green peas. But most of the vegetable models are in a non-linear form (e.g. Lozano *et al.* 1983).

An advanced form of correlation is employed by Suvarnakuta *et al.* (2007) (figure, 3.5):

$$\frac{q}{q_0} = a\left(\frac{X}{X_i}\right)^2 + b\left(\frac{X}{X_i}\right) + c \tag{3.16}$$

where a, b and c are empirical constants and different for different temperatures (table 3.6).

Drying temperature (°C)	*a*	*b*	*c*
60	−0.8288	1.8170	0.0366
70	−0.9026	1.9663	−0.0433
80	−0.9492	1.9938	−0.0421

Table 3-6 Empirical constants for equation 16 at different temperatures (Suvarnakuta *et al.* 2007),

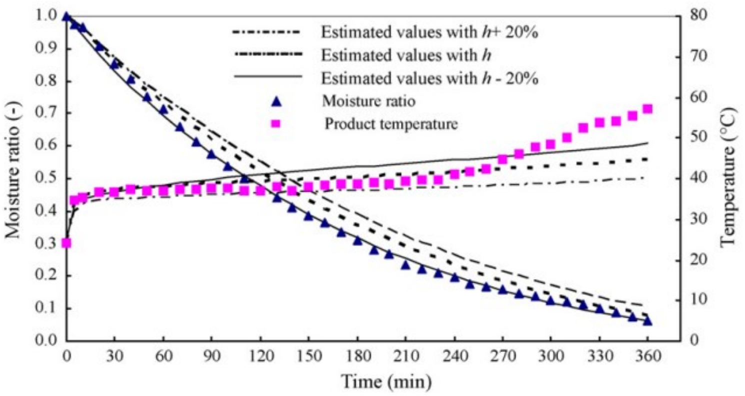


Figure 3-5 Shape change of carrots undergoing the drying process (Suvarnakuta *et al.* 2007),

3.2.2. Experimental data on quality degradation for different processes

Three different processes are considered for the preparation process, namely air-dry, freeze-dry and freezing. All of these processes affect the quality of the raw materials across all of the indicators. The quality indicators studied on a number of products are: nutrient content, colour intensity, microbial content, vitamin C, texture and shrinkage. The quality degradation for these processes is based on existing literature, experimental data and kinetic models for data fitting, and is as described below.

- *Air-dry process*

Nutrient content

Carotene, Tocopherol, Ascorbic acid, β-carotene and Lycopene are a number of components of the nutrient content in different products. Table 3.7 presents observations on each material for the preparation process, together with the models and references used for this observation.

Some examples for the nutrient content change during the air-dry process based on different process times and temperatures and are illustrated below:

- Potatoes: Ascorbic acid loss of 11 to 37% for a process time of 30 to 240min.
- Carrots: Ascorbic acid loss of 15 to 43% for a process time of 30 to 240min
- Green Peas: Ascorbic acid loss of 5 to 19% for a process time of less than 240min
- Onions: Nutrient content loss of 2.5 to 15% for a process time of 30 to 240min
- Green Peppers: Nutrient content loss of 12 to 32% for a process time of less than 240min

Colour intensity

Certain parameters in a material can control colour intensity. In the case of carrots, for instance, β-Carotene controls the colour intensity. The carrot β-Carotene ratio is (β_t/β_i), where β_i and β_t are the β-Carotene contents of fresh and dried carrots at the end of the drying experiment.

- Potatoes: a colour intensity loss of 9 to 15% at a process time of less than 400min is experienced.
- Carrots: β-carotene retention is 68 to 76% at a process time of 120 to 300min.
- Green Peas: a colour intensity loss of 10 to 45% for a process time of less than 240min is experienced.
- Onions: colour intensity is retained for high temperatures and low process times

Microbial content

The microbial content for all of the food products must be within the legal and safe range. Lavelli *et al.* (2006) have measured the level of chlorogene acid and sugars in TBC, yeasts and lactic acid bacteria in regards to legal ranges within carrots.

		Air Dry process			**Reference**
		Product	**Models and/or Data**	**Observation**	
Quality Indicator	**Nutrient Content**	Potatoes	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	An ascorbic acid loss ranged between 11 and 37% at a process time of 30 to 240 min. The Kinetic model has an error rate of 11% for the low process time range <30 min, for the higher process time range the error rate is negligible. An increase in the process temperature increases the nutrient content.	Kaminski and Tomczak ,2000
		Carrots	☐Experimental Data ☐Zero order kinetic ☑First order kinetic	An ascorbic acid loss ranged between 15 and 43% at a process time of 30 to 240 min. An increase in process temperature increases the nutrient content.	Devahastin and Niamnuy, 2010
		Green Peas	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	An ascorbic acid loss ranged between 5.3 and 19% at a process range <240 min. The kinetic model has a negligible error rate compared to the real experimental data. An increase in the process temperature increases the nutrient content.	Kaminski and Tomczak, 2000
		Onions	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A nutrient content degradation between 2.5 and 15% at a process time between 30 to 240 min for three process temperatures - 60, 70 and 80°C	Kaymak-Ertekin and Gedik, 2005
		Green Peppers	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A nutrient content loss of 12 to 31.8% at a processing time <240 min and a process temperature between 50 to 80°C	Di Scala and Crapiste, 2008
	Colour Intensity	Potatoes	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	The first order kinetic model is fitted to the experimental data. The redness and yellowness increases throughout the drying process. The colour intensity degrades by 8.8 to 14.8% during a process time between 0 and 400 min.	Krokida *et al.* 2001
		Carrots	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	The β-carotene content retention ratio is between 68 to 76 with a process temperature of 60, 70 and 80°C and a process time between 120 to 300 min	Suvarnakuta *et al.* 2007
		Green Peas	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	At a process time of <240min and a process temperature of 60, 70 and 80°C, the colour intensity of green peas degrades by 10 to 45%	Van Loey, 1996
		Onions	☐Experimental Data ☐Zero order kinetic ☑First order kinetic	The first order kinetic model is used to measure the colour intensity of the onion. The colour intensity is retained more during the higher process temperature with a lower process time.	Vega-Galvez *et al.* 2009

Microbial Content	Carrots	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	Experimental data used for the degradation of TBC, yeasts and lactic acid bacteria and the kinetic model to measure the changes in chlorogene acid and sugars with regards to time and temperature. Increasing the time and temperature increases the degradation of the microbial content and takes in into a legal and safe range	Lavelli *et al.* 2006
Vitamin C	Potatoes	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	A 35% vitamin C loss as the process time increases from 0 to 350 min and a 7% loss as the temperature increases from 30 to 45°C and a 5% for an increase from 45 to 60°C	Mclaughlin and Magee, 1998
	Carrots	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A 20 to 30% vitamin C loss for a process time <300 min and a very small 2-3% vitamin C loss for temperatures between 60 to 80°C	Lin *et al.* 2013
Texture	Potatoes	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A significant decrease (<56%) in Fmax as the process time increases from 0 to 180 min. Increasing the temperature from 50 to 80°C increases the Fmax and therefore the texture	Troncoso and Pedreschi, 2007
	Green Peas	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	No changes in the hardness of the green peas for a process time of <140min and a reduction of 45 % after 140 min at a given temperature of 80 °C. A decrease in the temperature decreases the hardness.	Van Loey, 1996
	Onions	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	At a process time of 60 to 240 min, the hardness decreases from 13 to 20.7% and there is a very small increase (<3%) in hardness, as the temperature increases from 60 to 80°C	Troncoso and Pedreschi, 2007
Shrinkage	Potatoes	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A moisture content reduction of 37 to 61% at a process time of <240min and a temperature of >60°C and <80°C	Wang *et al.* 2010
	Carrots	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	There is a huge moisture content loss of 45 to 66% as the process time increases to 240min and the temperature to 80°C	Suvarnakuta *et al.* 2007
	Green Peas	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A moisture content loss of 45 to 65% at temperatures of 50, 60, 70 and 80° and at a process time of 80 to 300min.	Simal et al 1996, Hatamipour and Mowla 2002
	Onions	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	The thiolsulphinate loss in onions during drying at various temperature of 50, 60, 70 and 75°C is 5-10% (air velocity of 1.2 m/s) and at a drying time of <240min it is 10-30%.	Kaymak and Gedik, 2005

Table 3-7 Quality changes during the Air-Dry process for selected materials

Shrinkage:

Shrinkage during drying has been found to be directly proportional to the product moisture content. Mclaughlin and Magee (1998) have found that shrinkage during the drying process is ideally almost three-dimensional.

- Potatoes: a moisture content loss of 37 to 61% for a process time of less than 240min.
- Carrots: a moisture content loss of 45 to 66% for a process time of less than 240min.
- Green Peas: a moisture content loss of 45 to 65% for a process time of 80 to 300min.

- Onions: a Thiolsulphinate loss of 5 to 30% for a process time of less than 240min.

Vitamins:

The majority (85±97%) of vitamin A activity in foods can be attributed to the α and β-carotene content (Sweeney and Marsh, 1971).

Because vitamin C is relatively unstable in regards to heat, oxygen, and light, the retention of this nutrient can be used as an indicator for the quality of the dried carrot slices. If vitamin C is retained well, other nutrients are also likely to be preserved. Prior to the drying, the carrot slices were blanched in order to inactivate ascorbic acid oxidase and to prevent an enzymatic degradation of vitamin C in the subsequent processes. However, a substantial loss of vitamin C content, from 770 mg/g solid to 443 mg/g solid, occurred during the blanching process. This was probably due to the leaching of the vitamin C into the blanch water. Replacing water with steam might have reduced this loss. Fresh carrots were found to contain 434 mg alpha-carotene/g solid and 1153 mg beta-carotene/g solid and Figure 3.6 shows, how these qualities change after the different processes (Lin *et al.* 1998).

The changes in potatoes and carrots after the drying process are shown below:

- Potatoes: Vitamin C loss of 35% at a process time of <350min
- Carrots: Vitamin C loss of 20 to 35% at a process time of less than 300min

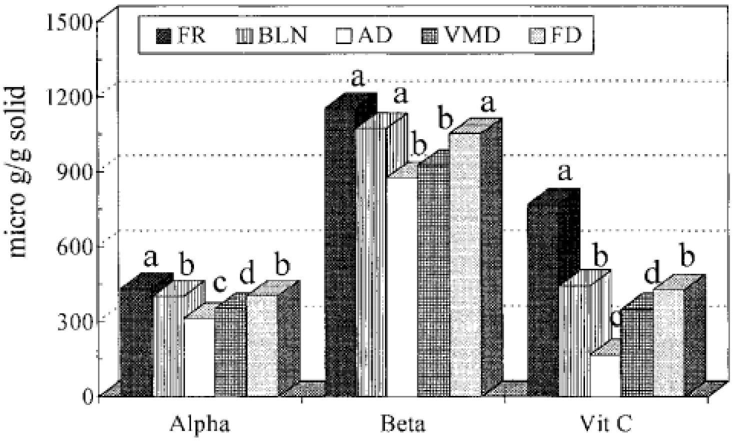


Figure 3-6. Alpha, beta and vitamin C changes after freezing (FR), air-drying (AD) and freeze-drying (FD) processes, as well as after blanching (BLN) (Lin *et al.* 1998),

Texture

For the texture analysis, F_{max} is measured, controlled and used. F_{max} is the maximum force on the component and the surface of the product that it can sustain before it breaks. F_{max} in potato discs decreases with the moisture content, and is significantly affected by the drying temperature. Similar results have been reported by Lewicki and Jakubczyk (2004) in regards to the convective drying of apple pieces. F_{max} increased with the drying temperature, since higher drying rates result in more rigid and crispier products with a higher volume and a well defined surface crust., Slow velocities of drying, on the other hand, lead to denser and more uniform products (Brennan, 1994).

- Potatoes: F_{max} loss of 56% at a process time of 0 to 180min
- Green Peas: Texture loss of 45% at a process time greater than 140min
- Onions: Hardness loss of 13 to 21% at a process time of 60 to 240min

Freeze Dry process

		Freeze Dry process			**Reference**
		Product	**Models and/or Data**	**Observation**	
Quality Indicator	**Nutrient Content**	Carrots	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	The α- β and total carotene loss is 2.4, 5.4 and 4.0% respectively. The ascorbic acid loss during the freeze dry process is 10-15%, many more components are lost during the process. On average, the nutrient content loss is around 15-25% at a process temperature of 20,25 and 30°C	Abonyi *et al.* 2003
	Colour Intensity	Potatoes	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	The parameter L measures lightness. L increases by 5% through the freeze dry process. The yellowness and redness increases as the process time increases and causes a darkness of the product. There is a very small change in colour intensity of 4-6% due to the low temperature (20-30°C).	Krokida *et al.* 2000
		Carrots	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A very small β-carotene loss, which is the most important component for colour intensity. Taking into account the low contact temperature of about 30°C and a low oxygen partial pressure during the freeze-drying, the main individual carotenoids lycopene and β-carotene, as well as the total carotenoid content, have almost been retained, which is not surprising. But the yellowness has increased and would cause a browning of the product.	Abonyi *et al.,* 2003
	Microbial Content	Carrots	☑Experimental Data ☑Zero order kinetic ☑First order kinetic	A microbial component loss, TBC 70-85%, yeast 20-40%, lactic acid bacteria 33-65%, total coliforms 31-81% and a chlorogene acid loss of 60-87%, as well as some other component losses. The microbial content loss is 77-86% at a time process of <240min and a temperature of 20, 25 and 30°C.	Lavelli *et al.* 2005
	Vitamin C	Potatoes	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	A small vitamin loss of 5-8% at a process time <300min and a temperature of 15,25 and 30°C	Wang *et al.* 2010
		Carrots	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	A vitamin C loss of 4-7%. The lower the temperature, the lower the amount of vitamin C retained and the higher the process time, the lower the amount of vitamin C retained.	Lin *et al.* 2013
	Texture	Potatoes	☑Experimental Data ☑Zero order kinetic ☑First order kinetic	A hardness and F*max* reduction of 14-19% at a process time <200min and a temperature of 20, 25 and 30°C. The lower the temperature, the higher the F*max.*	Troncoso and Pedreschi, 2007

	Carrots	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	Very similar to potatoes in texture, and a reduction in hardness and F*max*. The lower the temperature, the higher the F*max* and the higher the process time, the lower the hardness. An F*max* reduction of 14-20%	Troncoso and Pedreschi, 2007
Shrinkage	Potatoes	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A moisture loss of 29, 36.5 and 38% at a process temperature of 20,25 and 30°C, respectively. When increasing the process time to 180 and 240 min, there is a moisture content loss of 45 and 52%, respectively.	Wang *et al.* 2010
	Carrots	☑Experimental Data ☑Zero order kinetic ☑First order kinetic	A moisture loss of 21-48% at a process time of <240min. Reducing the process temperature from 35 to 25°C and from 25 to 15°C causes a reduction in the moisture content of 4 and 3%.	Krokida *et al.* 2003, Krokida *et al.* 1998, Srikiatden and Roberts 2006,
	Green Peas	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	The moisture content loss is 37-49% at a process time >60 and <240min. Varying the process temperature has a small effect of 1-3% on the moisture loss.	Alves-Filho *et al.* 2002

Table 3-8 Quality changes during the Freeze-Dry process for selected materials

Colour intensity

A low temperature and low oxygen partial pressure during the freeze dry process should cause a good retention of the main individual carotenoids lycopene and ß-carotene, as well as of the carotenoid content. The parameter L measures the lightness of the product throughout the freezing process. L in potatoes only changes from 4 to 6% at a process temperature of 20 to 30°C. A very small increase in the carrot's yellowness occurs, which would cause a brownish colouring in carrots for process temperatures of 30°C.

Vitamin C

No significant loss of vitamin C occurred during the freeze-drying, as the temperature was very low during the drying process.

There is a good vitamin C retention in the freeze-dry process.
- Potatoes: a vitamin loss of 5 to 8% at a process time of less than 300min
- Carrots: a vitamin loss of 4 to 7% at the same process time.

Texture

The hardness and F_{max}reduction in the freeze-dry process is lower than for the air-dry process.
- Potatoes: a hardness loss of 14 to 19% at a process time of less than 200min
- Carrots: a hardness loss of 14- 20% at a process time of 0 to 200min

Shrinkage

The moisture loss in the freeze-dry processes is very similar, but slightly lower than for the air-dry process:

- Potatoes: a 29 to 38% moisture loss at a process time of less than 180min
- Carrots: a 21 to 48% moisture loss at a process time of less than 240min
- Green Peas: a 37 to 49% moisture loss at a process time of less than 240min

Microbial content

The microbial components, including TBC, yeast, lactic acid, coliforms, chlorogene acid and some other bacteria, have each been measured to be at a legal level, as is the total level of the microbial content. The total microbial content loss in carrots is 77 to 86% at a process time of less than 240min, which is within the legal level.

Nutrient content

Nutrient parameters, such as α, β and the total level of carotene, ascorbic acid and other components are measured in terms of the total nutrient content.

The total nutrient content loss is between 15 to 25% in carrots at a process temperature of 20 to 30°C. This percentage loss would increase the shelf life of carrots to a few months.

Freezing process

		Freezing process			**Reference**
		Product	**Models and/or Data**	**Observation**	
Quality Indicator	**Nutrient Content**	Carrots	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	A nutrient content loss of 10-15% at a process time of <240min. Varying the process temperature has a negligible effect on the nutrient content loss.	Fuchigami *et al.* 2006
	Colour Intensity	Carrots	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	A complete retention of the colour intensity at any process time and temperature. However, at a temperature of 0 to -20°C, there is a small colour intensity loss of 2-3%.	Fuchigami *et al.* 2006
	Vitamin C	Carrots	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	The vitamin C loss for carrots is very similar to the nutrient content loss, as it is one of the nutrient components. A 10- 16% loss at a process time <240min and a small change of 1-3% as the process temperature decreases from -15 to -70°C.	Fuchigami *et al.* 2006
		Green Peas	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	A 25-41% loss of vitamin C at a process time of <300min. Varying the process temperature by 10-15°C changes the vitamin C loss to 5-10%.	Giannakourou and Taoukis, 2003
	Texture	Carrots	☑Experimental Data ☐Zero order kinetic ☐First order kinetic	The freezing process causes the hardness, F*max* and texture to increase. The surface of the product becomes fragile.	Fuchigami *et al.* 2006
		Green Peas	☑Experimental Data ☐Zero order kinetic ☐First order kinetic		Martins and Silva, 2006
	Shrinkage	Carrots	☑Experimental Data ☐Zero order kinetic ☑First order kinetic	The water and moisture content is retained, as they are frozen. There is a small fraction loss after defrosting the product.	Fuchigami *et al.* 2006

Table 3-9 Quality changes during the freezing process for selected materials

Nutrient content

The nutrient content loss is much lower for the freezing process, compared to any other process. It is only 10 to 15% at a process time of less than 240min.

Colour intensity

During the freezing process, the colour intensity is retained in full. However, a small colour intensity loss may occur at a high process temperature (close to zero). In carrots, there is a small colour intensity loss of 2 to 3% at a process temperature range of 0 to -20°C

Vitamin C

This is very similar to the nutrient content loss, as it is one of the nutrient components.

- Carrots: a 10 to 16% vitamin loss at a process time of less than 240min
- Green Peas: a 25 to 41% vitamin loss at a process time of less than 300min

Texture

The Freezing process increases the hardness and the F_{max} of the product and will make the surface fragile.

Shrinkage

The shrinkage during the freezing process is very small, as it freezes the moisture content and the water components. The moisture is lost during the defrosting process.

Rehydration

Air-Dried materials undergo a rehydration processes in order to retain the moisture content of the dried materials and therefore their shape. The retained moisture can be calculated and measured experimentally (Krokida and Marinos-Kouris 2003).

$$-\frac{dX}{dt} = k_r(X - X_e) \tag{3.17}$$

$$X = X_e - (X_e - X_i)e^{-k_r t} \tag{3.18}$$

The moisture content increases to approximately 80% of the initial level for dried products. Table below (3.10) shows the moisture content increase for different materials after rehydration.

Rehydration			**Reference**
Product	**Models and/or Data**	**Observation**	
Potatoes	☑Experimental Data ☑Kinetics model	A 76.3-79.2% moisture content increase at process temperatures of 40, 60 and 80°C	Krokida and Marinos-Kouris, 2003
Carrots	☑Experimental Data ☑Kinetics model	An 80-83.2% moisture content increase at a process time <180min.	Krokida and Marinos-Kouris, 2003

Onions	☑Experimental Data ☑Kinetics model	A 77-85% increase in moisture content with a 4% increase as the process temperature increases from 40 to 60 and 60 to 80°C	Krokida and Marinos-Kouris, 2003
Green peas	☑Experimental Data ☑Kinetics model	An 80% moisture content increase with very small variations for different process times and temperatures	Krokida and Marinos-Kouris, 2003
Peppers (green, red and yellow)	☑Experimental Data ☑Kinetics model	A very high rehydration rate at almost 3.5 and it increases as the process time increases. For the process time <200min	Krokida and Marinos-Kouris, 2003
Leeks	☑Experimental Data ☑Kinetics model	A rehydration rate, which increases rapidly and settles after a process time of 50min.	Krokida and Marinos-Kouris, 2003
Tomatoes	☑Experimental Data ☑Kinetics model	A very high level of rehydration and moisture content regaining, which increases as the process time and temperature increases.	Krokida and Marinos-Kouris, 2003

Table 3-10 Rehydration and regaining of the moisture content at process temperatures of 40, 60 and 80°C

Figure 3.7 shows the rehydration ratio for different dried materials. The rehydration ratio measures the extent to which different materials retain their moisture content after going through a rehydration process.

Even though the rehydration process raises the moisture content back up to around 80% of the initial level, and therefore increases the nutrient content, the freezing process still retains a higher level of nutrient content.

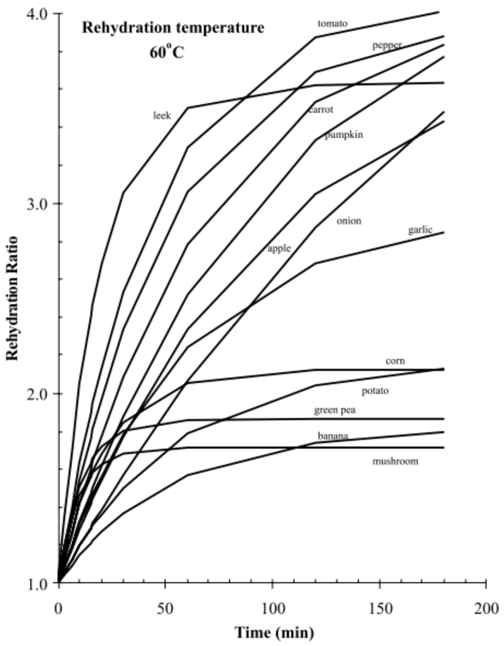


Figure 3-7 Rehydration ratio at 60°C for a number of materials (Krokida and Marinos-Kouris, 2003)

3.3. Food process energy consumption

The energy consumed by food manufacturing systems should be measured for each process and the entire system in order to find the optimum solution. Preparation processes use up most of the energy consumed by the system. This process is required, as it is the main step in order to increase the shelf-life of raw materials in order to overcome seasonality problems.

In this section, published data for the preparation processes (for both drying and freezing processes) is presented. A proposed mathematical model to measure the energy consumption, which is linked to the quality indicator models, is described in the next chapter.

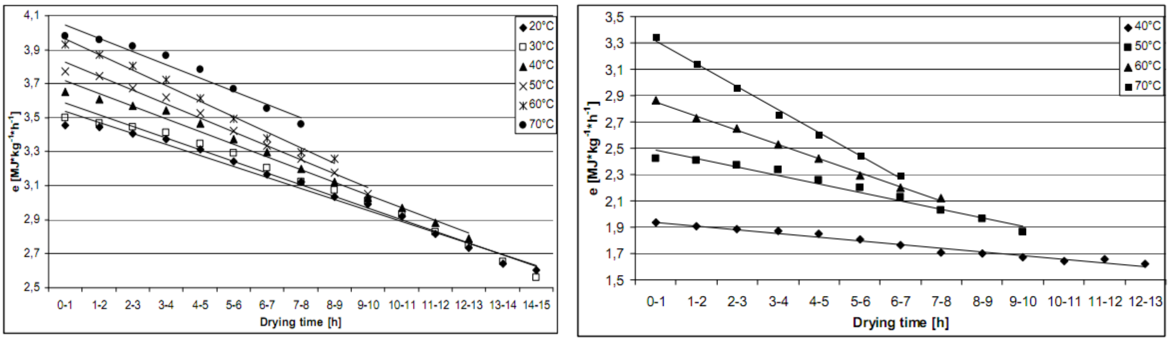
- <u>*Drying process*</u>

Two drying processes are being considered (freeze and air dry processes). Rudy (2009) shows that the energy used for air-dry processes is lower than for freeze-dry processes. This is because the time of the process and the electrical power for the air-dry process is less than that for the freeze-dry process (figure 3.8).

The energy consumed for each process can be measured by looking at the process time and the process power.

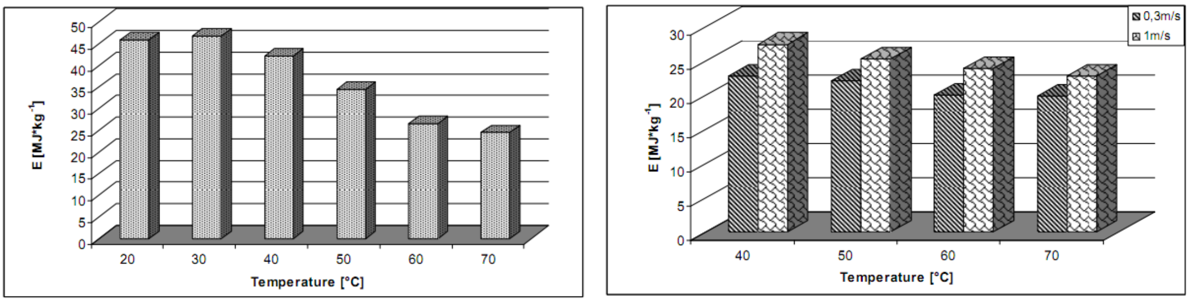
$E=K.Power.t$ (3.19)

This equation states that the electrical energy (*kWh*) consumed for the drying process is equal to the average electrical power supplied (*kW*), multiplied by the process time in hours. In this equation, *K* is the coefficient and starts with *K*=1. *K* reduces, as the temperature, which affects the power, and the process time increases (Xu *et al.* 2005).



The energy inputs involved in the freeze drying process

The energy inputs involved in the air drying process



Total energy inputs in the freeze drying process

Total energy inputs on the air drying process

Figure 3-8 Energy input for freeze-dry (left) and air-dry (right) processes (Rudy 2009)

- *Freezing process*

The freezing process can also use equation 3.19 in order to measure energy consumption. Figure 3.9 shows a real example by Ferreira *et al.* (2006), indicating how energy is used at different freezing temperatures.

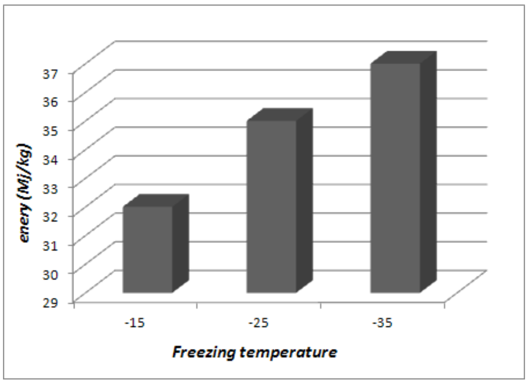


Figure 3-9 **Energy used for freezing process at different temperatures (Ferreira *et al.* 2006)**

The experimental data, together with equation 3.19, measure the parameters in the energy model (next chapter).

3.4. Conclusions

Drying is a popular process in regards to food engineering. Drying processes have advantages, such as weight, storage space and cost reduction, as well as increasing the shelf life of products, however, this process also disrupts the quality of the product.

In the food industry, the final stage is sterilisation, which affects the quality of a product. The key changes to products after sterilization are:

- A reduction in the quality of the product, changes to the texture, and a softening of the material.
- A reduction in the bacterial activity, which makes end products safe.
- A reduction in vitamins, such as vitamin C, thiamine and folate content.

Sterilisation not only affects a product in terms of quality, but also from an economical point of view. For example, the heat used for sterilisation affects the energy consumption and the carbon footprint. After reviewing existing supply chain management and food engineering literature, a decision to integrate food engineering with supply chain modelling has been made in order to control the quality and cost of the product. A food supply chain model will be developed in order to minimise the cost of the production and to also guarantee product quality.

For this purpose, quality and energy models are being created, which will measure the optimum solution for the entire system. These models are described in the next chapter. In order to measure the parameters for these models, some existing literature and experimental data, as well as literature models, will be presented and modelled in this chapter.

Chapter 4

Optimisation of food product quality and energy consumption in supply chains

4.1. Supply Chains in the Food Industry

The differences between supply chains in the food industry and other supply chains is the importance of key factors, such as food quality and safety, weather related variability and other characteristics, such as shelf-life, demand and price variability, which makes the underlying supply chain more complex and harder to manage than in other cases (Salin, 1998).

In the FMCG (fast moving consumer goods) sector, the product improvement process is based on fundamental research and development, which is a key factor for customer satisfaction. Hence, new methodologies are being developed from time to time in order to improve existing products and services. At the same time, this process is being controlled in order to reduce production costs. Supply chain management is a research area with a set of developed techniques, which identify bottlenecks and optimise all of the steps from the supplier to distribution. The supply chain is a series of logistical internal and external activities between companies in order to increase efficiency by sharing information between entities and to improve customer satisfaction at the lowest possible price (Shah, 2005). A good example of this is the work by Yu *et al.* (2013), who have developed a network-based food supply chain model focusing on fresh materials. Their model focuses on cost optimisation and is linked to the disposal of spoiled food products.

Whilst there are some variations between enterprises, all food companies follow a similar path and business process in regards to environmental issues, demand management, inventory management, production planning and manufacturing campaign planning. The main factor considered in this chapter is environmental issues, which refers to the quality control of a product in order to minimise waste and energy consumption.

In order to control and manage quality and energy consumption, mathematical models have been developed and integrated into the supply chain. Integrating quality models into the food supply chain will cause system problems. This is because of the complication of quantifying food quality and managing product quality throughout the process. It is very important to control product quality (e.g. Smith *et al.* 2004), and to maintain a high quality product during the various processes and processing conditions. Rong *et al.* (2011) have researched the optimisation of food quality degradation in the production and distribution planning process. This model optimises the quality of fresh food raw materials throughout the supply chain system. In their work, fresh raw materials are considered. The shelf life of the product is therefore low. Rong *et al.* showed that lowering the temperature reduces quality degradation and increases the shelf-life of a product. They have considered a kinetic model in order to measure the quality degradation with only one raw material and product. The generated results are linear and non-linear in the case of zero and first order reactions, respectively. This kinetic model is integrated into the supply chain, and mixed –integer linear programming is used for the production and distribution. However, in their work, energy consumption has not been considered as a key factor.

Flexibility of seasonal raw materials and products is an important factor in the food industry. In this chapter, a preparation process is presented and integrated into the production system in order to increase the shelf-life of the raw materials. The focus of this chapter is on the preparation processes, which aims to reduce the inventory wastage produced by expired materials. Two drying processes, air- and freeze-dry, and a freezing process are being considered and compared at this point. Fresh food materials are a source of vitamins, minerals and other bioactive compounds, such as pigments and volatile compounds, which undergo degradation during the drying process (Gregory, 1996). A quality model is developed in order to control the variation in these quality indicators.

4.1.1. Problem Statement

As mentioned before, in order to overcome the seasonality problem, a new food process is being integrated into the existing production line. The integration of the preparation process will affect the character of the raw materials before entering the inventory state and/or cooking process. The aim is to introduce a new methodology in order to model and optimise food quality, whilst controlling and minimising the process energy consumption in such a way that it can be integrated in a mixed-integer linear programming model used for the manufacturing system throughout the supply chain.

Two production lines are considered and compared, namely the drying and the freezing process (figure 4.1.). In the case of the drying process, there are two drying types, air-dry and freeze-dry, with the potential of blending their output materials. The freezing process, on the other hand, is a single process and has been integrated into the production line. As shown in figure 4.1, a similar supplier is used with similar recipes, raw materials and distribution centre.

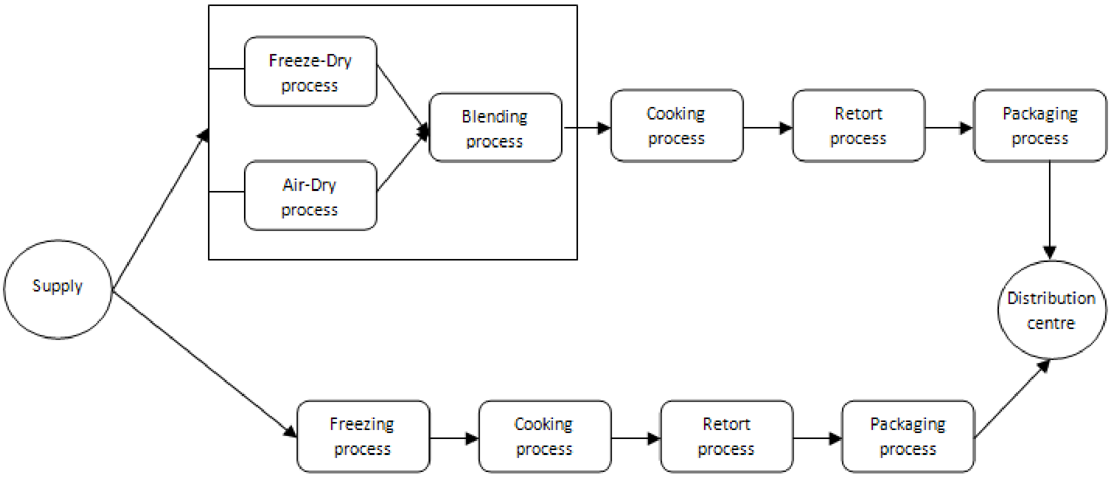


Figure 4-1 Production line after integrating a preparation process

This chapter addresses and describes the following areas: quality models and the modelling approach, compiling quality and energy models, integrating the preparation process into the production line and manufacturing system, as well as computational experiments based on data obtained from literature.

4.2. Quality model

Long shelf-life raw materials are essential in the food industry, and an integration of the preparation process would provide an advantage in this respect. Moreover, the two freezing and drying processes have other advantages, such as:

- Ensuring a good monitoring of the process time and product quality,
- Supporting just-in-time processing and seasonal ingredients,
- In the case of the drying process, it reduces the weight of the material, which means that transportation costs, storage space and packaging costs will also be reduced.

As mentioned in the previous chapter, despite all of the advantages, the drying/freezing process does affect the product quality. The major quality indicators affected are colour intensity, texture, microbial content, nutrient content, vitamin content, shape, volume and size. In this work, these quality indicators are being considered so that they can be controlled and optimised simultaneously.

There are two types of indicators, namely time-dependent indicators (texture, colour intensity, vitamin content, including ascorbic acid, thiamine and riboflavin, nutrient content, including ascorbic acid, beta-carotene, carotenoids, lycopene, thiosulphiate and microbial content) and static indicators (shape, volume and size).

4.2.1. Modelling quality approach

The first challenge is to quantify the quality in a mathematical form. The results in regards to measuring quality are mostly in a non-linear form, as shown in chapter 3. This adds a level of complexity to the model. A new methodology is therefore introduced, which linearises the non-linear models in order to maintain tractability when incorporated into supply chain models, which would simplify the optimisation model throughout the entire system. This model guarantees product quality across all indicators with the benefit of integrating it into the supply chain model.

Two classes of quality models have been introduced: linear and blending quality models. The linear model is applied to all tasks and inventories in order to measure and control the quality for all quality indicators. Two preparation processes have been considered for the production line: freezing and drying. In the case of drying, more than one drying process is being used, therefore a blending model is applied after the preparation task to determine, what portion of the product from each drying process (if both are employed) should be used in order to achieve optimum product quality with minimum energy usage and expenditure.

4.2.1.1. Linear quality model

In this section, the linear quality model is introduced and discussed. This model simplifies quality control, modelling and optimisation by linearising non-linear models. The model also shows, how the different quality indicators are affected by alternative processes.

The first step is to model and calculate the quality of a certain indicator for the product at each stage. The following linear model is introduced for this. In the model, quality is affected by the process and its processing variables, such as time and temperature.

$$q_{out,i} = B_i + C_i . q_{in,i} + \sum_D A_{iD} . u_{jD} \ , 0.5 \leq u_{jD} \leq 1 \qquad (4.1)$$

Here, $q_{out,i}$ represents the quality (of a specific indicator, *i*) of the product after each task (*j*). The $q_{out,i}$ at each stage becomes an input quality for the next stage, i.e, $q_{in,i}$. In this model, different processes will have different effects. Figure 4.2 shows the effect of the process on quality. The material processed in the task undergoes a number of transformations described by parameters *A, B* and *C*. A reflects the effect of the process variables, B reflects an absolute change in quality and C reflects a proportional change in quality. These degrees of freedom can be tuned, so that the linear model is a reasonable fit for the more detailed non-linear behaviour. Controlling product quality throughout the food supply chain requires a focus on both time and temperature, as demonstrated by Zhang *et al.* (2003). The variable set *u* is introduced in the model, which captures how the quality of the product is also affected by the process degrees of freedom (e.g. temperature, processing time u_{jD}).

Since quality is <1, u_{jD} is the normalised degree of freedom and should be between 0.5 and 1. The upper boundary (u_{max}) is set as 1 and represents the maximum degree of freedom (max. temperature or process time that can be used at every process) and the lower boundary of (u_{min}) is set as 0.5. This has been chosen to limit the maximum allowable loss of quality.

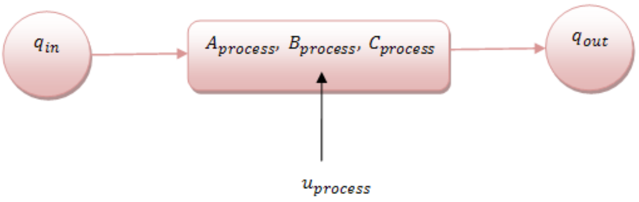


Figure 4-2 Modelling quality and process

Figure 4.3.a shows how the model linearises the non-linear model, and figure 4.3.b shows how the input quality affects the output quality. *A* in the model represents the slope of the linear model and is a degree of freedom multiplier, whilst *B* is the offset quality model. *C* is the input quality multiplier and affects the model as shown in figure 4.3b. This figure (fig 4.3b) illustrates the quality of the product against *u* at each stage, where $q_i^1$and q_i^2 represent the quality of indicator *i* at stage 1 and 2, respectively. All three parameters (*A, B* and *C*) can be determined by regressing operating or experimental data.

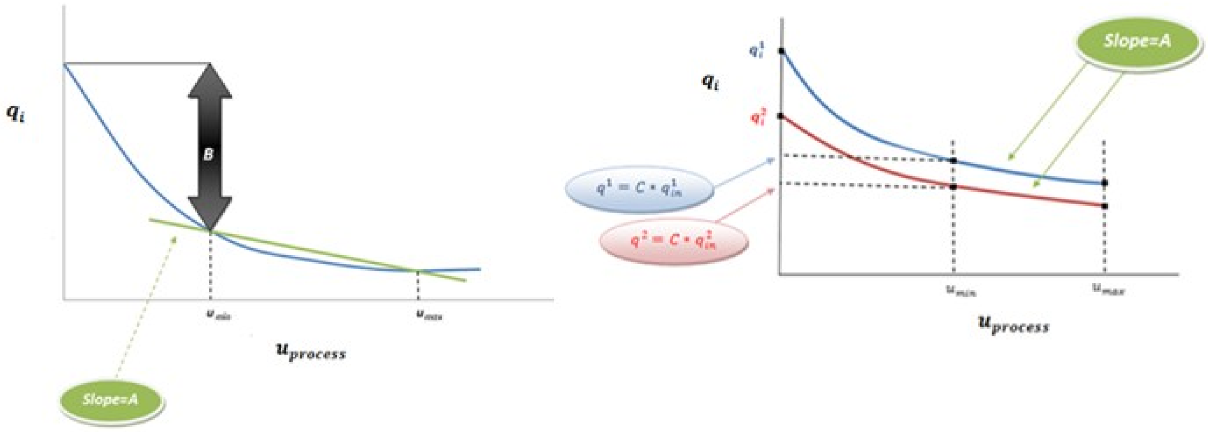


Figure 4-3 a) Linearity of the model, B=0, b) Linearity of the model, A=0

4.2.1.2. Blending quality model

At every stage of the process, materials undergo different tasks and the level of each quality indicator for each material therefore differs. Usually, the end product with a quality that best matches the consumer expectation, is chosen, however, we are introducing an alternative mixing option here. This way, the model optimises the quality with regards to energy usage by including parts of each processing type (figure, 4.4).

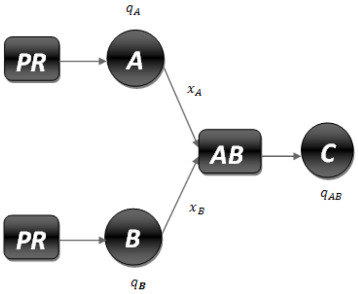


Figure 4-4 Blending and mixing process

$$q_{AB} = x_A.q_A + x_B.q_B \text{ ,} where\ x_A + x_B = 1 \tag{4.2}$$

Here, PR is the drying process, and q_A and q_B are the quality of the final products produced by process type A and B, respectively. q_{AB} is the quality of the product after blending and x_A and x_B are the blending fractions, by which the two processes are mixed, where the sum of x_A and x_B must equal 1.

Application correction

This model is then updated by applying a correction factor. The correction factor is necessary and causes the linear model to be closer to its original non-linear shape in order to illustrate the properties, which blend in a non-linear fashion. This increases the accuracy of the results.

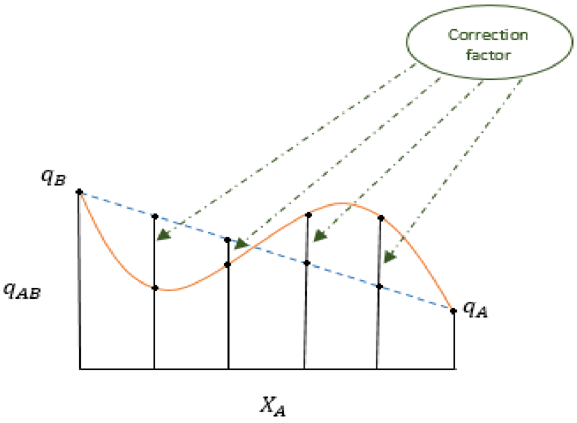


Figure 4-5 Correction factor

The updated version of the model is as follows:

$$q_{AB}^k = x_A^k.q_A + (1 - x_A^k).q_B + corr^k\ \forall k \tag{4.3}$$

$$q_{AB} \leq q_{AB}^k + M\left(1 - y_A^k\right) \forall k \tag{4.4}$$

q_{AB}^{k}, is the quality after blending at every data point. k is the data point. The data point is a fixed point in the model, which has been chosen to apply the correction and calculate the differences between the linear model and the corrected model. The data point suggests, which portion of each processing type should be taken. x_A^k is the set of allowed blend fractions of A, and y_A^k is 1 if and only if the k^{th} value of x_A^k is chosen. Hence, we avoid non-linearity by discretising the allowable blend fractions.

$Corr^k$ is the correction factor, which is applied to the model in order to increase the accuracy of the results, as shown in figure 4.5. It may be necessary to apply the correction factor to all data points, so that the linear model can be analysed point by point, and applying the correction where required. The sign of the correction factor changes depending on the shape of the curve of the non-linear model (e.g. concave, convex or sinusoidal) (figure, 4.5). The correction factor non-linearises the linear model for each data point.

Constraint 4.3 therefore defines the possible values of q_{AB} (essentially the set q_{AB}^{k}), while constraint 4.4 defines the actual value selected during the optimisation.

Only one data point is chosen at a time. y_A^k is a binary variable and takes the value 1 if the k^{th} point (blending fraction) is chosen and 0 otherwise. This means that $M(1 - y_A^k)$ is inactive at every data point (when $y_A^k = 1$).

Only one y_A^k can take a value of one and therefore we add:

$$\sum_k y_A^k = 1 \tag{4.5}$$

So $y_A^k = 1$, means we are at data point k and hence the correct q value will be constrained from above by $q_{AB}^{k}$and the term $M(1 - y_A^k)$ is inactive only for the specific k. For all other k, the $y_A^k = 0$ and 4.4 is non-binding from above.

Hence, constraint 4.4 is necessary and ensures that at every data point (when y_A^k is 1) $q_{AB} = q_{AB}^{k}$.

Advantages of the model

- Linearising the non-linear model to simplify the quality control at every stage.
- Can be applied throughout the entire system
- Has the advantage of taking into account all necessary quality indicators
- Process conditions affecting the quality are integrated into the model.
- The quality model can be linked to the energy model using the process conditions, which provides the advantage of optimising them simultaneously.

4.3. Energy consumption

The previous section demonstrates how to quantify and model the quality of the material before and after each task in order to control the quality and therefore the waste. Energy is another key factor, which is taken into account by industrial companies. Just as with quality, the process degrees of freedom affect the energy, e.g. the process time and temperature. This has the advantage of being able to link the two models together and it eases the optimisation work.

Every task and process consumes different levels of energy. The freezing and drying process have different effects on the system. Using the freezing process will cause an additional energy consumption at the inventory stage, as well. This is because the inventory requires materials to be stored in the low temperature store. Dried materials, on the other hand, are normally stored at room temperature and have a negligible energy consumption.

Base-delta energy model

The base-delta model is used to model energy consumption using the same degrees of freedom as the quality model. The degrees of freedom generate an opportunity to link the two models together, and ease their integration into the entire supply chain system.

$$Energy = f(T, t) \tag{4.6}$$

$$E(u_1, u_2) = E_{base}\left(u_1^{base}, u_2^{base}\right) + a_1\left(u_1 - u_1^{base}\right) + a_2\left(u_2 - u_2^{base}\right) \tag{4.7}$$

$a_n = slope\ of\ the\ n^{th}\ degree\ of\ freedom\ (time, temp\ \ldots)$

$$a_n = \frac{E(u_n^{base}+\delta u_n)-E(u_n^{base}-\delta u_n)}{2\delta u_n} \tag{4.8}$$

The variables in this model are the degrees of freedom; which are the same as for the quality model. In the energy model, the base is set and is shifted to the left and right with the fraction of delta. This fraction measures the energy consumption after any changes (Figure, 4.6). The parameter a_n is the slope of the n^{th}degree of freedom, time and temperature, u_n is the n^{th} degree of freedom, and $E(u_1, u_2)$ is the energy consumed by the first and second variable.

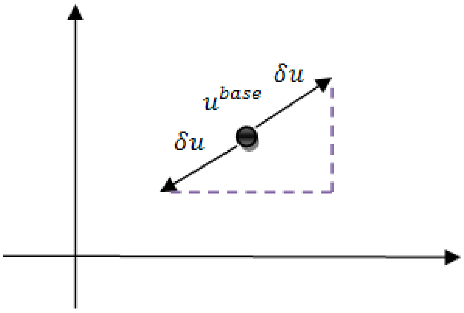


Figure 4-6 Correction factor

At the blending stage, the energy consumption blends with the same portion as the quality (coefficient x). The blending model for energy is:

$$E_{AB}^k = x_A^k . E_A + (1 - x_A^k). E_B, \forall k \tag{4.9}$$

The elements and concept of equation 4.8 are the same as for the quality model (equation 4.2).

Since the energy and the quality model use the same process variables, they are linked and integrated together in order to generate a single optimum result for both. The parameters for both the quality and energy model are measured with the experimental data and models introduced in the last chapter. Later, these models are included in the real industrial world case study introduced by the industrial partner Unilever. The case study and the results are demonstrated in chapter 6.

4.4. Integrating the quality and energy model and optimising these in the manufacturing system

The approach for this model is based on a food processing chain, as shown in figure 4.1. Food processing is important, because in this model, all of the fresh raw materials are required to undergo a preparation process (freezing or drying) in order to increase their shelf-life and to decouple supply and demand seasonality. The focus of this chapter is on the preparation process. The supply chain system, on the other hand, includes all of the main elements for the manufacturing system, from raw materials to the distribution centre: supply, drying process, cooking, packaging, inventory and storage. Supply chain management looks at all of the elements and optimises the system as a whole. The quality of the materials is measured and controlled after every task by using the proposed quality models. An inventory constraint and shelf-life waste model is also applied in this model in order to control the material waste in regards to products, which have passed their expiry date and which are below the acceptable quality level.

The drying process has been divided into two process types (air- and freeze- dry). The linear quality model is being applied to the drying process in order to guarantee the quality of the materials across all indicators. Materials undergo a blending process after a very short storage period, which has a negligible effect on the quality, and the inventory constraints are therefore not disturbed. Later, the dried materials are moved to a longer-term inventory before starting the cooking process (figure, 4.1). The freezing process for materials, on the other hand, avoids the blending process. This process is considered as a separate individual task instead. The results of the preparation process in regards to the quality and energy usage for both are then compared and discussed.

The key objectives of the model are as follows:

- Relate the material’s output quality to the input quality for the next process
- Link the quality of the material to the degrees of freedom process
- The ability to propagate quality indicators through the process: in effect a “state“ quantity
- Maintain model linearity
- Link the energy usage to the quality model

4.4.1. Model assumptions

The following assumptions are made in the model:

- The materials, which meet the quality constraints, are used for the task, and the remaining materials are considered to be waste, and must be disposed of.
- Only one process type is considered at a time.
- Product storage and inventory is available at every stage.
- A short-term inventory exists after the cooking stage therefore assumes a negligible change in product quality and energy consumption.
- The fraction of each batch leaving the inventory (β) is assumed to be 1. This means that what goes into the inventory is used downstream.

4.4.2. Nomenclature

The following notations are used for the purpose of modelling:

Index:

s = set of states

i = quality indicator

j = processing type

t = time

t' = time in period, lifetime of product

k = data points

D = degree of freedom

p = product

Parameters

a_{jsD} = Degree of freedom energy multiplier for every process at state s

α_{jps}^{g} = Variable numbers of batches with quality higher than minimum qualty for p at every stage

α_{jps}^{n} = Variable numbers of batches with quality lower than minimum qualty for p at every stage

A_{jpDi} = Degree of freedom quality multipier for every product and process for inidicator i

B_{ipj} = quality model offset for every product and process for inidicator i

β_{jps} = fraction of each batch leaving from each stage

BS_{jpt} = Batch size for each product at time t

C_{ipj} = quality multiplier for every product and process for inidicator i

Cap_{j}^{max} = maximum capacity for every task

$corr_{ips}^{k}$ = correction applied to the model at each data point for indicator i, product p and stage s

$Demand_{st}$ = demand at t of each stage

$Demand_{spt'}$ = demand for every product at time period t' (lifetime of every product) for each stage

$Demand_{sjpt}$ = demand at time t of state s for every product and process j

$DisposalCost_{s}$ = disposal cost of waste at every state

$Energy_{js}^{base}$ = base energy for every process at stage s

$LifeTime_{sp}$ = lifetime of individual product at stage s

M = slope of the quality model

$PurchaseCost_{s}$ = purchase cost at stage s

q_{min} = minimum quality accepted by the consumer

$StorageCost_{s}$ = storage cost at stage s

$TaskCost_{sj}$ = task cost at stage s of processing type j

u_{base} = Degree of freedom for base energy

Binary Variables

$y_{is}^{k} = 1$ only if the k^{th} value of x_{j}^{k} is chosen

$\gamma_{spt} = 1$ if the batch does not refer to waste and 0 otherwise

Variables

$Energy_j = Energy\ usage\ for\ every\ process\ j$

$Energy_{js} = Energy\ usage\ at\ stage\ s\ for\ process\ j$

$Energy^k_{ips} = Energy\ used\ at\ every\ data\ point\ for\ indicator\ i\ and\ for\ every\ product\ at\ stage\ s$

$Energy_{ipjs} = Energy\ used\ for\ every\ product\ and\ process\ for\ indicator\ i\ at\ stage\ s$

$Inventory_{st} = inventory\ at\ stage\ s\ and\ time\ t$

$Inventory_{spt} = inventory\ for\ every\ product\ at\ stage\ s\ and\ time\ t$

$Outflow_{st} = flow\ quantity\ from\ every\ stage\ to\ a\ task\ at\ time\ t$
$Outflow_{spt'} = flow\ quantity\ for\ every\ product\ from\ every\ stage\ to\ a\ task\ at\ time\ period\ t'$
$PR_{st} = production\ of\ every\ stage\ at\ time\ t$
$PR_{sjt} = production\ of\ every\ stage\ for\ every\ process\ at\ time\ t$
$q_{ipjs} = Value\ of\ quality\ indicator\ i\ of\ state\ s\ for\ process\ type\ j\ for\ every\ product$
$q_{ips} = Value\ of\ quality\ indicator\ i\ of\ stage\ s\ for\ every\ product$
$q^k_{ips} = quality\ of\ indicator\ i\ at\ the\ blending\ stage\ applied\ to\ every\ set\ data\ point$
$Supply_{st} = supply\ of\ the\ materials\ at\ stage\ s\ and\ time\ t$
$u_{jD} = D^{th}\ degree\ of\ freedom\ of\ task\ j$
$u_{jsD} = D^{th}\ degree\ of\ freedom\ of\ task\ j\ and\ stage\ s$
$Wastage^{expired}_{st} = wastage\ produced\ from\ the\ expired\ materials$
$Wastage^{quality}_{st} = wastage\ produced\ by\ the\ quality\ model$
$Wastage_{st} = total\ waste\ produced\ in\ the\ system$
$x^k_j = set\ of\ allowed\ blended\ fractions\ from\ process\ j$

4.4.3. Mathematical formulation

In this section, all of the constraints of the model are introduced and presented.

- **Mass balance constraints** are required in order to balance the inventory in regards to production and consumption.

$$Inventory_{st} = Inventory_{st-1} + PR_{st} - Outflow_{st} - Wastage_{st} - Demand_{st}\ \ \forall_{s,t} \qquad (4.10)$$

$$Inventory_{st} \geq 0 \qquad (4.11)$$

- **Inventory constraints** are introduced in order to establish a first-in-first-out policy in the model in regards to the inventory policy, and to limit waste due to the limited lifetime of materials and products (Papageorgiou *et al.* 2001).

$$Inventory_{spt} \leq \sum_{t'=t+1}^{t+LifeTime_{sp}} Outflow_{spt'} + Demand_{spt'}\ \ \forall s,p \qquad (4.12)$$

- **Capacity control constraints** are applied, so that the production quantity of each task does not exceed the capacity of it.

$$PR_{sjt} \leq Cap_j^{max} \; \forall_{j,s,t} \tag{4.13}$$

- **Production constraints** lead to products with a quality that is higher than the minimum quality after each task entering the inventory state.

$$PR_{st} = \sum_p \sum_j \alpha_{jps}^g . BS_{jpt} \;\; \forall_{s,t} \;\; \alpha_{jps}^g \geq 0 \; and \; integer \tag{4.14}$$

- The **Outflow constraint** only causes fraction β of the product at each stage to enter into the next task. This fraction is applied in order to control the capacity of the tasks. It only causes a fraction β of each batch, which does not refer to waste, to leave the inventory stage. The β fraction is assumed to be 1 for now, and this allows for flexibility to adapt the model in future. γ controls the waste batches and it is set to 1, if the batch has a quality higher than the minimum quality, and if it is not an expired batch, or 0 if the batch refers to waste.

$$Outflow_{st} = \sum_p \sum_j \gamma_{spt} . \beta_{jps} . \alpha_{jps}^g . BS_{jpt} \;\; \forall_{s,t} \; 0 < \beta_{jps} \; \leq 1 \tag{4.15}$$

- **Linear quality models** quantify the quality and linearise non-linear models. In this model, *j* and *s* have a 1 on 1 relationship. *u* is a variable and shows by how much the degree of freedom (temperature or process time) has to change in order to achieve the required quality across all indicators.

$$q_{ipjs} = B_{ipj} + C_{ipj} . q_{ipjs-1} + \sum_D A_{jpDi} . u_{jD} \;\; \forall_{i,p,j,s} \; 0.5 \leq u_{jD} \leq 1 \tag{4.16}$$

- **A base-delta energy model** has been integrated, so that the energy model, which matches the degrees of freedom of the quality model, shares a similar decision variable *u*.

$$Energy_{js} = \sum_D a_{jsD} . (u_{jsD} - u_{base}) + Energy_{js}^{base} \; \forall_{j,s} \tag{4.17}$$

- The **blending quality model** enforces the model at the blending stage in order to take appropriate fractions of matrix (x) from each processing type to achieve an appropriate quality product.
  In this equation *x* is the blending fraction and it should sum up to 1. The binary variable y_A^k is necessary here, it is 1 when we are at data point *k* and 0 otherwise. The model must select a particular point, hence equation (4.19).

$$q_{ips}^k = \sum_j x_j^k . q_{ipjs} + corr_{ips}^k \; \forall k, i, p, s \tag{4.18}$$

$$\sum_j x_j^k \;\; = 1 \; \forall j \tag{4.19}$$

$$\sum_k y_{is}^k = 1 \;\; \forall i, s \tag{4.20}$$

- The **correction constraint** is applied to every data point and ensures that the blending quality model is accurate, if certain quality attributes blend in a non-linear way.

$$q_{ips} \leq q_{ips}^k - \; M\left(1 - y_{is}^k\right) \forall k, j, p, s \tag{4.21}$$

- The **blending energy model** forces the energy model to go through all of the data points simultaneously, together with the blending quality model.

$$Energy_{ips}^{k} = \sum_j x_j^k . Energy_{ipjs} \ \forall k \ \sum_j x_j^k \ = 1 \ \forall j \tag{4.22}$$

- The **total energy usage** for every process is equal to the summation of the energies consumed at each stage.

$$Energy_j = \sum_s Energy_{j,s} \tag{4.23}$$

- **Wastage Constraints:** There are two different wastage constraints. In the production line, the quality control constraint is applied in order to control the quality of the product. Regarding the inventory and storage area, on the other hand, a constraint is applied in addition to the quality control constraint in order to control the shelf life of the product.

1) The product at each stage at a time t with the quality of any indicator lower than the minimum quality of that indicator refers to waste.

$$Wastage_{st}^{quality} = \sum_p \sum_j \alpha_{jps}^n . BS_{jpt} \ \ \alpha_{jps}^n \geq 0 \ and \ integer \tag{4.24}$$

2) Even though the wastage variable has been introduced in the inventory section in regards to the limitation of the lifetime, an extra constraint is required here in order to ensure that the stored materials for each period cannot be used once their lifetime has passed (at time period *t+L*).

$$Wastage_{st}^{expired} = Inventory_{spt} - \sum_{t'=t+1}^{t+LifeTime_{sp}} Outflow_{spt'} + Demand_{spt'} \ \forall s,t \tag{4.25}$$

Therefore, the total waste is the sum of waste produced due to both quality issues and a limited life time.

$$Wastage_{st} = \ Wastage_{st}^{expired} + Wastage_{st}^{quality} \ \forall s,t \tag{4.26}$$

- The **demand constraint** ensures that the overall demand for all products from all processing types does not exceed the maximum demand.

$$Demand_{st} = \sum_p \sum_j Demand_{sjpt} \ \forall s,t \tag{4.27}$$

- The **objective function** optimises the process by minimising costs and energy usage.

$$Min\left(\sum_{s,t} Supply_{st} . PurchaseCost_s + \sum_{s,t} Inventory_{st} . StorageCost_s + \sum_{s,t} Wastage_{st} . DisposalCost_s + \sum_{s,j,t} PR_{sjt} . TaskCost_{sj}\right) \tag{4.28}$$

- **Summary of Formulation:** In conclusion, the entire mathematical formulation is outlined from equations 4.9 to 4.26 and is presented as follows:

Objective

$$Min\left(\sum_{s,t} Supply_{st} . PurchaseCost_s + \sum_{s,t} Inventory_{st} . StorageCost_s + \sum_{s,t} Wastage_{st} . DisposalCost_s + \sum_{s,j,t} PR_{sjt} . TaskCost_{sj}\right)$$

Subject to:

$$Inventory_{st} = Inventory_{st-1} + PR_{st} - Outflow_{st} - Wastage_{st} - \ Demand_{st} \ \forall_{s,t}$$

$$Inventory_{st} \geq 0$$

$$PR_{st} = \sum_{p}\sum_{j} \alpha^{g}_{jps}.BS_{jpt} \ \forall_{s,t} \ \ \alpha^{g}_{jps} \geq 0 \ and \ integer$$

$$PR_{sjt} \leq Cap^{max}_{j} \ \forall_{j,s,t}$$

$$Outflow_{st} = \sum_{p}\sum_{j} \gamma_{spt}.\beta_{jps}.\alpha^{g}_{jps}.BS_{jpt} \ \ \forall_{s,t} \ 0 < \beta_{jps} \ \leq 1$$

$$Inventory_{spt} \leq \sum_{t'=t+1}^{t+LifeTime_{sp}} Outflow_{spt'} + Demand_{spt'} \ \forall s,p$$

$$q_{ipjs} = B_{ipj} + C_{ipj}.q_{ipjs-1} + \sum_{D} A_{jpDi}.u_{jD} \ \forall_{i,p,j,s} \ 0.5 \leq u_{jD} \leq 1$$

$$Energy_{js} = \sum_{D} a_{jsD}.u_{jsD} + Energy^{base}_{js} \ \forall_{j,s}$$

$$q^{k}_{ips} = \sum_{j} x^{k}_{j}.q_{ipjs} + M\left(1 - y^{k}_{is}\right) + corr^{k}_{ips} \ \forall k,i,p,s$$

$$\sum_{j} x^{k}_{j} \ = 1 \ \ \forall j$$

$$\sum_{k} y^{k}_{is} = 1 \ \ \forall i,s$$

$$Energy^{k}_{ips} = \sum_{j} x^{k}_{j}.Energy_{ipjs} \ \ \forall k \ \sum_{j} x^{k}_{j} \ = 1 \ \forall j$$

$$Energy_{j} = \sum_{s} Energy_{j,s}$$

$$q_{ips} \leq q^{k}_{ips} - \ M\left(1 - y^{k}_{is}\right) \forall k,j,p,s$$

$$Wastage^{quality}_{st} = \sum_{p}\sum_{j} \alpha^{n}_{jps}.BS_{jpt}, \ \alpha^{n}_{jps} \geq 0 \ and \ integer$$

$$Wastage^{expired}_{st} = Inventory_{spt} - \sum_{t'=t+1}^{t+LifeTime_{sp}} Outflow_{spt'} + Demand_{spt'} \ \forall s,t$$

$$Wastage_{st} = \ Wastage^{expired}_{st} + Wastage^{quality}_{st} \ \forall s,t$$

$$Demand_{st} = \sum_{p}\sum_{j} Demand_{sjpt} \ \forall s, t$$

4.5. Solution methods and results

This project focuses on the preparation of raw materials using a soup production process as an example. The goal of this project is to develop a new methodology in order to measure, control and optimise product quality, whilst minimising cost and energy consumption. As part of this project, the quality and energy models introduced in the previous sections have been implemented into the supply chain model in order to achieve the given objectives.

The focus is on the processing and manufacturing systems. Product waste occurs in products, which have a lower quality than the minimum acceptable quality, and in regards to products whose shelf-life has passed. In this model, quality and energy control are the key objectives, and the key variables in the formulation are u and x, where u represents at what temperature and processing time the process generates an optimum solution, and the set variable x represents at what part the two processes should blend to achieve optimum product quality and energy. These are determined to optimise the model for the given objectives subject to the production, energy consumption, cost, as well as quality and demand constraints.

It is necessary to use processed raw materials with a long shelf-life; three preparation processes (freezing, air- and freeze dry) are therefore introduced. The recipe for this product and the main raw materials used are: potatoes, carrots, green peas and onions. These raw materials are required in batches every day, except for inactive days, such as weekends and bank holidays. The initial quality indicator of each batch varies between 0.9 and 1. These batches undergo a preparation process and later pass through a short inventory followed by a long inventory before the cooking process. In this chapter, the model is optimised solely for the preparation process in order to explore how different drying processes might optimise the process from a quality and cost point of view and compared to the freezing process. In the later chapters, the model is applied to the cooking and packaging process with a longer inventory.

4.6. Results discussion

In order to solve the problem, the model is implemented in AIMMS in combination with CPLEX optimisation software. The test runs were performed on a 2.66 GHz Pentium 4 PC (with 3.49 GB of RAM).

At the preparation stage, an objective function is applied in order to optimise the decision variables u and x, i.e. it is a *recipe design* formulation.

$$Obj = max[a.q_j - b(Energy_j)] \tag{4.29}$$

Where a and b are the weightings given to the quality and energy consumption as shown in table 4.1. These are measured by nomalising the base energy and initial qualities. This weighting places the energy and quality on the same scale in regards to the objective (4.27). The weighting is different for each process.

Process\Weighting	a	b
Drying	0.9762	0.0238
Freezing	0.9881	0.0119

Table 4-1 Quality and energy weightings

The decision variable set, which is set at the first state of the preparation process, is *u,* which controls the quality of the product in parallel to the energy consumption. Therefore, the model finds the optimum solution by changing the variable set *u*. However, at the second stage of the preparation process, two different drying processes are able to blend in order to generate a better material in terms of quality and energy. The decision variable at this stage is *x,* which shows how much the two processes should mix in order to generate an optimal solution for the material. It should be stressed that energy consumption directly affects the task cost and that the quality affects the disposal cost.

Then, the optimal results for the preparation process recipe are implemented into the model in order to establish the main objective function, a cost minimisation of the system through supply chain planning. In the case of infeasibility, the model goes back to the first stage in order to change the decision variables *u* and *x*. Hence, a decomposition procedure is used. There are two ways to solve the problem: decomposition as described here, or a simultaneous approach with an appropriate objective function and constraints on the quality. The simultaneous approach is mainly used for dynamic processes and optimises the quality, energy, inventory and costs simultaneously. But the decomposition method simplifies the optimisation problem. By using this method, the quality and energy decomposite from inventory optimisaiton and/or cost optimisation. The decomposition method is the more popular method, especially amongst industrial companies. This is because the method is easier to solve, cheaper and less time cosuming.

Figure 4.7 illustrates the structure of the model and the solution method. At stage 0, the input data and the initial values (initial quality etc.) feed into stage 1, where the fresh raw materials undergo a preparation process (drying or freezing). The input data stems from literature, mostly from data surveys and some other models presented in chapter 3.

Stage 1 optimises the quality and energy using linear models. The optimised volumes feed into the blending stage (for dried materials) to optimise the blending portion, and check for feasibility. Later, the optimised volumes are used as input data for the cost minimisation model for the whole system. If the final result satisfies the demand, the simulation ends, otherwise it starts again.

4.6.1. Linear quality models for the preparation process

The results presented are the composite values across six quality indicators, namely nutrient content, colour intensity, microbial content degradation, vitamin C, texture and shrinkage. The quality indicator for the microbial content moves into the opposite direction to all other indicators. Therefore, in order to make the optimisation more straightforward, a microbial content degradation has been considered, which moves in the same direction as the other indicators.

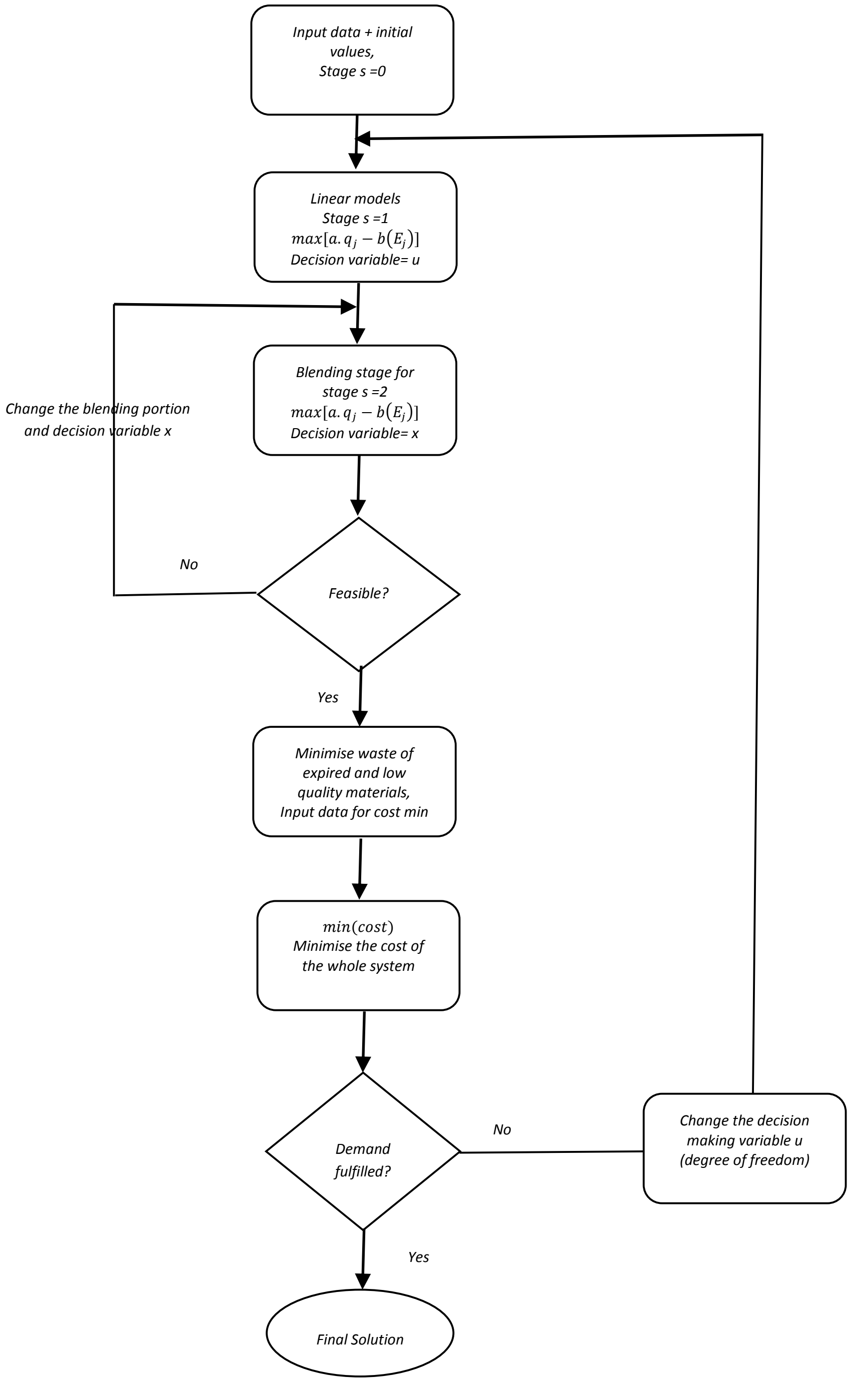


Figure 4-7 Flowchart for illustrating the structure of the model and the solution method

The linear quality model is applied to the preparation process in order to measure the quality changes for each quality indicator and to optimise it across all indicators. Equations from chapter 3 (3.1 to3.18) are used to measure the linear quality model parameters *A1, A2, B* and *C* (table 4.2, 4.3 and appendix A1). In this section, the linear quality model is applied to the three different processing types, which are then compared with the experimental data (figures 4.1-4.4).

Drying		Composite	Quality	
Parameters	A1	A2	B	C
Carrots Air-Dry	-0.00138	-0.000627918	0.15264	0.651169
Carrots Freeze-Dry	-0.00031	0.00039436	0.034917	0.948412
Potatoes Air-Dry	-0.00139	-0.000782786	0.053468	0.81067
Potatoes Freeze-Dry	-0.00048	0.000456018	0.040194	0.963796
Onions Air-Dry	-0.00078	0.000735388	0.111883	0.745207
Onions Freeze-Dry	-0.00028	0.001477636	0.074656	0.884355
Green Peas Air-Dry	-0.00154	0.002659455	0.047504	0.595988
Green Peas Freeze-Dry	-0.0005	0.001745912	0.107318	0.756771

Table 4-2 Linear model parameters for the composite of the quality indicators

Freezing		Composite	Quality	
Parameters	A1	A2	B	C
Carrots	-0.00011755	-0.000723204	0.104492	0.871867
Potatoes	-0.00015553	-0.000253211	0.103304	0.871961
Onions	-0.00097326	-0.003475735	0	0.661722
Green Peas	-0.00014739	-0.001354979	0.032536	0.933054

Table 4-3 Linear model parameters for the quality degradation

In figures 4.8 to 4.11, we analyse the quality degradation of the four products by changing the process degree of freedom for the air-dry, freeze-dry and freezing processes.

Figure 4.8 shows how the quality changes as a result of a change in temperature (varying u) whilst fixing the process time. In this figure, the process time is fixed at 2 hours and the process temperature varies, where the maximum temperature (u=1) is set at 70˚C for the air-dry process and at 40˚C for the freeze-dry process. The graphs indicate an increase in quality as the temperature increases, except for air-drying carrots and potatoes, where a small decrease has been observed. The increase in quality is expected, as a higher temperature for the same process time would generate a sudden temperature change in the material and the quality would therefore not degrade as much. Having said that, reducing the temperature helps the product to retain its nutrient and moisture contents, whereas shrinkage has been found to be directly proportional to the product moisture content. This is well observed in the case of the air-dry process, but not so much in the freeze-dry process because of the temperature difference. Since shrinkage and nutrient content in potatoes and carrots have a large effect on the quality, the figures show a small reduction in the overall quality as the temperature increases.

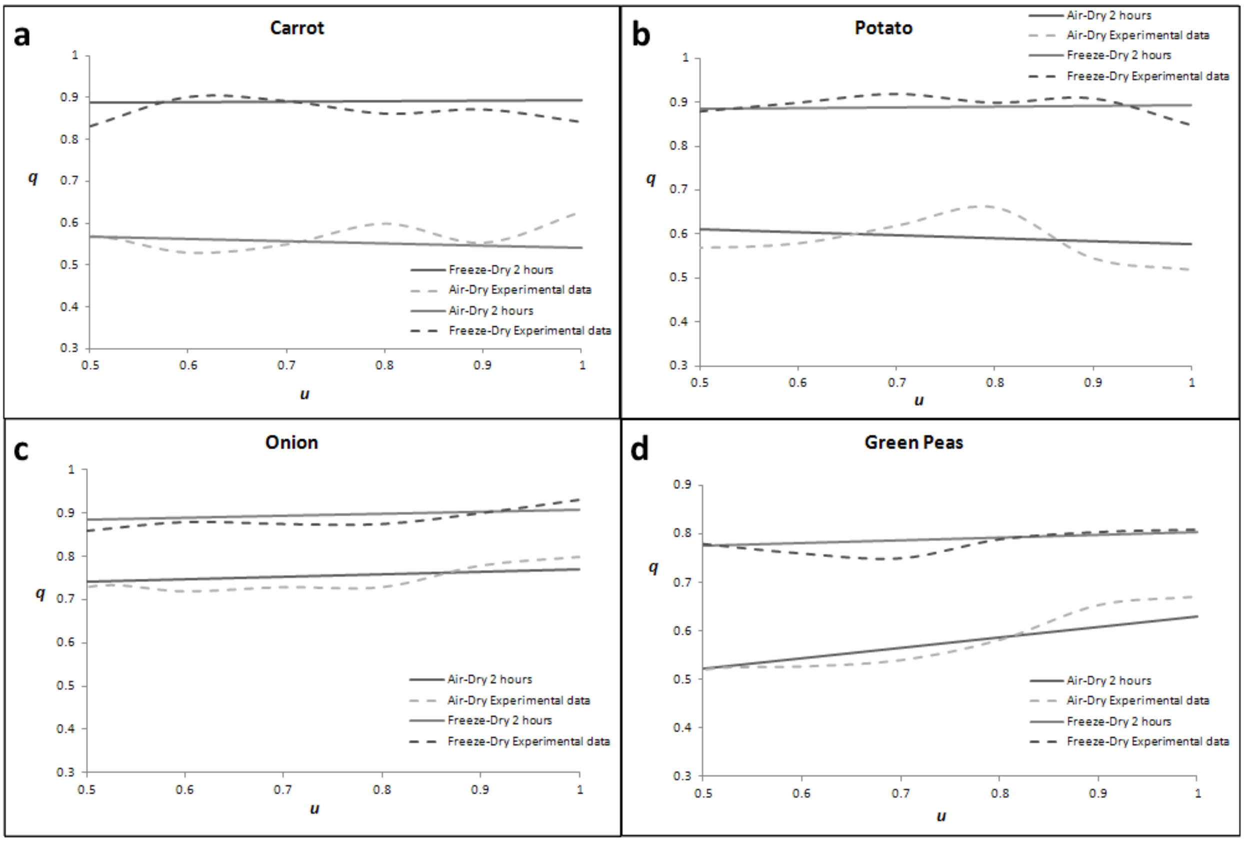


Figure 4-8 Linear model quality vs both the air- and freeze-dry process experimental data for a fixed processing time for (a) Carrots (b) Potatoes (c) Onions (d) Green peas

Figure 4.9 keeps the air-dry process temperature fixed at 70˚C and the freeze-dry process at 40˚C, whereby the variable process time u=1 is 2 hours. This figure shows that the quality of all four products degrades as the process time increases. This is because a low process time helps the material to retain most of its contents (e.g. nutrient and moisture contents) due to the high drying rate. Also, low temperatures and high drying rates lead to the development of more rigid and crispier material, which increases the crystallinity and crust on the product. Higher temperatures and lower drying rates, on the other hand, result in dense products.

For all four materials, the freeze-dry process is shown to lead to a higher quality product compared to the air-dry process. This is because materials are exposed to very low temperatures before being dried. This helps them to retain most of their contents (e.g. nutrient and moisture contents), which ultimately leads to higher quality. For instance, vitamin C is relatively unstable in regards to heat, oxygen and light. Air-drying would therefore lead to a large reduction in vitamin C content. However, no significant loss of vitamin C occurs during freeze-drying, due to the low temperatures.

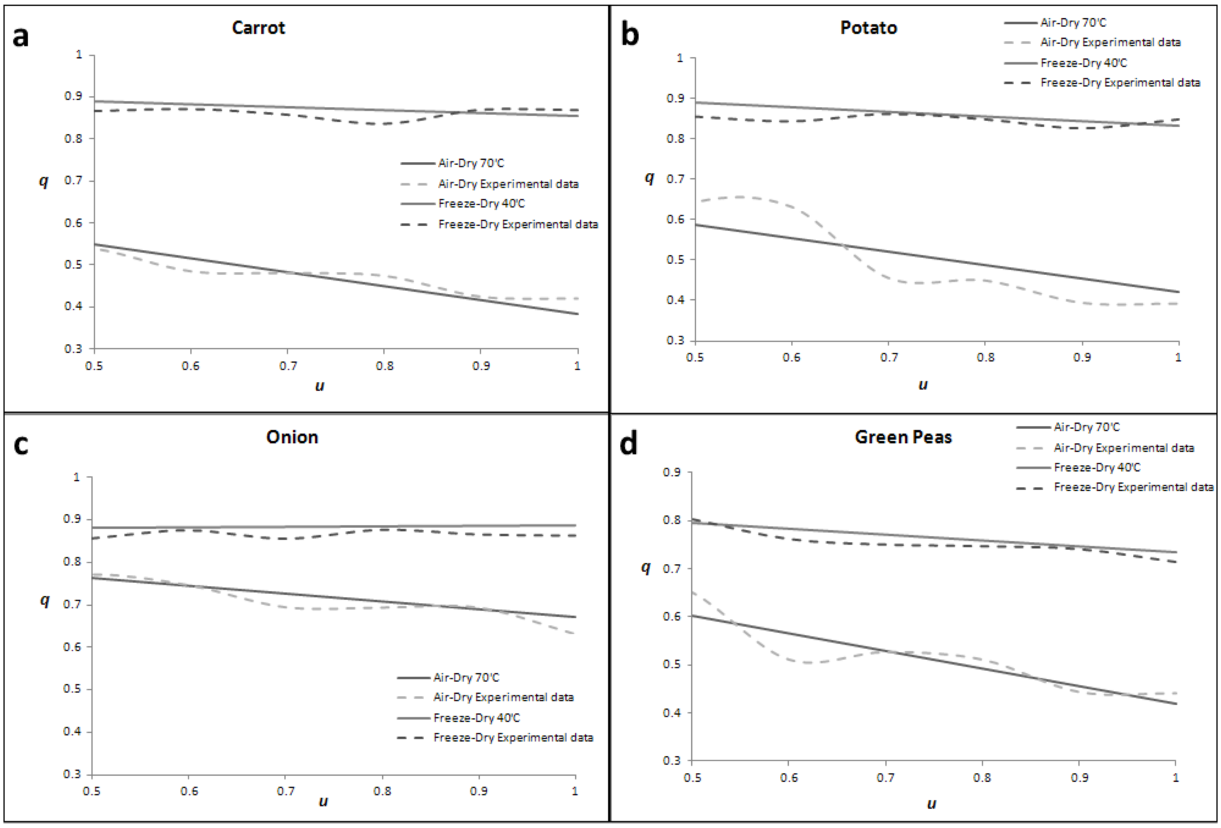


Figure 4-9 Linear model quality vs both the air- and freeze-dry process experimental data for fixed temperatures for (a) Carrots (b) Potatoes (c) Onions (d) Green peas

In figure 4.10, the process time is set to 2 hours with a variable process temperature, where the minimum temperature (u=1) is set at -25˚C. Figure 4.11, on the other hand, keeps the temperature fixed at -25˚C and makes the process time variable with the maximum time (u=1) set at 2 hours.

Figure 4.10 calculates the linear quality model and compares it with the freezing experimental data. This shows, how the quality indicators degrade for the different products as the process time and the temperature vary. All products except for onions show a quality degradation at a fixed temperature and with an increased process time (figure, 4.10). This means that for the slower process, all three products generate a better quality, whilst in the case of onions, the faster the process, the better the product quality. If the process time is kept constant, however, a lower temperature generates better quality results in all four products, which was expected (figure, 4.11). This is because a low temperature helps the material to retain its quality.

Across all three processes, the air-dry process shows the most degradation in regards to its microbial content. This is because a high drying temperature reduces microbial activities. Except for the microbial content degradation, the rest of the quality indicators are shown to have a higher quality if they undergo the freeze-dry or freezing process.

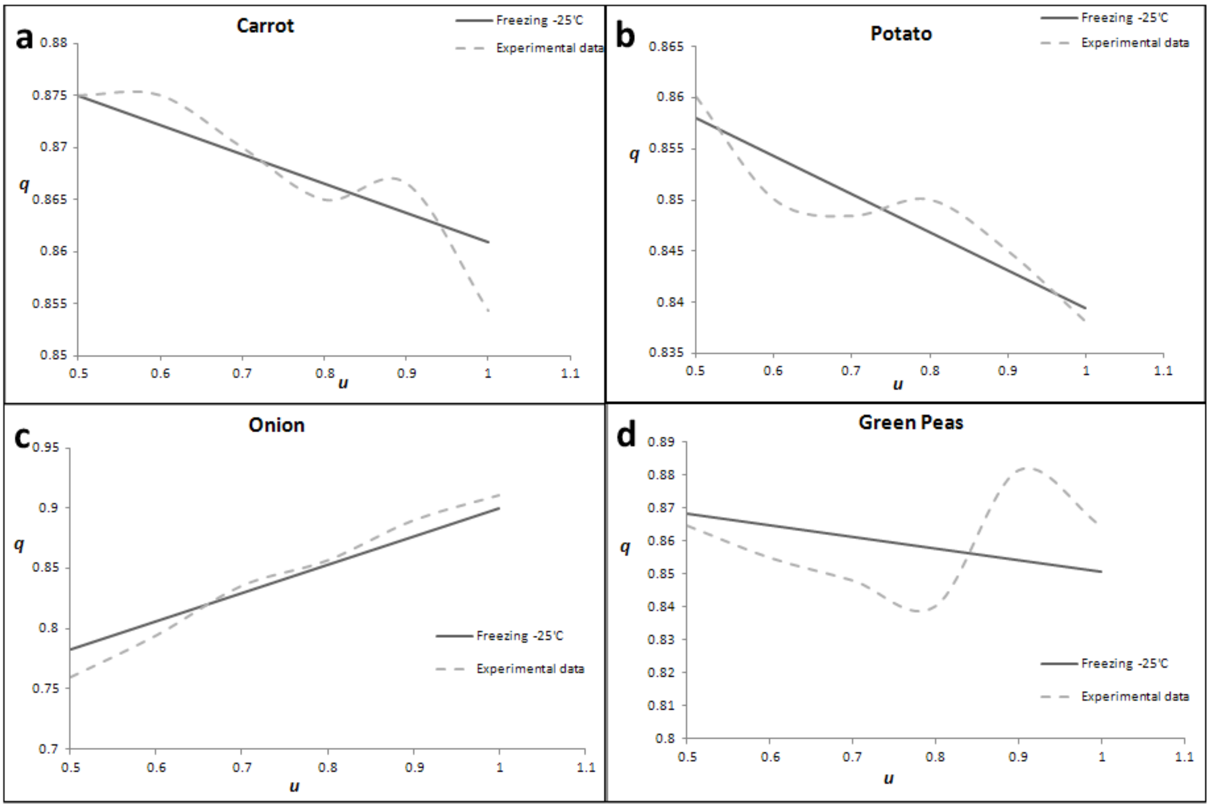


Figure 4-10 Linear model quality vs freezing process experimental data for fixed temperature for (a) Carrots (b) Potatoes (c) Onions (d) Green peas

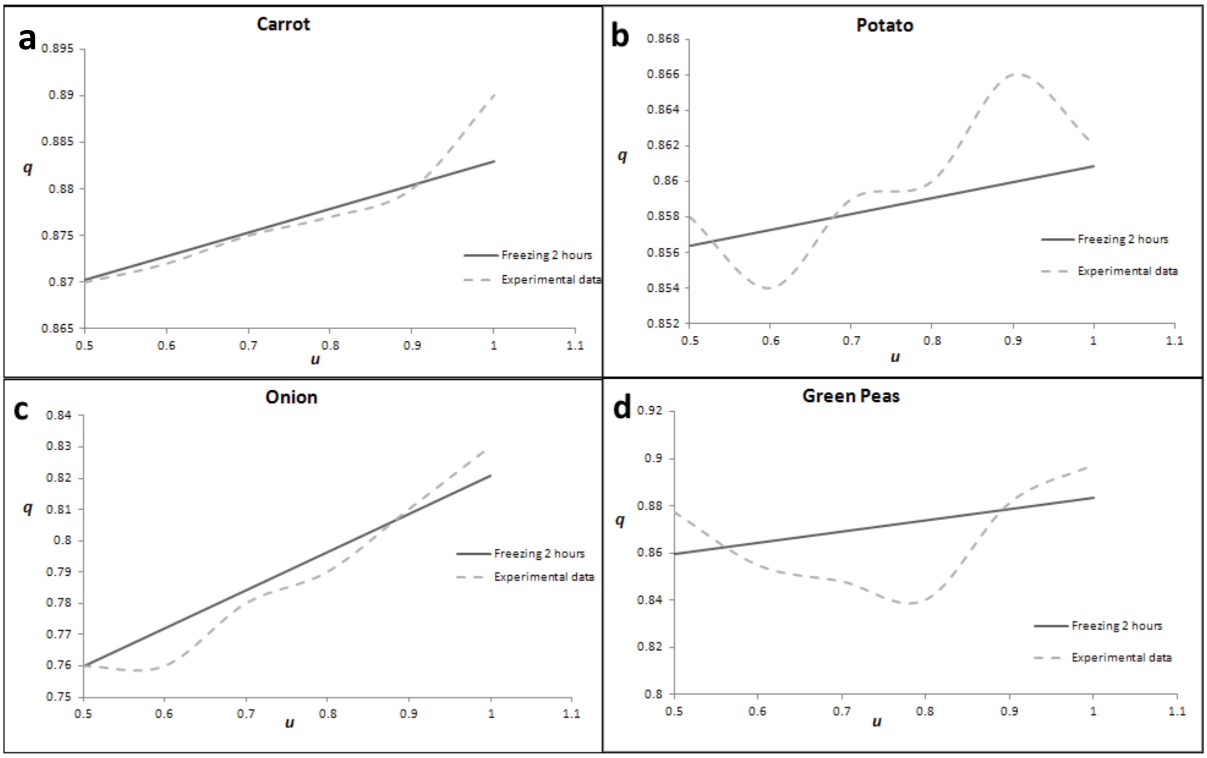


Figure 4-11 Linear model quality vs freezing process experimental data for fixed process time for (a) Carrots (b) Potatoes (c) Onions (d) Green peas

4.6.2. Integration of linear and energy models

In order to optimise the model with respect to quality itself, the model appears to indicate the use of materials that have undergone the freeze-dry process. However, in this report the quality and energy models are considered by and integrated into the supply chain system in order to optimise the costs, energy usage and quality. Equations 4.5 to 4.8 are used to measure and control the energy usage for each processing type. The parameters of these equations are calculated using equation 3.19, together with the experimental data (figures 3.8 and 3.9) presented in the previous chapter. The parameters for every processing type are shown in the following tables:

Material	**Potatoes and Carrots**		**a**
	a1	a2	Energy (base)
Air-Dry	-0.0416667	-0.1	18
Freeze-Dry	0.0416667	-0.2	45
Freezing	0.033333	-0.25	35

Material	**Onions**		**b**
	a1	a2	Energy (base)
Air-Dry	-0.025	-0.1	16
Freeze-Dry	0.0416667	-0.2	42
Freezing	0.05	-0.35	33

Material	**Green Peas**		**c**
	a1	a2	Energy (base)
Air-Dry	-0.025	-0.15	17
Freeze-Dry	0.03333	-0.1	43
Freezing	0.0416667	-0.3	34

Table 4-4 Energy consumption for all processing types for (a) Potatoes and carrots, (b) Onions and (c) Green peas (MJ/Kg)

Figure 4.12 shows the optimum u for equation 4.27 and the best process to work with. The shaded part refers to the frozen materials, which are not permitted to be blended with any other processed material. The bright section, on the other hand, shows the range at which the two processes can be mixed in order to generate optimum results. The model contains constraints, such as if $u_1 = 0.5$ then $u_2$must be at least 0.75. This means that if the processing time is at its lowest, the temperature cannot be at its lowest for drying and at its highest for freezing, and must be must at least 0.75 times the base unit. Also, a minimum quality constraint is added ($q_{min} = 0.7$). Given the constraints, the optimum solution is the purple area in figures 4.12.a, b and c and the red area in figure 4.12.d. The x-axis in figure 4.12 represents the variable set u for both the temperature and the process time (u_1, u_2 respectively).

Table 4.5 shows the optimal solution for the different materials for the variable u in the linear quality model for air- and freeze-drying, as well as for the freezing process. This set variable u indicates, what kind of relation of the degree of freedom (process time and temperature) should be used in order to achieve optimum quality across all indicators. Again, this information can be included in an overall planning model for cost minimisation with quality constraints.

	u	Carrots	Potatoes	Potatoes	Green Peas
Air-Dry Process	Process Time	0.5	0.583	0.5	0.5
	Temperature	1	0.725	1	1
Freeze-Dry Process	Process Time	0.5	0.5	0.5	0.5
	Temperature	1	1	1	1
Freezing Process	Process Time	0.5	0.5	0.5	0.5
	Temperature	1	1	1	1

Table 4-5 Optimal u used for different materials and processes

Except for air-drying potatoes, the optimum solutions for air- and freeze- dry processes appear to be high temperatures and low processing times, and in the case of the freezing process, the model suggests working with the lowest possible temperature and process time in order to achieve optimum product quality and energy.

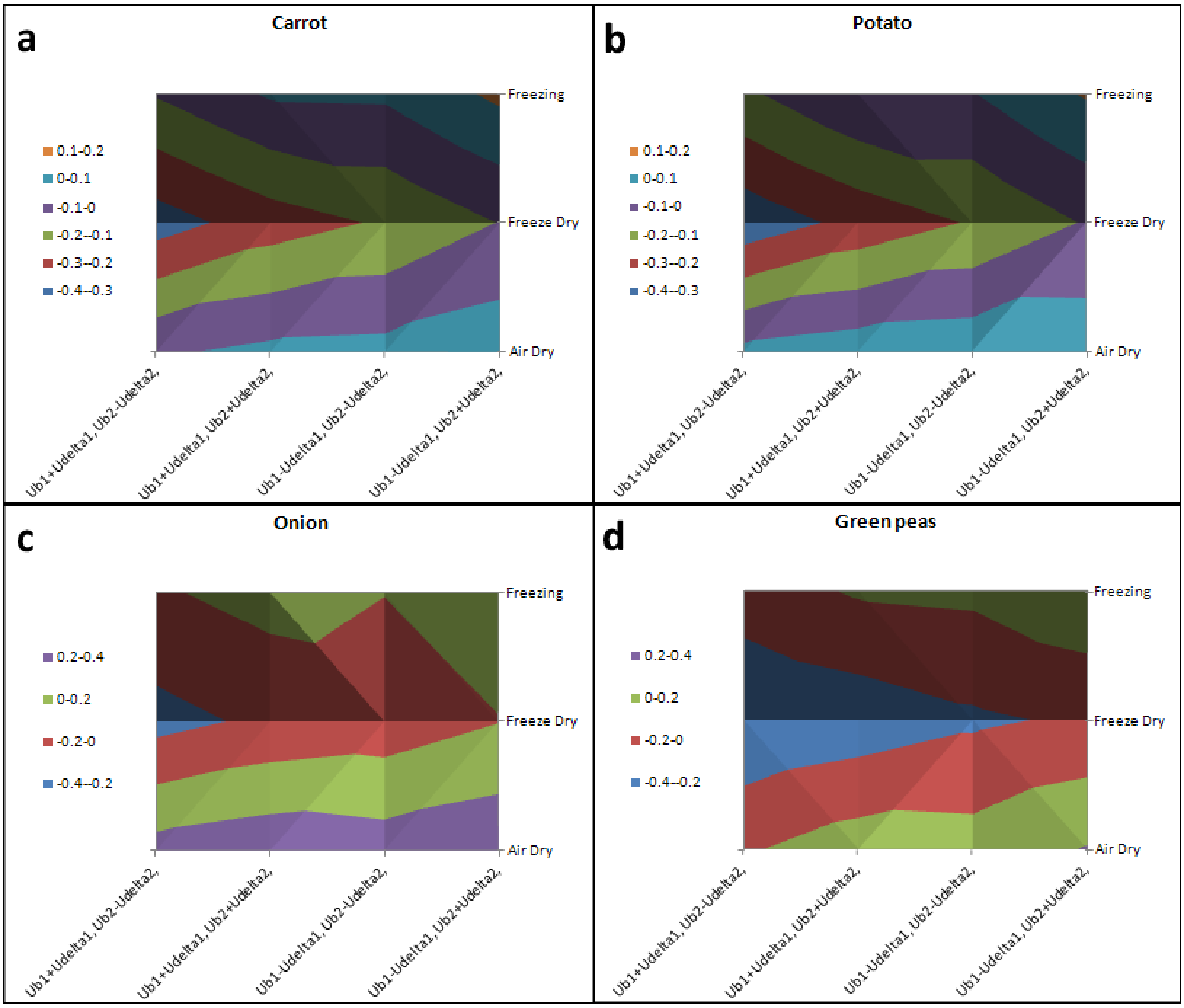


Figure 4-12 Results for different u and processing types by integrating energy and quality models

4.6.3. Blending model for the drying process

The parameters used for the blending model are shown in tables 4.6 and 4.7. Table 4.6 shows the composite correction factor for all of the products at different data points, and table 4.7 shows the slope between the two data points (M) for the composite indicators for all of the products (in the appendix, tables A2 and A3 show the parameters for the individual quality indicator).

Correction Factor			**Composite**			
Data point	0	0.2	0.4	0.6	0.8	1
Carrots	0.001309	-0.00275	-0.003258069	-0.0096	-0.00445	-0.00167
Potatoes	0.00257	-0.0028	-0.008117052	-0.01168	-0.00385	-0.00099
Onions	0.010422	0.000516	-0.004040153	-0.00514	0.002164	0.006621
Green Peas	-0.00116	-0.0057	-0.00458754	-0.00632	-0.00605	-0.00324

Table 4-6 Correction factor calculated for different materials at different data points

M	Carrots	Potatoes	Onions	Green Peas
Composite	-0.01617691	-0.017704458	-0.010449828	-0.019732735

Table 4-7 Parameter M calculated for the different materials

After having integrated the quality and energy models into the supply chain model, the model appears to suggest blending the products from the freeze- and air-dry processes according to the proportions given in table 4.8. Table 4.8 shows the optimum blending fraction for each material, where $x_a$represents the fraction from the air-dry process and $x_b$represents the fraction from the freeze-dry process. The optimum quality of all dried products across all indicators after blending is presented in figure 4.13.

Objective function		
Constraint	qmin	0.7
Blending fraction	**Xa**	**Xb**
Potatoes	0.6	0.4
Carrots	0.4	0.6
Onions	1	0
Green Peas	0.4	0.6

Table 4-8 Optimum results for blending

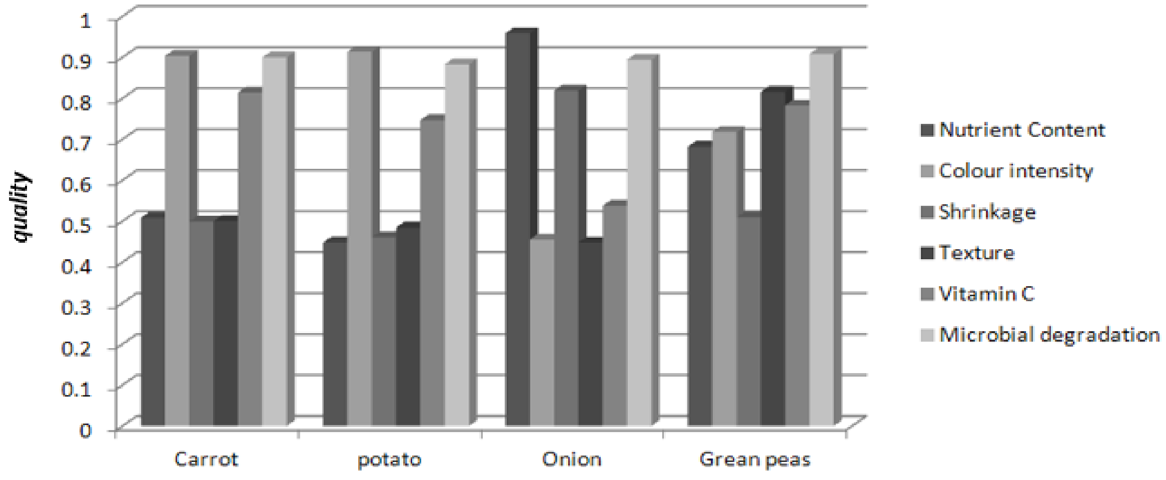


Figure 4-13 Dried product quality after blending

4.6.4. Comparison between the two preparation processes before and after blending

Figure 4.14 and 4.15 compare the quality and energy usage for both processes before and after blending the drying process outputs. The air-dry process generates lower quality products, but it also consumes the lowest amount of energy. The freeze-dry process, on the other hand, generates better quality products for most of the materials, but it also uses the highest amount of energy. After blending the two drying process outputs to obtain the optimal material in terms of quality and energy, the process is then compared to the freezing process. The green peas do not show much difference in regards to energy consumption during the preparation process and after blending the two processes. Onions show a similar quality both in regards to the drying and freezing process, but there is a significant difference in terms of energy consumption. The results indicate that the freezing process generates a better quality product. The energy used for carrots after blending is higher for the drying process compared to the freezing process. However, by going through the system, the downstream energy usage for the frozen material is much higher. This is because at the inventory state, the frozen materials have to be stored in low temperature freezers, while the dried materials can be stored at room temperature.

To conclude, the results for the preparation process show that the freeze-dry process generates the best quality materials, but it requires the highest use of energy, whereas the air-dry process requires the lowest amount of energy. Therefore mixing them would generate an ideal solution for products, combining good quality with relatively low energy consumption.

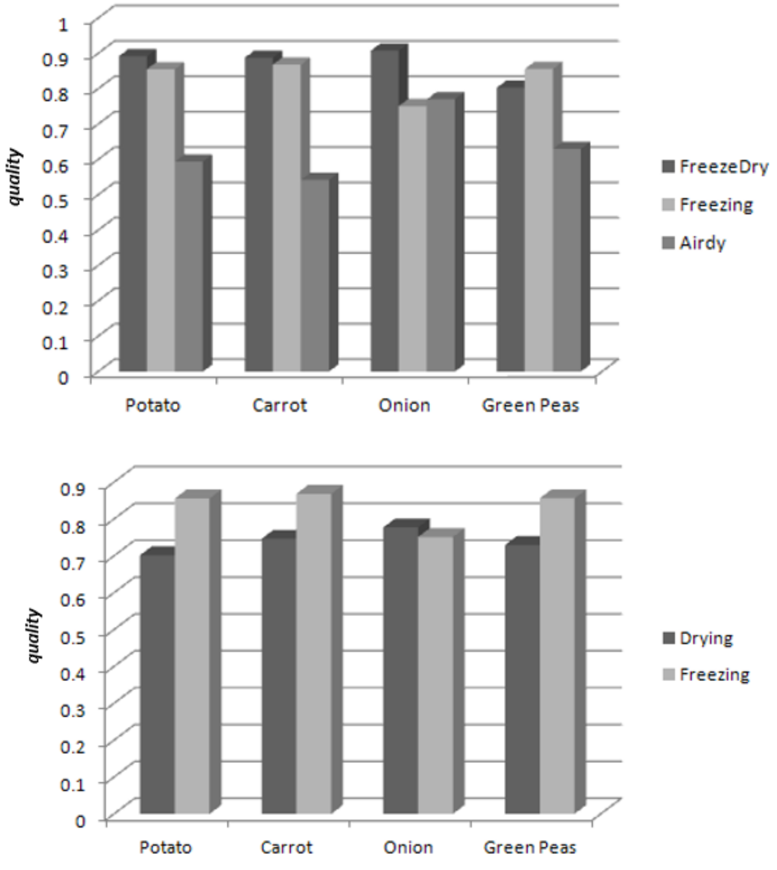


Figure 4-14 Quality degradation of composite indicators, top before blending and bottom after blending

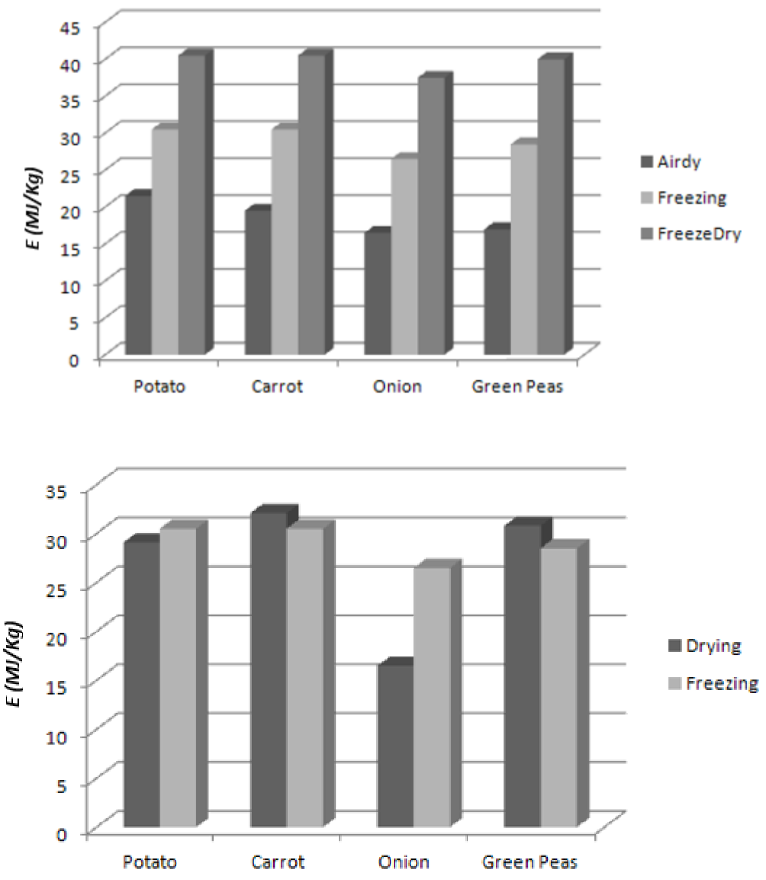


Figure 4-15 Energy usage for different preparation processes, top before blending and bottom after blending (MJ/Kg)

4.7. Comments

This chapter presented a mixed-integer linear programming model for food processing and manufacturing systems with a focus on product quality during the preparation process, which is strongly related to the degrees of freedom process (e.g. temperature and processing time). This is based on the quality degradation and energy consumption of raw material food products during the preparation process, in order to increase their shelf life and inventory. A new methodology is applied to simplify the existing models. It is a (*i*) linear quality model, which linearises the quality model and optimises the product quality across all quality indicators and is applied to the process, but could also be applied to the inventory. (*ii*) There is also a base delta model in order to relate the energy consumption for every process to the linear quality model. (*iii*) The blending quality and energy model, which indicates how much processes should be mixed in order to achieve a product with optimum quality and energy usage. These models add something new to planning literature, as they allow for the calculation of intensive variables (in our case quality indicators) associated with the material stages (and the dependence of these on the task's degrees of freedom), whilst retaining a linear model.

The quality and energy models have been integrated into a supply chain planning system in order to optimise the costing and wastage of a product throughout the entire system. The main contribution is therefore the introduction of a new methodology in order to simplify the ways of optimising quality and, in parallel, to control the product's energy consumption. Managing the product quality, energy consumption and controlling the temperature and processing time can be integrated into the decision-making process of the manufacturing system. Also, a number of interrelationships have been developed between the quality and the processing conditions. The model here presented is therefore a useful tool in regards to production and manufacturing planning in the food industry.

The first and second order kinetic models can apply to the long-term inventory stage, which is time and temperature dependent and changes the quality (Rong *et al.* 2011). However, the quality and energy models have not been applied to the inventory in this chapter, as there is only a short-term inventory, which assumes a negligible quality change and energy consumption. For the long-term inventory, however, these models have been applied. The project only presents the quality and energy consumption results for the products after the preparation process. However, these models can also be used for cooking and packaging, as well as for inventory purposes, in order to consider the manufacturing system as a whole in regards to supply chain management. The next chapter therefore considers these, as well as the effects of longer-term storage on quality and energy consumption in order to overcome seasonality problems, and how these issues affect the costs in regards to scheduling and planning an entire supply chain system.

Chapter 5

Supply chain planning and scheduling by integrating quality and energy models

In the previous chapters, a new methodology and mathematical models have been introduced and described. Also, we have shown how the parameters are calculated and how the variables are integrated in the supply chain system. The solution algorithms and optimisation methods have also been presented.

Storage, thawing, cooking and packaging processes for both frozen and dried materials affect the product quality and consume energy. Every process in the supply chain model affects the quality of the product. As a result, a supply chain model is developed, which is based on the interrelationship between the raw materials, the processing conditions and the final product quality. Moreover, based on the developed model, key factors in the whole chain are determined. Thus, the planning and scheduling model presented in this chapter enables a comparison of the two manufacturing systems based on optimum processing conditions and on obtaining maximum quality at minimum cost and energy usage.

5.1. Introduction

In order to overcome seasonality issues in regards to food manufacturing, it is essential for materials to achieve process flexibility. Flexibility can be classified in four different ways: volume, delivery, operational decisions and storage flexibility. A flexibility in volume and delivery is expensive and time consuming. Therefore, operational decisions and storage flexibility should be considered. Since these flexibilities require a shorter time horizon, Schutz and Tomasgard (2011) suggest using tactical or operational planning. In order to achieve storage flexibility, a preparation process is integrated into the manufacturing system to increase the shelf-life of the fresh raw materials, and therefore increasing the inventory flexibility.

The planning and scheduling in a supply chain is modelled in order to find the optimum solution for such flexibility. The challenge is to integrate the quality and energy models into a quantitative supply chain planning model for every stage, task and process. In this chapter, two manufacturing systems in food supply chains have been studied (freezing and drying preparation processes). The freezing process is set as a benchmark and the drying process is compared against it.

An STN formulation with a direct approach is used to plan the inventory time period and quality and energy models have simultaneously been included in the optimisation model. The STN formulation was initially proposed by Kondili *et al.* (1993). This formulation has been refined by Shah *et al.* (1993) in regards to the fixed time horizon, which is divided into known and equal time intervals. Fixed known equally sized time intervals are not realistic, and the required approximations may compromise the flexibility and optimality of the solution. A more realistic continuous time horizon has been used by many authors (e.g. Lee *et al.* 2002, Maravelias and Grossmann 2003a). Continuous time horizon formulations are hard to solve due to poor LP relaxations, and because of big-M time matching constraints. However, both the discrete and the continuous time STN formulations behave moderately well in regards to the cost minimisation objective function. In this work, the demand is fixed and known, and the objective is to minimise the production cost and the inventory for the fixed demands within given due dates. As Maravelias and Grossmann (2003a and 2003b) have shown, continuous time STN formulations behave poorly. They (2006) propose an algorithm based on a discrete-time STN formulation for the minimization of the make-span of multipurpose batch plants. Looking at a few examples, they demonstrate that this approach is computationally efficient for many problem groups and process networks. In the food industry, the demand is known and a short scheduling period is required. This thesis therefore uses a discrete time STN formulation and applies quality and energy models to it so that the quality and energy are controlled and optimised whilst overcoming seasonality problems by using a direct approach.

Whilst there are differences between companies, all food companies follow a similar path and business process. Having covered quality and energy consumption in regards to environmental issues in the previous chapter, this chapter reviews inventory management and manufacturing planning processes.

Inventory management: The overall demand is known and given, but it is seasonal. The inventory is therefore managed in order to overcome seasonality problems and to reduce waste produced by planning the manufacturing campaign.

Manufacturing campaign planning: Inventory management and production line planning to produce the right amount of products.

This thesis considers soup for exemplary purposes. The seasonality problem for this product is shown in figure 5.1. It demonstrates seasonal demand and supply, where a maximum demand and a minimum supply of raw materials can be seen during winter. The main question is whether to use frozen or dried materials for the product. There are advantages and disadvantages for both. In this report, we compare two production lines, one using fresh raw materials undergoing a freezing process, which later requires low temperature storage and a defrosting process, and the drying process, which dries raw materials and allows storage at room temperature. The interrelationship between the quality and the processing conditions have been defined. The quality models will be integrated into a supply chain model in order to enable a comparison in terms of quality and cost.

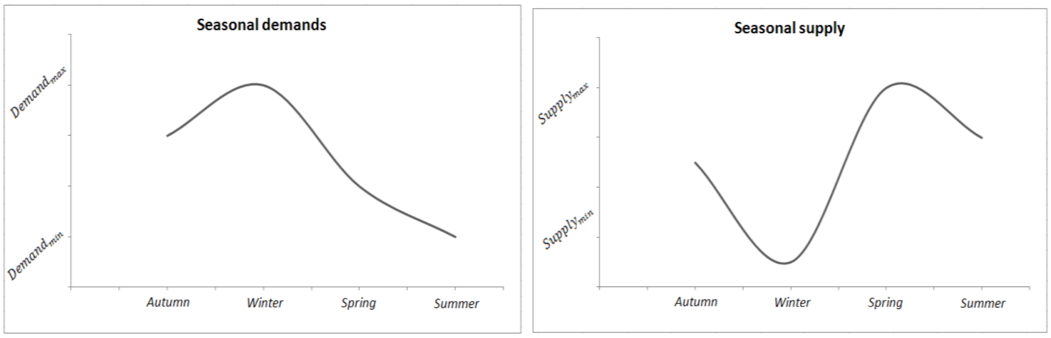


Figure 5-1 Seasonal demand (left) and seasonal supply of key raw materials (right)

5.2. System objective

In this chapter, a multi-objective problem is being presented. In order to tackle this problem, planning and scheduling models for both frozen and dried materials are being run. The systems are then compared based on all of the criteria shown in figure 5.2. Criteria are defined as below:

- Demand fulfilment: in order to see, which of the two system better fulfils consumer demand,
- Flexibility and seasonality: to see, if the system overcomes the seasonality or not. If so which of the two systems better overcomes the seasonality problems,
- Product quality: in order to measure, which system provides the best quality product,
- Product waste: to find out the system with lower product wastage.
- Energy consumption has also been added to the criteria list in order to measure and identify the system with the least energy consumption and of course with the lowest cost.

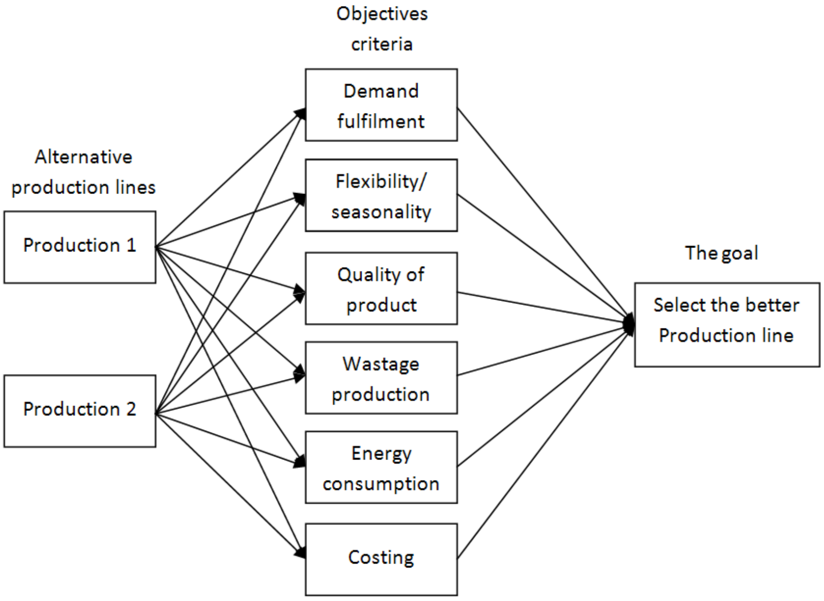


Figure 5-2 Comparison of objective criteria

5.3. Planning and scheduling

Storage plays a key role in the model, and the optimisation of the storage system is essential. This is because the inventory stage considers all of the criteria objectives presented in figure 5.2. The inventory stage affects the product quality and consumes energy. By optimising the inventory stage, the product benefits from flexibility in order to fulfil demand. It also minimises waste generated from expired products (due to first in first out constraints) and low quality products.

Raw materials are stored for some time before being used. The storage time is directly related to demand and indirectly to quality and energy consumption for optimisation purposes. At this stage, planning and scheduling for the supply chain model is applied in order to measure how long the materials should be stored for until they meet the demand. Here, a rolling horizon method is used for the planning interval of the material’s shelf-life.

The rolling horizon method considers three periods (the past, planning intervals and the future). The past is known and contains information, which could feed into the model as input data. The planning interval refers to the given data (in this case the material's shelf-life) and the future is the unknown part of the horizon.

The past and the future must match in regards to the time period. This is the period by which the horizon is rolled forward (in this case one week). After each rolling forward, the future will be in the planning interval, and one period in the planning interval will be the past, which will then be the input data in order to help forecast the future (figure 5.3).

In this thesis, we have defined a time period of one week for the rolling horizon, where the materials are fed into storage every day except for weekends and official holidays. Then, the window rolls forward by one week.

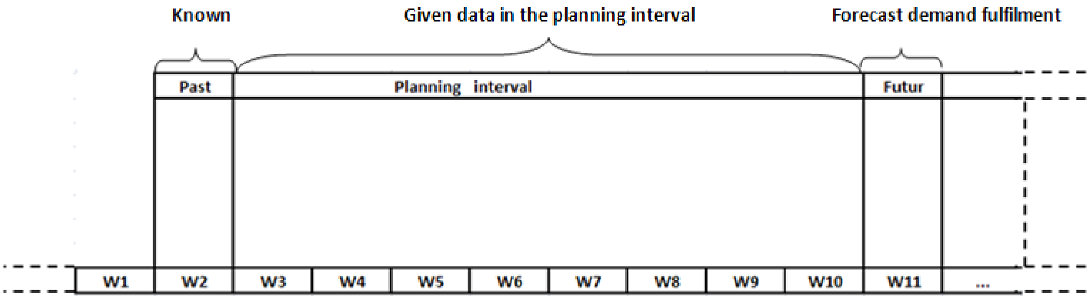


Figure 5-3 Rolling horizon

5.4. Quality and energy measurement

Quality

The quality of the materials differs depending on the season. During winter, lower quality raw materials are used, as there are no fresh raw materials. The raw materials used in winter are usually frozen or dried. The best quality raw materials, on the other hand, are used during spring. Figure 5.4 shows the initial quality of the raw materials used in this work during the different seasons. The data stems from the "Food Engineering Handbook" (Heldman *et al.* 2007 and Laboza, 1982).

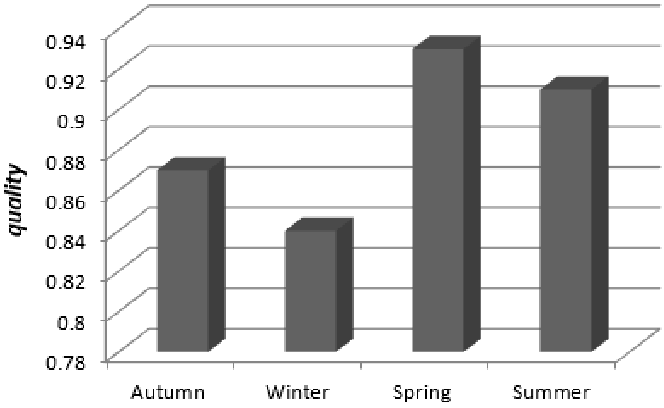


Figure 5-4 Initial quality of the raw materials used during the different seasons, where the y-axis represents the initial quality.

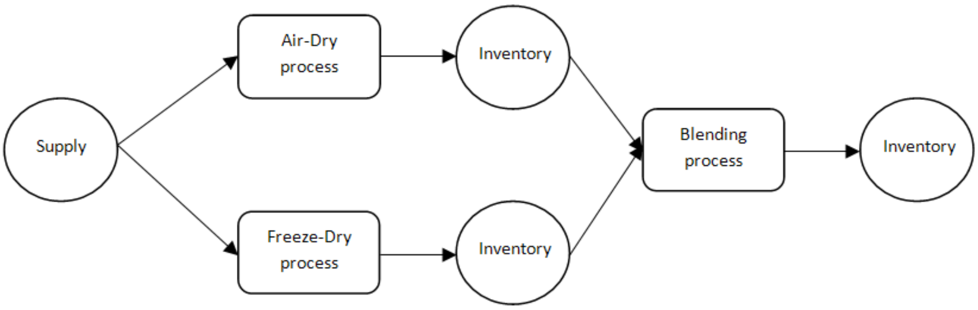


Figure 5-5 Drying process

Dried raw materials

The fresh raw materials undergo a drying process before being stored in the inventory. According to the model, the drying task combines two different drying process types, namely the air- and freeze-drying process (Fig, 5.5).

Both linear and non-linear blending quality models (4.1 – 4.4), as introduced in the previous chapter, are being used to measure, control and optimise the quality of the materials. As mentioned in chapter 3, experimental data and regressions based on the kinetic models are used for the parameters.

Frozen materials

In this work, temperature plays an important role. The Arrhenius equation is therefore essential and the kinetic models (equations 3.2 – 3.10) are an appropriate means of measuring quality. However, the first order kinetic models would lead to non-linearity problems. Linear quality models (equation 4.1) are therefore being applied to every task and stage in order to quantify the quality degradation.

Energy usage

Adding a freezing and/or drying process task would have a significant effect on the energy usage. The blending stage, however, which follows the drying process, allows us to use portions of products from each drying process, so that the products have balanced energy consumption and quality. Later, the dried materials are stored at room temperature in the appropriate storage facilities. The energy usage is negligible in this respect. The frozen materials, on the other hand, are stored at a low temperature. The inventory stage uses energy in order to keep the temperature as low as necessary for some time before proceeding to the production stage, where the materials are defrosted before being used.

The drying process uses electrical power in order to dry the materials, and during the freezing process, the temperature reduction will affect the costing. In the following subsections, different models are used to measure the energy usage of each production line.

Dried raw materials

The energy consumed for dried materials at each stage is measured using the energy equations in chapter 4 (equations 4.5- 4.8), the parameters in equation 3.19 and the experimental data in chapter 3. In order to calculate the total drying process cost, the energy consumption is multiplied by the energy unit cost.

Frozen materials

The energy cost for the fresh raw materials depends on the temperature. In order to determine the costs, thermal characteristics are taken into account. The performance coefficient (COP) is used to measure the costing (Wang *et al.* 2010).

$$COP = \frac{Q_L}{E} = \frac{T_L}{T_e - T_L} \tag{5.1}$$

Where Q_L is the heat transferred from a lower to a higher temperature, E is the input energy. T_e, T_L are the environment (room) and the lower temperatures. For instance, if the room temperature is 293 K and the lower temperature is 275K, then the COP is 15.3. This means that for every unit of energy from an electrical source, 15.3 units of heat are absorbed from the product by the freezer. In this report, 275K is set as a base unit in order to measure the optimum solution for shelf-life extension and energy usage. For example, if the product temperature should be reduced to 277K, then the COP is 17.3 units and the ratio variance between this and the 275K is 0.88. The cost for the 275K energy usage is known and fixed, whereas the energy cost can be calculated and compared with the drying process energy costs. Note that this cost is the theoretical minimum. We do not consider efficiencies at this stage, as they involve a trade-off against capital cost and the main purpose of this work is to draw insights and to demonstrate the benefits of the model, rather than to make a specific recommendation.

5.5. Modelling supply chain systems

The key elements are processing, manufacturing and inventory systems, and the model concentrates on manufacturing and inventory systems. Waste is caused by products below the minimum quality, as well as by products whose shelf-life has passed. Waste control is therefore a key objective in this model, and the key variables for the formulation in regards to controlling waste levels include: the production level with regards to the quality, where u is a key variable, as well as the inventory level with respect to the shelf-life and the product quality, where the production and outflow (consumption) are a key variable in addition to u. These are determined in order to optimise the model for the given objectives subject to inventory, production, mass balance, cost, quality and demand constraints.

Storage after cooking is intended to cool the cooked materials before packaging, as packaging at high temperature will affect the product quality. This cooling process, however, requires energy consumption.

Quality and energy usage during the first inventory stage are negligible, as the product is only held for a short amount of time, and only the second inventory stage affects the quality of the product.

The model considers two manufacturing systems (Fig 5.6) and compares them after their optimisation based on energy and product quality. Both systems attempt to overcome the seasonality problems by freezing and drying the raw materials. The planning and scheduling model measures the periods over which the materials are stored in order to overcome the seasonality problems. Parallel to this, the model optimises the system quality, energy consumption and overall cost. For planning and scheduling purposes, a one-year rolling horizon with planning intervals for the life-time of the frozen/dried material and a time horizon of two weeks plus the planning horizon are being considered.

The model uses soup as an example, and four raw materials have been considered: carrots, potatoes, green peas and onions. The raw materials are purchased and kept for a few weeks, which is inventory stage 1. This first inventory stage is usually a long-term inventory before cooking. In the case of dried raw materials, the storage could last up to a few months at room temperature. Frozen raw materials, on the other hand, are stored for only a few weeks before cooking, as otherwise they will expire. Frozen raw materials are kept in a low temperature freezer. The fresh raw materials are stocked up every day in batches, except for inactive days, such as weekends and bank holidays. The initial quality of each batch for the main product ingredients is mostly at 0.9 for green peas, 0.91 for carrots and potatoes and at 0.88 for onions.

The key objectives of the model are as follows:

- Relate the quality of the output material to the quality of the input material
- Relate the quality of the material to the degrees of freedom process
- Relate the seasonality problems to the process
- Ability to plan for demand fulfilment by using the rolling horizon method
- Maintain model linearity
- Relate energy usage and material waste to the quality model

Model assumptions

The following assumptions have been made in the current model:

- The materials, which satisfy the quality requirement, leave the task, and the leftovers are considered to be waste, and added to the disposal cost.
- A single, aggregated supplier of raw materials is used (this does not affect the core problem being modelled).
- Only one manufacturing system is considered at a time.
- Product storage and inventory are available at every stage.
- The inventory stage directly after the preparation process shows negligible quality changes and energy consumption.
- There is a short inventory after the cooking process, which does not affect the quality of the product and does not disturb the shelf-life constraint.
- The packaging process only affects the cost and not the quality of the product, due to a very short processing time after the cooking process.
- The fraction of each batch leaving the inventory (β) is assumed to be 1.

The goal of the project is to develop a new technology for existing production lines in order to meet consumer demand in terms of quality and quantity. This model has to meet the demand for good quality at the lowest possible cost.

The overall problem can formally be described as:

Given:

- The time horizon
- External demand and sales prices
- The available units and storage, and their capacities
- The production recipe (mass balance coefficients)
- The amount of available raw materials and their delivery times, as well as their price
- The initial quality of the raw materials
- The processing and production data (production rate, cost and time, as well as quality model parameters)

- The minimum product requirement
- The minimum quality of the product acceptable to consumers

Determine:

- Production plan and degrees of freedom process
- Inventory policies
- The product quality following each task
- The production quantity of each task
- The final product quality and quantity.

In order to optimise the given multi-objective problem (minimising cost and energy consumption and maximising quality) the demand needs to be fulfilled.

The model concentrates on manufacturing and inventory systems. The key variables for the formula to control waste levels include: a production level with respect to quality, where u is a key variable, as well as an inventory level with regards to the shelf life of the product, where the production rate is a key variable. These are determined in order to satisfy consumers, subject to the inventory, production, mass balance, cost, quality and demand constraints. The discretisation approach is used over a one-year time horizon of 52 weeks in order to facilitate the mathematical formulation.

Mathematical modelling

The multi-objective function aims to optimise the quality of the production by minimising the cost and energy usage of each manufacturing system and by comparing the two systems by running a rolling horizon algorithm for the planning and scheduling models in order to increase the flexibility of the materials and to fulfil the demand. For this model, the following two considerations have been integrated into the model

- $CARD_{\mathrm{t}_0} \leq CARD_t, \forall_t$ is required to generate an optimum and feasible solution. The direct approach increments the time in the time-related models in order to reach to the feasible optimum solution, which could be local or global.
- $\tau_l = 1$ if the production line l is chosen, otherwise 0.

Freezing requires additional energy consumption for thawing materials, where the quality of the frozen materials degrades very fast. At the cooking stage, the energy consumption and quality for both processes behaves in a similar fashion.

Here, the quality and energy models from the previous chapter have been used. The first objective is:

$$Obj = max[a.q_j - b(Energy_j)] \tag{5.2}$$

The decision variable for the objective function is u. Therefore, the model finds the optimum solution by changing the u variables. However, at the first stage of the preparation process, the outputs of the two different drying processes can be blended together, in order to generate a better material quality and in terms of energy consumption. A blending model has therefore been introduced in regards to quality and energy. For this model, the objective function is the same as before, but the decision variable is *x* instead of *u. x* shows how much the two processes should mix in order to generate an optimal solution in regards to the material.

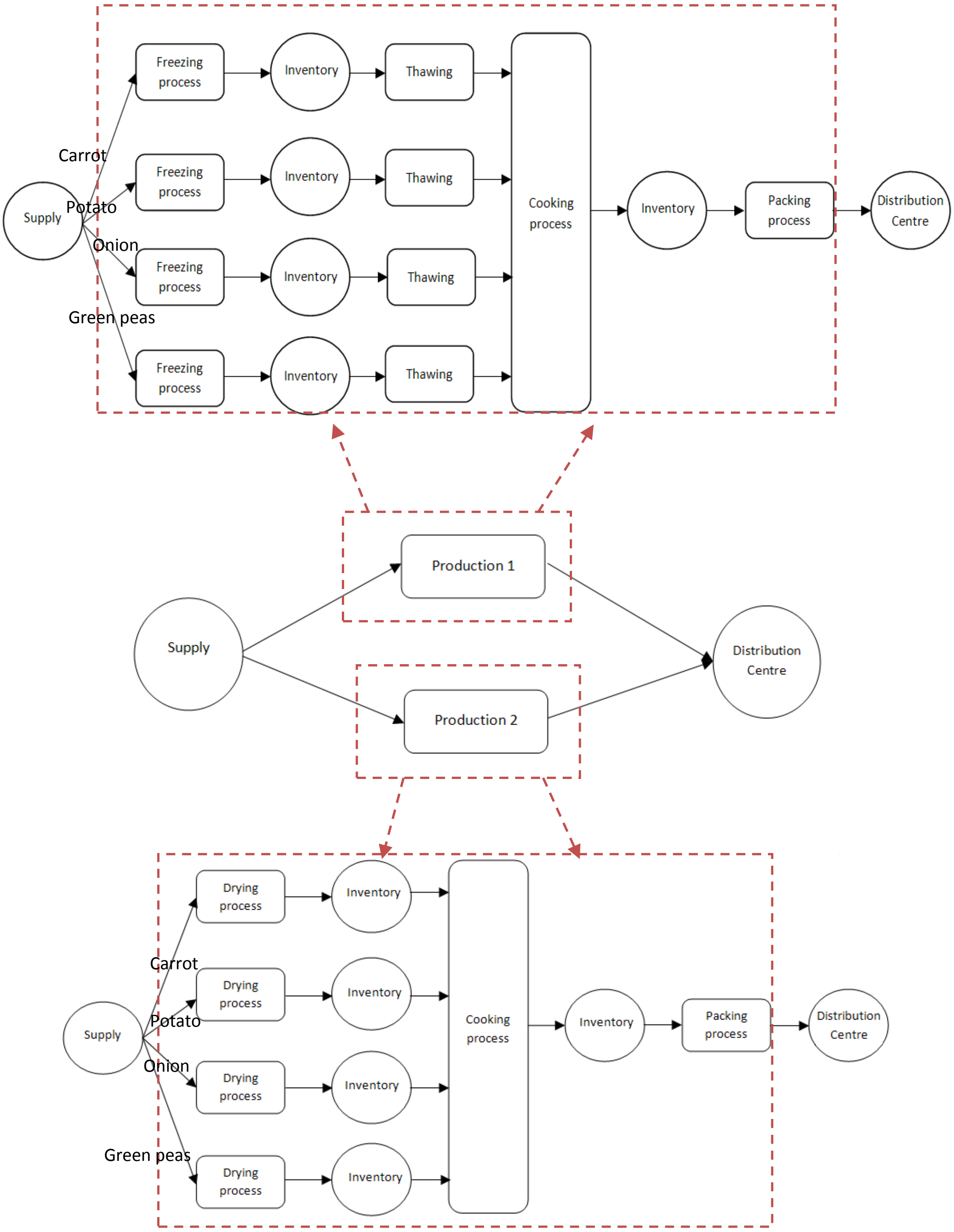


Figure 5-6 A system using frozen raw materials (production 1) and dried raw materials (production 2)

For the first period of the preparation stage, the model suggests to use 100% of the freeze-dry materials, however, after inventory and storing the materials for some time, the model suggests to use some air-dried materials. This is because the quality degradation of freeze-dried materials is higher compared to air-dried materials. Hence, the blend fractions can be a function of time.

The model also shows that for the preparation process, the freezing process is the optimal one of the three, however, this changes after the inventory stage, as the frozen materials degrade much faster in regards to quality than dried materials. Storing material in the freezer also requires additional energy.

Direct approach:

The model is applied to the whole supply chain system. In order to solve this, we have used a direct approach and have broken the problem down into a number of steps in order to simplify the problem.

First, we optimise equation 5.2 for the linear quality model, the energy model and the blending models at t=0. This is done over a one-week time period and the optimum solution is fed into the second step of the inventory plan in order to optimise the expired materials and waste model.

During stage 2, a rolling horizon method is used in order to check the feasibility of the solution over a time period of 8 weeks (figure 5.7). In the case of infeasibility, the model is incremented by one time period and started again. This means that the rolling horizon method results in a time period, which pushes the final product into a feasibility region. The feasible region is generated by the constraints set in the model. The results are then fed into the main objective (cost minimisation for the whole supply chain system), which is calculated over a one-year time horizon. The system checks for demand fulfilment. If the demand has not been fulfilled, the process is repeated, but with a different time horizon in the rolling horizon method. Once it is feasible, the process is stopped (figure 5.8).

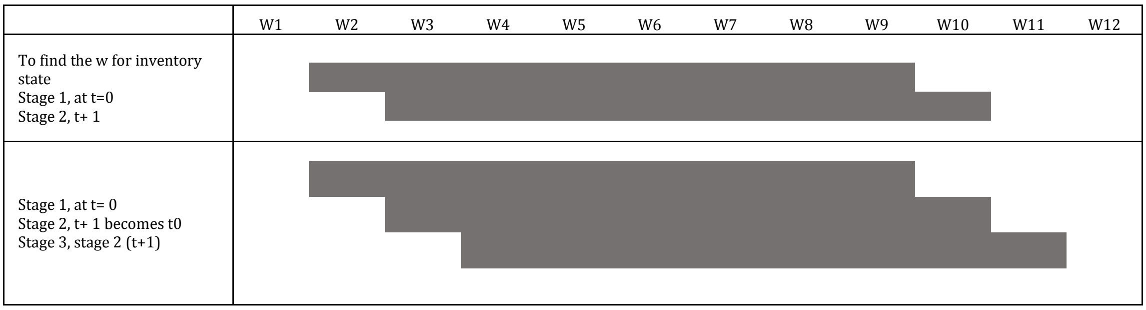


Figure 5-7 Solution method (rolling horizon)

The steps taken in the overall “direct” multi-objective approach are as follows:

Objective 1,

Step 1) Use the linear quality and energy models to optimise them with regards to *u*.
Step 2) Use the blending quality model and energy models and optimise them with regards to *x*.

Objective 2,

Step 3) During the first time period, find the maximum value for factor *w* in order to find an estimation of the appropriate time interval, where *w* is the inventory time period. This model states for how long the product should stay in the inventory stage after the preparation process and before entering the next stage in order to achieve maximum quality and minimum energy consumption.

Objective 3,

Step 4) Minimise the waste produced through expired materials and based on quality (after setting a minimum quality constraint).
Step 5) If the results are not feasible, increment the time interval and repeat step 4.

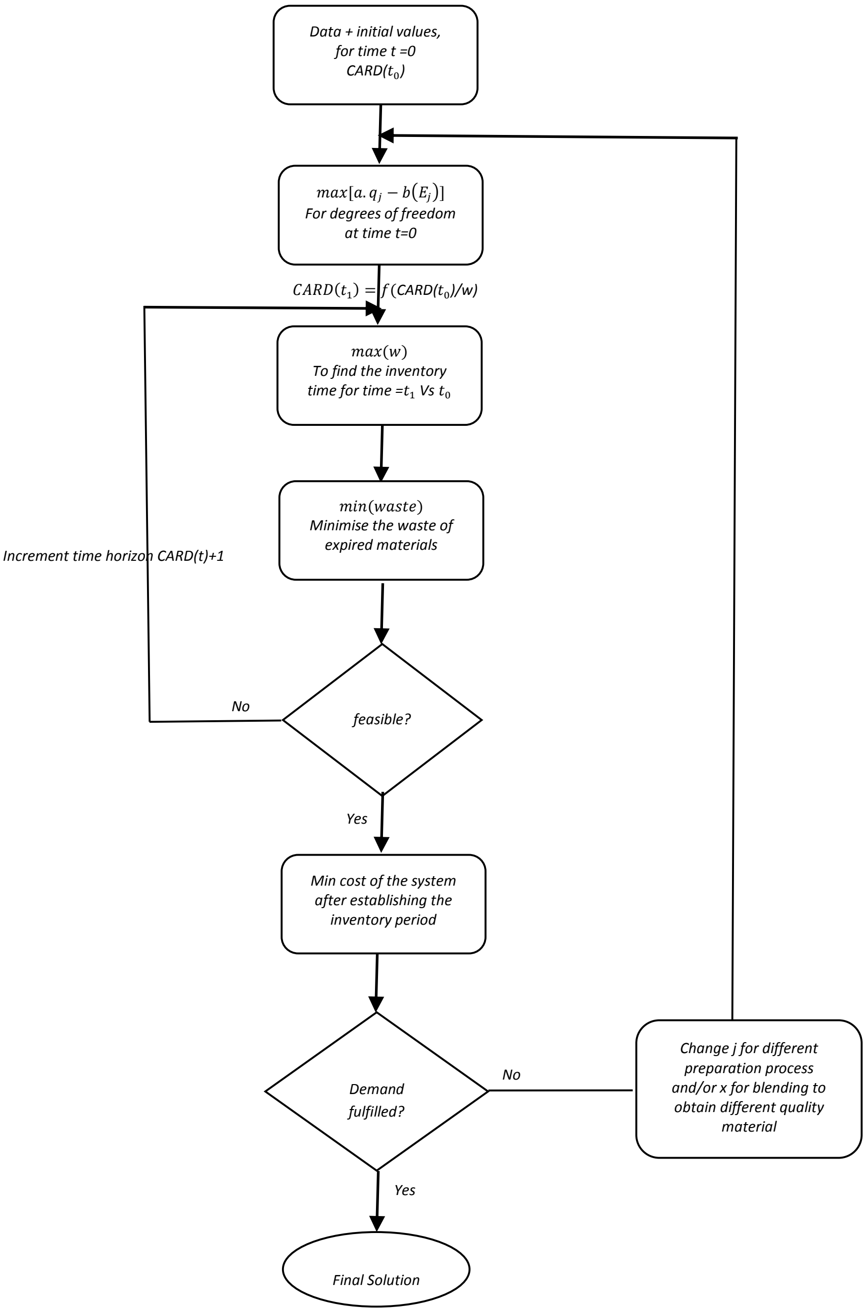


Figure 5-8 A flowchart illustrating the structure of the model and the solution method (direct approach)

Objective 4,

Step 6) If the results are feasible, minimise the cost model.

Step 1 applies to all stages, while step 2 only applies to the preparation process. The following feasibility questions have to be checked:

- Do we fulfil the demand?
- Does the quality satisfy customer expectations?

5.6. Discussion of the results

Initially, the model suggests freezing materials at -70^{o}C, however, after the first inventory stage, the model updates the temperature to -35 ^{o}C for freezing purposes. This is because the inventory process lasts approximately three months on average and when comparing energy consumption and product quality this new temperature is suggested (Figure 5.9).

For the best local minimum cost in regards to energy consumption and quality, a number of graphs have been generated (Figure 5.10 to 5.12). Figure 5.10 shows the energy consumed after each stage for each process type (dried and frozen). It clearly shows that the highest energy for both process types is being consumed during the preparation process, whereby the freezing process consumes more energy than the drying process. The other big difference between the two process types is in regards to the inventory stage, where the energy consumption for the dried materials is almost negligible, whereas the freezing process uses energy in order to keep the materials cool. In this figure, stage-1 is the initial stage, where the fresh raw materials feed into the preparation process (state-2). State 3 is the first inventory stage (right after the preparation process). This is a short inventory process. Stage-4 is the cooking process followed by a longer inventory (stage-5) and packaging (stage-6).

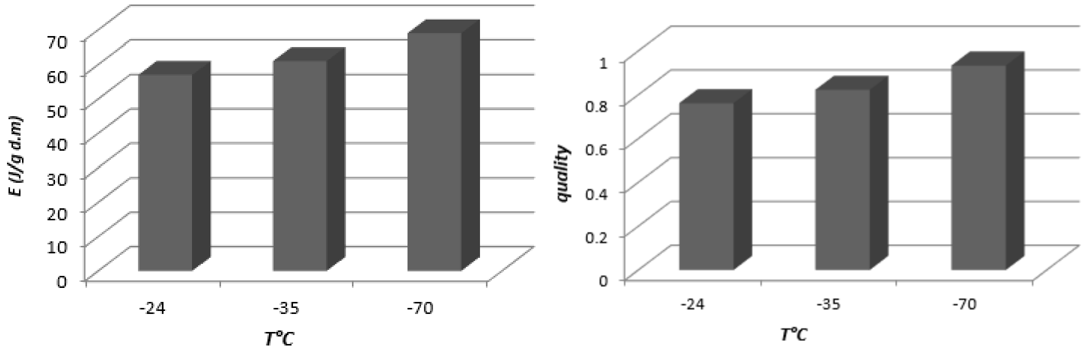


Figure 5-9 Energy usage and quality change in regards to the freezing process

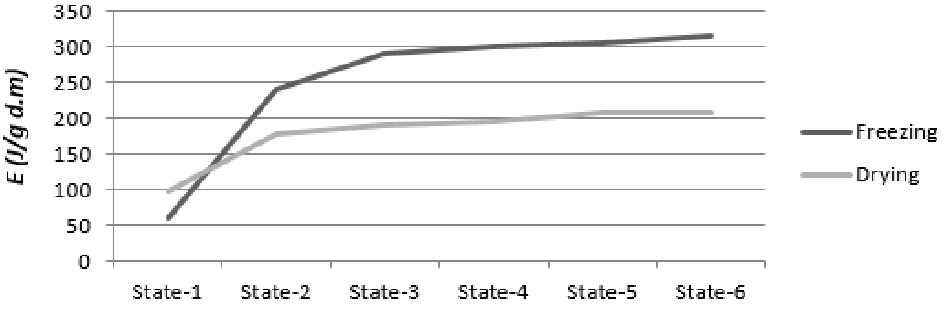


Figure 5-10 Energy consumption (J/g d.m) by production line

Figure 5.10 and 5.11 show the quality degradation for all four products throughout the system, both for the freezing and the drying process. The figures suggest that by using the freezing process, a slightly lower quality final product is achieved compared to dried materials. The initial quality for both processes appears to be equal, but the materials after the preparation process are of higher quality when undergoing the freezing process. It should be mentioned here that the drying process takes advantage of the blending stage, where both air- and freeze-dried materials can be blended.

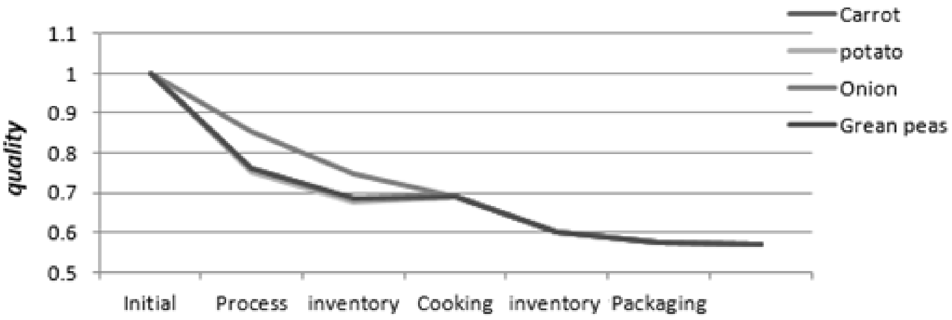


Figure 5-11 Quality degradation during the freezing process

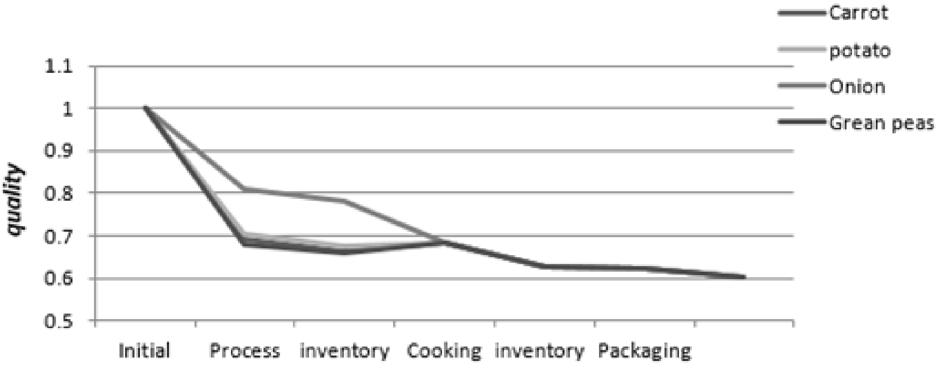


Figure 5-12 Quality degradation during the drying process

In summary:

- All of the input data stems from existing literature and by contacting the relevant partners or as generated from the models shown in chapter 3.
- Quality and energy models and graphs can be used to show every stage's quality degradation and energy usage.
- Seasonality problems are overcome by both processes, but freezing requires significant amounts of energy for the long inventory periods. The model suggests storing the materials at -24°C for three months, so that the quality degradation and energy consumption can be optimised.
- The four materials considered are green peas, onions, carrots and potatoes
- When combining all of the materials, we obtain an overall quality: $q_{product} = \sum_A q_A . x_A$; this is a linear function. The portion for each material in the final product is provided by a proposed recipe.
- There is a further step for frozen materials in the pre-cooking stage. The frozen materials must be thawed before cooking.
- The recipe is assumed to be fixed.
- Energy usage is variable. Since the processing of potatoes requires the most energy, the smaller the potato portion, the higher the quality and the lower the energy usage. The energy for the cooking process is proportional to the time taken for the potato to cook.
- Shelf-life wastage is zero, because the shelf-life range is considered to be large enough to avoid the material's expiry with the planned energy cost, which plays a role in regards to

quality in the end (in the case of freezing). Waste is therefore only produced due to the minimum quality constraint.
- The lower the freezing temperature, the higher the product quality, however, the quality difference is small compared to the required energy usage.

In ordered to solve this, the model has been implemented into AIMMS in combination with CPLEX optimisation software. The test runs have been performed on a 2.66 GHz Pentium 4 PC (with 3.49 GB of RAM).

The optimisation runs have been carried out by discrediting the entire system (between 120 to 180min) into a number of intervals, 9 in this case, and by using the feed rate as a decision variable for each interval. Subsequent considerations have resulted in the reduction of the time frame, in which the feed rates have been manipulated, together with the reactant feed rates, which have been set to 0 towards the end of the system in order to take the distribution out and to end the process after the packaging / inventory stage. Having a constraint, which stops the simulation when a feasible local optimum has been hit, has reduced the number of iterations. However, because of this constraint we have had to run the simulations more than once, in this case 18 times, with different input data in order to compare the results and to find the best local minimum.

The dried materials are stored at room temperature, where the quality is not significantly affected. The fresh raw materials, on the other hand, are stored at a low temperature during the inventory stage. The inventory stage uses energy in order to keep the temperature as low as required. During this stage, the quality of the product is also affected. During the cooking process, the dried materials cook easier and faster than fresh raw materials. This also leads to lower energy usage during the cooking process for dried materials compared to fresh raw materials.

The waste produced due to the shelf-life constraint has been optimised and the model suggests a 3 month inventory for dried products in order to overcome this problem. This will reduce wastage due to the shelf-life constraint to close to zero. β is active, which affects the capacity constraint. β is the fraction of each batch leaving each stage, which can be over or under 1 given the demand during the different seasons of the year. In order to achieve this, a rolling horizon approach has been used with a single time step (one week) for each iteration. The planning interval is 8 weeks, with one week of a rolling horizon for a 10 week periodic window. This model runs over the period of one year, 52 weeks with 5 working days and 2 inactive days (weekends) in each week, plus official holidays.

Dried materials can be kept for a few months, but fresh raw materials are best kept for a few weeks. This can be achieved by reducing the temperature. Figure 5.13 shows the quality degradation for the materials over an 8-week window.

The differences between the two processes are as follows:

As shown in figure 5.13, and as expected, the quality of the material largely degrades during the preparation process (drying process) and much less so during the other processes. Figure 5.14 shows the quality drop for all four products during each stage. It shows that onions suffer the smallest quality drop after drying and that green peas suffer the highest quality degradation.

The quality degradation when using fresh raw materials, on the other hand, is significant after each process. Taking the product through the outbound logistics system also affects the quality; this has not been modelled explicitly in this case.

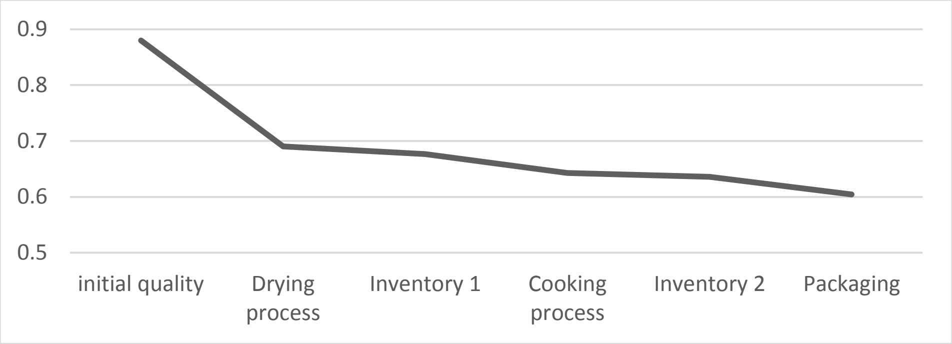


Figure 5-13 Quality degradation with an 8-week window

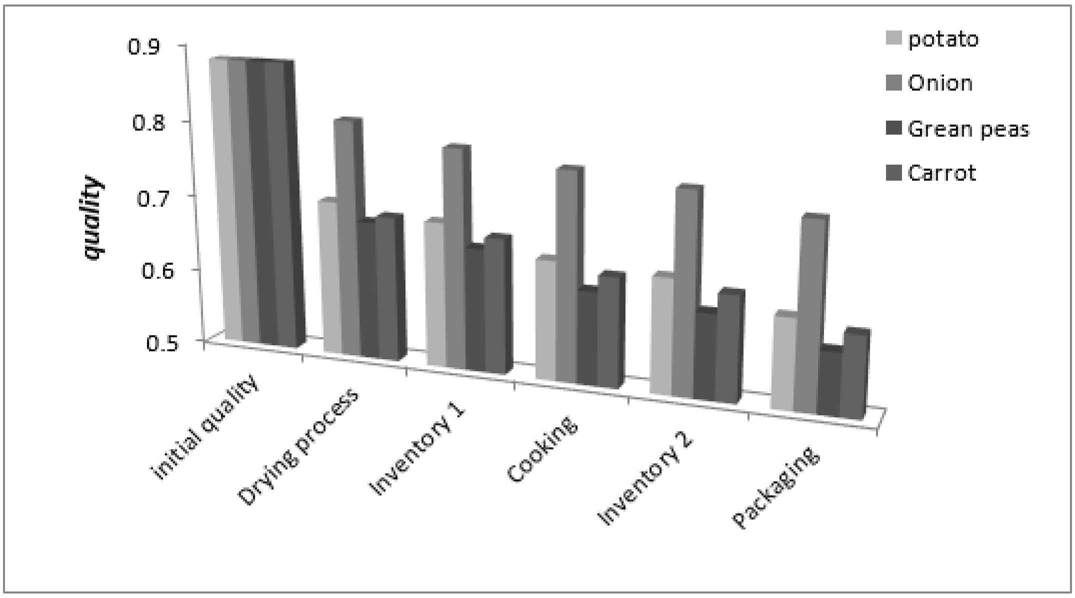


Figure 5-14 Quality degradation of dried materials over an 8-week window

During the preparation process, the best local optimum result for frozen raw materials is not feasible, therefore, the next optimum solution (local optimum) is considered.

The preparation process contains restrictions in that the process time and temperature cannot be at their minimum, 0.5, 0.5, because the materials should be dried or frozen. During the inventory stage, however, there are no restrictions, because the products can be stored at room temperature for a long time. The optimum degrees of freedom (scaled) for all four products and all three processes are shown in Table 5.1. All of these optimum solutions are within the feasible region.

The results of the inventory planning shows, that we must keep the material inventories as low as possible. This stage also suggests that materials should be kept at the lowest possible temperature.

For the cooking process, we use blending models, *x* where all of the parameters are known. Then, the linear model is applied in order to find the ideal cooking time and temperature. Table 5.2

shows the different recipes used for the model. The recipes are provided by the collaborator from the products which are not being used currently. Also the recopies in the table 5.2 is not presenting all the ingredients, and only the ingredients that are more likely to affect the quality and shelf life of the product is presented here. These recipes show the fraction at which each raw material should be mixed during the packaging stage.

	u	Carrots	Potatoes	Onions	Green Peas
Air-Dry Process	Process Time	0.5	0.583	0.583	0.5
	Temperature	0.725	0.725	1	1
Freeze-Dry Process	Process Time	0.583	0.5	0.583	0.583
	Temperature	1	1	0.725	1
Freezing Process	Process Time	0.5	0.583	1	0.583
	Temperature	1	1	0.5	0.725

Table 5-1 Optimum and feasible degrees of freedom

Soup	Quantity	Ingredient	Quality and energy affected by the process
Green peas	1 teaspoon	olive oil/ butter	No
	1	Onion	YES
	2 1/2 cups	chicken or vegetable stock	No
	1/2 teaspoon	salt	No
		Freshly ground black pepper	No
	1 (10-oz) bag	frozen peas	YES
Carrots	2 tablespoons	olive oil	No
	1	Onion	YES
	1 tablespoon	Spices	No
	1kg (2¼ lb)	carrots, chopped	No
	1 litre (1¾ pints)	vegetable stock	No
	500ml (17 fl oz)	water, or as needed	YES
Onions	900g (2 lb)	sliced yellow onions	YES
	750ml (24 fl oz)	beef stock	No
	250ml (8 fl oz)	chicken stock	No
		Water as needed	No
Potatoes	55g/2oz	Butter	No
	425g/15oz	potatoes, peeled and diced	YES
	110g/4oz	Onions	YES
	1 teaspoon	salt	No
		Freshly ground black pepper	No
	900ml/1½pt	chicken or vegetable stock	No
		Herbs and spices	No

Table 5-2 Recipes in the model

The weightings of the quality and energy in the model are similar to the ones in chapter 4 (table 4.1). They are used in the model in order to simplify the optimisation. For determination purposes, the average quality at the first stage and the average energy in the same stage have been taken and optimised together (using a similar approach as the blending optimisation) in order to determine the percentage at which they should be mixed. It is assumed that we can apply this weighting to all of the stages and that the whole system will achieve the optimised solution. The user would then be free to use other weights as appropriate.

The constraints added to the cooking process are: the temperature (u_1) cannot be lower than 0.7. Also, a low temperature and short processing time is not feasible. This is, because it will violate at least one of the quality indicators and will be costly. As a result, a second optimum solution is considered (Table 5.3).

	u	Potatoes	Carrots	Onions	Green Peas
Dried products	Process Time	1	1	1	1
	Temperature	0.7	0.7	0.7	0.7
Frozen products	Process Time	0.5	0.5	0.5	0.5
	Temperature	1	1	1	1

Table 5-3 Degree of freedom for the different materials and processes

The parameters in the cooking and thawing process for the energy consumption and quality models have been estimated based on data published by Ferreira *et al.* (2006). Also, the parameters for the quality changes in peas during the cooking process are based on a paper by Xie and Xiog (1999), whilst the material quality changes during cooking are based on Huarte-Mendicoa *et al.* (1997). After cooking, the previously frozen material remains at a higher quality compared to the dried materials, which is in agreement with the results presented by Manzi *et al.* (2004) in connection with a study on mushrooms.

The following tables (Table 5.4 and 5.5), together with the graphs (Figures 5.15 to 5.17), illustrate the total energy usage and quality degradation for the overall optimised result for an 8-week time interval. The figures also show the quality and energy changes between each stage and process. Figure 5.19 compares the freezing and drying process.

Optimum	Dried		Frozen	
Product	Quality	Energy(Mj/kg)	Quality	Energy(Mj/kg)
Potato soup	0.6787	33.2	0.6662	48.18
Carrot soup	0.8058	36.2	0.6937	49.18
Onion soup	0.7833	20.6	0.6709	46.18
Green Pea soup	0.7534	34.9	0.7187	48.18

Table 5-4 Quality degradation and energy usage for different production lines and products

Product	Dried		Frozen	
Packaging	Quality	Energy (Mj/kg)	Quality	energy (Mj/kg)
Potato soup	0.6312	37.7	0.6	53.18
Carrot soup	0.7494	40.7	0.6243	54.18
Onion soup	0.7285	25.1	0.6038	51.18
Green Pea soup	0.1136	39.4	0.6468	53.18

Table 5-5 Quality degradation and energy usage for different production lines and final products

Figure 5.15 shows the quality degradation for both the drying and the freezing process over an 8-week time interval. There is a significant quality degradation during the preparation process in terms of the drying processing, followed by the inventory stage, which only has a small effect on the quality of the materials. During the preparation process, we air-dry and freeze-dry the materials and blend them in order to achieve optimum quality and the least possible amount of energy consumed. A rehydration processes has been integrated into the system just before the cooking process. At this stage, the materials gain nutrient and moisture content, which will increase the quality of the materials before feeding them into the cooking process.

The quality degradation during the preparation process for frozen materials, on the other hand, is lower than for dried materials, but the quality degrades more than that for dried materials throughout the system. A thawing stage has been integrated into the system for the freezing process, just before the cooking stage. The thawing state un-freezes the frozen materials before feeding them into the cooking stage. At this stage, the quality of the materials degrades as shown in figure 5.15.

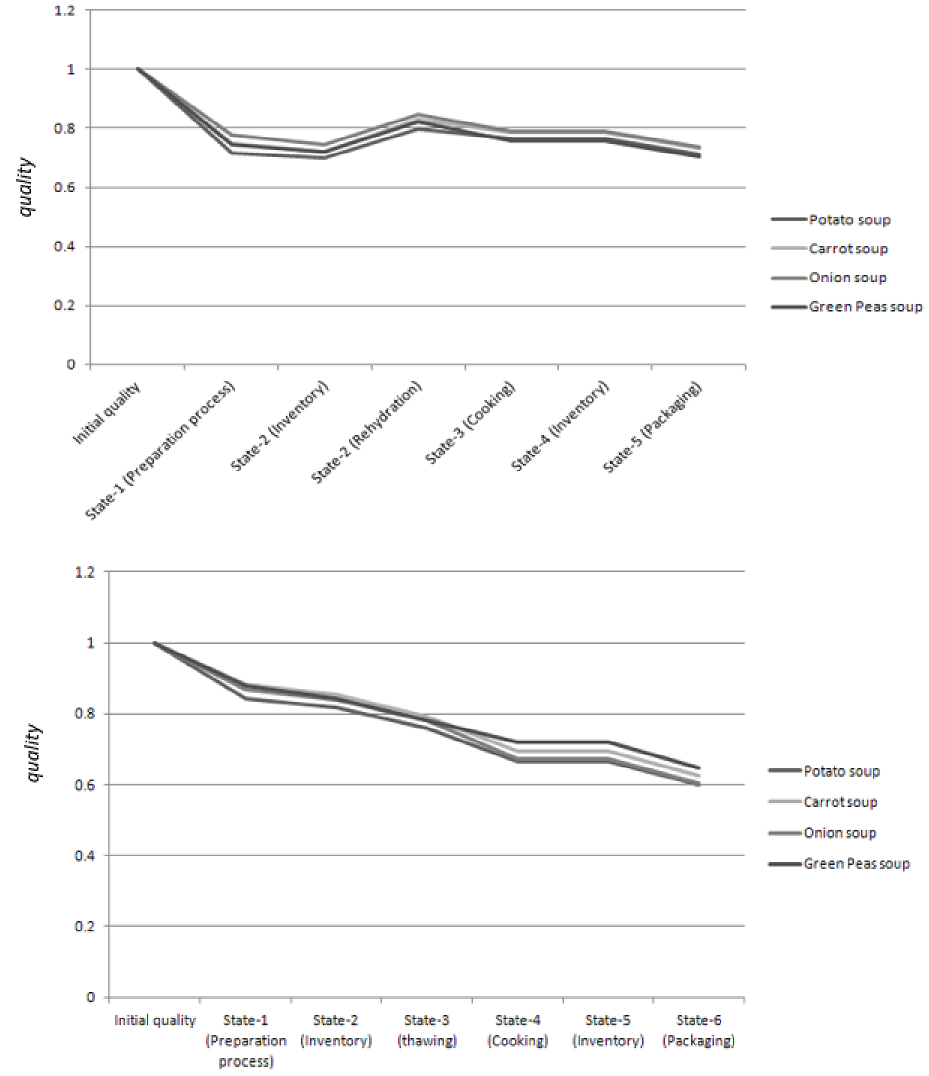


Figure 5-15. Quality degradation for each state after the drying process (top) and the freezing process (bottom)

Figure 5.16 shows the energy consumption for the two processes (dried and frozen) for the four products. As shown and expected, the energy consumption for the freezing process is higher than for the drying process. The energy consumed for all four products during the freezing process is almost the same (all around 50 (J/g d.m)). This is because all stages after the preparation process consume energy (inventory stage, thawing stage etc.). The drying process, on the other hand, is different. As shown in figure 5.16, the energy consumed for onion soup is much lower than for potato or carrot soup. This is because the major energy consuming stage is the preparation process, where the materials undergo a drying process. Softer materials (e.g. onions) consume less energy than materials with harder surfaces (e.g. potatoes or carrots). Also, the energy consumption for dried materials during the inventory stage is very small and could almost be negligible. Therefore, the big difference in energy consumption stems from the preparation process.

Figure 5.17 compares the energy consumption for the two processes (freezing and drying) in one graph in order to show the variance more clearly. Carrot soup is considered in figure 5.17 and shows that the freezing process uses much more energy compared to the drying process. As mentioned before, the energy consumption for the drying process during the inventory state is negligible, but frozen materials consume energy during this stage.

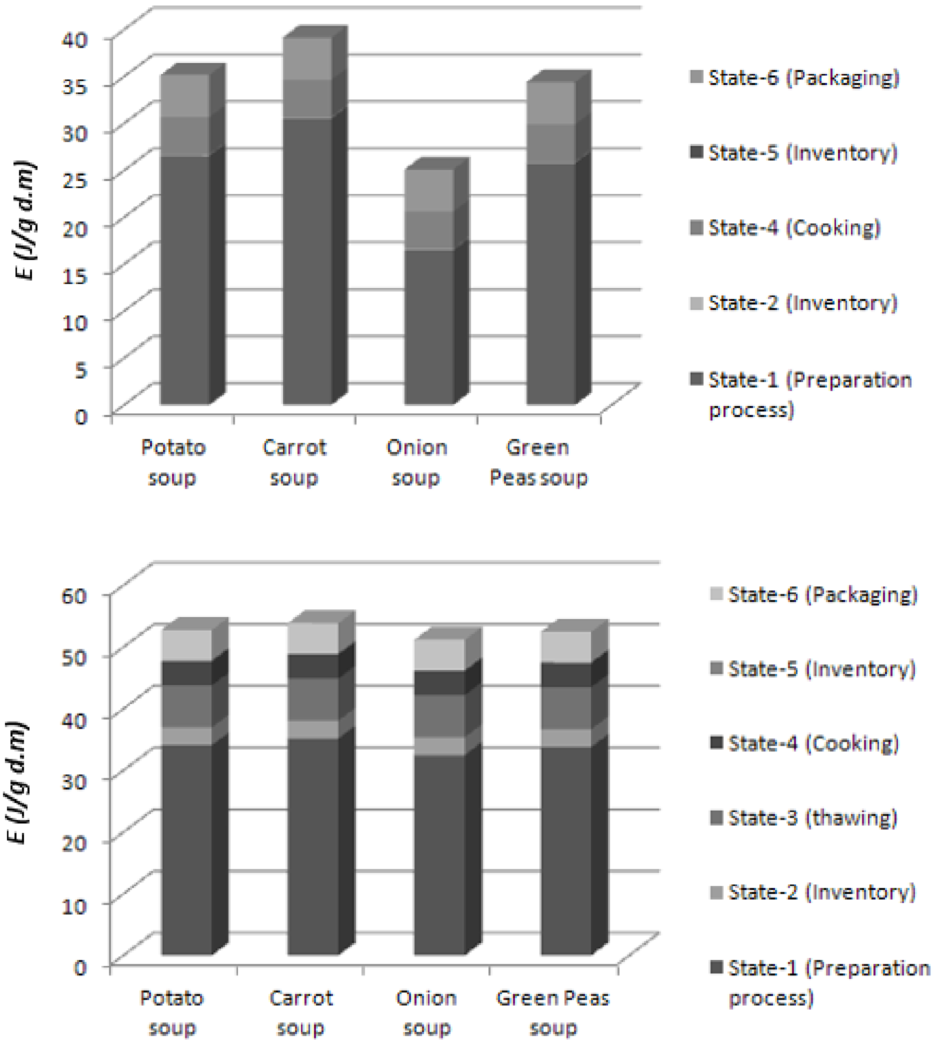


Figure 5-16 Final product energy consumption (J/g d.m), dried top and frozen bottom.

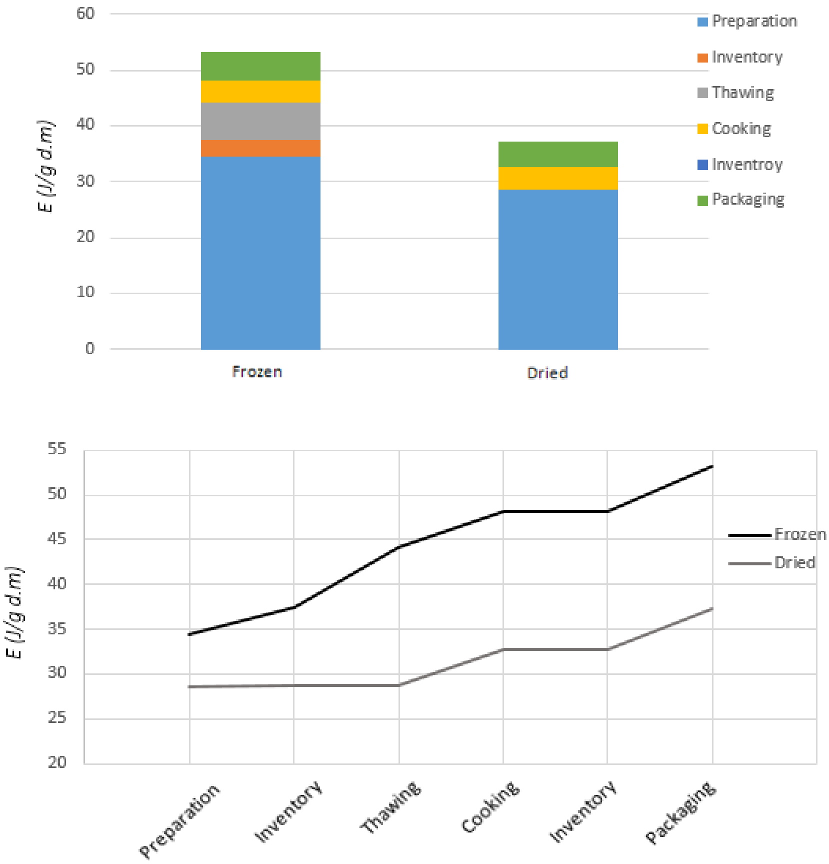


Figure 5-17 Freeze and dry processes, y-axis is the energy consumption (J/g d.m)

5.7. Comments

In this chapter, a multi-objective, sequential problem is modelled. The objectives are first to optimise the quality-energy models, the periodic time model, as well as the flexibility and feasibility for optimising the costs. As part of this process, planning and scheduling models are presented with both rolling horizons and direct approaches. In this model, two manufacturing systems are being compared. When running the first objective (energy and quality model) it appears that using the second production line (raw materials preparation) based on a freezing process is preferable, however, when the model is run for the entire system and with a flexibility constraint and variables, it appears that using the first production line for raw materials preparation, i.e. based on an air-drying process, is preferable. This is mainly due to the duration for which the materials and products are supposed to remain in the inventory on average (several weeks) before proceeding to the next stage or process. The optimum process energy consumption and quality degradation profile is presented in section 5.6.

In this work, a single supplier and single distribution centre has been assumed. In future, this work could be extended to a multi-supplier and distribution network with a more detailed supply chain model (chapter 7).

In the next chapter, we demonstrate how these concepts can be applied to two real-world case studies, which have been provided by our industrial collaborator.

Chapter 6

Industrial Case Studies

In this chapter, the concepts, process parameters, variables and models are applied and tested within a real world food industry supply chain system. The industrial party has shared their data on manufacturing and inventory processes, as well as any additional constraints, which need to be applied and integrated into the model and tests for the model variables and objectives. All of the input data for the models and objectives in this chapter have been presented by Unilever (the industrial partner).

Due to confidentiality, the case studies in this chapter are described on a no-name basis. Hence, the third party supplier names, as well as any other sensitive information, are not being disclosed. Only symbols are used to represent various details. Also, percentages and ratios are used, rather than exact figures, in order to demonstrate the applicability of the model.

6.1 Industrial Case 1: Solo recipe and ingredient product, soya milk

The first product considered is soya milk. The total year-on-year market demand for soya milk is in decline, as are the company's customers and demands. Therefore, the company is conducting a feasibility study to investigate possible ways of increasing their profit. The profit margins on soya milk, however, are very limited, and there are not many factors, which can play a role in profit maximisation.

6.1.1 Problem specifications

In order to increase the profit for soya milk, there are a number of factors to consider:

Market demand is in decline: since the market is in decline, it is difficult to increase the sales rate and the company should try to maintain the current demand. In order to maintain the current demand, the quality of the product must be high. There are a number of factors, which can affect the quality of the product. To name a few, harvest, process time and process temperature, logistical times and conditions, inventory conditions etc. The focus should therefore be on the purchase behaviour, where both intrinsic factors (physical properties of the product i.e. texture, flavour appearance, shelf life etc.) and extrinsic factors (packaging) are considered. Quality indicators have been discussed in previous chapters and are important factors which need to be optimised.

Multi-supplier model: this will allow us to consider more than one supplier at a time, which will give us a better quality/ cost for the raw material. Currently, the company only has one third-party supplier at a time in the model.

Supplier shipment: the availability of ports and ships and their costs are a major consideration. The time of delivery is also a factor, which will have an effect on the quality of the product and on its shelf-life.

Initial inventory: This is a short inventory of the product after shipment. This is dependent on storage availability.

Manufacturing system (Figure 6-1): Two products, namely powder (solid) and drink (liquid) are considered. Different raw materials are used for either of them. Each product has a different shelf-life. Also, they each use different manufacturing systems and their costs are different.

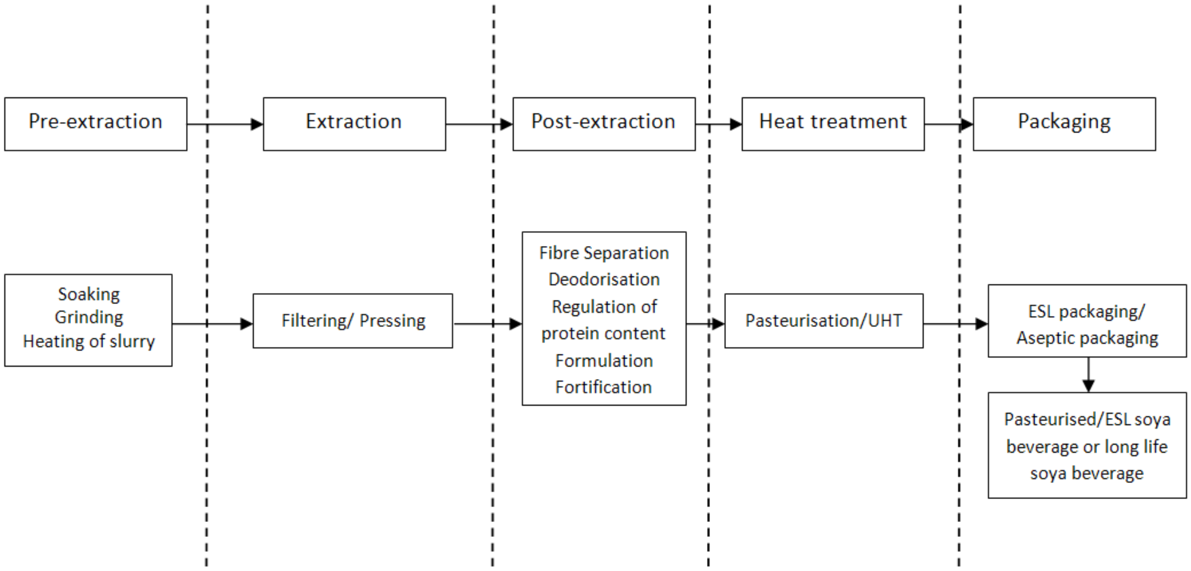


Figure 6-1 Soya milk manufacturing system

The utilisation and factory capacity: there are limited capacities for each line. Also, there currently is a production plant shut-down, which will limit the production capacity further. This has an effect on being able to supply towards a potential demand increase during times of a shut-down.

Inventory: the second inventory stage is in the warehouse before shipping to customers. This inventory is on site. The warehouse availability and duration must be considered. This is usually between three to seven weeks.

Shipments to the customers: the company is responsible for shipments to customers. For these shipments, port availability and shipment duration should also be considered.

Major issue: seasonality of soya beans

Soya milk is a solo recipe product, and the main raw material ingredient is the soya bean. The soya bean is also the only material in the product, which is subject to seasonality. Soya bean seasonality has a direct effect on product quality and wastage. During low season, the beans are in bad condition. They can break easily leading to increased wastage.

Waste from raw materials is produced during the first stage due to the physical condition of the raw material. This is mainly related to breakages in the beans. They may cause acidic by-products.

6.1.2 Problem solution

As mentioned above, there should not be much elaboration in regards to the demand, as the demand is in decline. The main consideration should be to maintain the demand.

The factory is based in Poland (Poznan), but the market demand is not only based in the Polish market, as this is an international product and is shipped globally. Also, it is worth mentioning that all shipment costs are based on Polish port prices and distances from Poznan.

Currently, a single supplier is used for the manufacturing system. Different suppliers can be taken into account (e.g. suppliers from different locations to overcome the soya bean seasonality issue). However, the supplier must be from a country which complies with Polish regulations. Considering the time horizon of one year (53 weeks), the demand is assumed to be flat. Supply, on the other hand, is very seasonal. This is shown in figure 6.2, where the dotted line is the supplier seasonality in Europe and the dashed line is the seasonality in South America, with the solid line being demand.

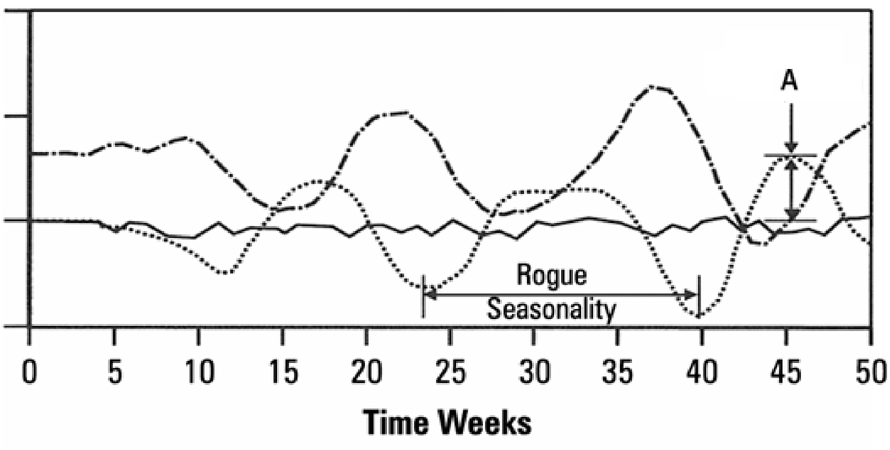


Figure 6-2 Soya milk demand and soya bean seasonality: the solid line is the demand, the dashed line is the supply in South America and the dotted line is the supply in Europe. The x-axis is the ratio between the supply in Europe vs South America and the demand.

Figure 6.2 shows that the supply of soya beans in South America is higher than in Europe. This source is also cheaper. On first analysis, therefore, South American soya beans appear to be a good replacement and a cheaper supply source than European beans in order to overcome the seasonality issues. However, there are other factors that need to be taken into account, such as shipment costs, shipment time, inventory cost and time, as well as quality checks. Firstly, the following quality indicators are measured in order to ensure that the product is within the legal range and that it is a good quality end product, whilst meeting a flat demand.

Quality indicators to consider:

- Protein content
- Protein yield
- Desired taste
- Colour
- Microbial content: this is mainly measured during the sterilisation / retort stage and must be within the legal limit

A South American supplier would also add a 12-week supply/ shipment time lag to the process. This time lag affects the quality of the product, as well as reducing the available shelf-life. It also adds additional costs to the system.

6.1.3 Potential modifications

In addition to the problems detailed in the previous sections, there is also a possibility of adding another stage to the manufacturing system. This stage would freeze or dry the raw material, to enhance the storage time, which in turn could overcome the seasonality of the soya beans.

This should also be compared to having fresh raw materials from another supplier in a different location. This supplier is from South America and ships fresh raw material during the time periods, when Europe cannot supply them.

In the model, South American supplier shipment costs, port costs and shipment availability and time lags are taken into consideration.

Adding a preparation stage would incur preparation process costs, inventory costs and the total capacity of the inventory stage is limited. The preparation process freezes or dries the soya beans in order to overcome the seasonality issue. The freezing process would maintain the quality indicators introduced in the previous section at a good level, but the inventory stage would be very costly. Dried raw material, on the other hand, results in a much cheaper inventory stage.

It is important to keep the demand flat in this market. Using fresh raw materials shipped from South America would ensure a high quality, but the shelf-life would drop by 33% due to the 12-week time lag from harvest to supply and shipment. Adding a new stage, on the other hand, would lead to quality degradation as shown in table 6.1 and the shelf-life would decrease as shown. This is a preparation process, where the raw materials are frozen or dried (as discussed before). The quality degradation is mainly calculated using the main quality indicators for degradation, such as the protein content, protein yield, desired taste, colour intensity and microbial content. These quality indicators are disturbed by the process time and temperature. The quality of each quality indicator is measured using the process time and process temperature and by having the initial quality as an input quality. This quality and shelf-life drop is a ratio of the process compared to the fresh raw materials shipped from Europe. The rate of the quality degradation for the raw materials undergoing the preparation process is much lower than for the fresh raw materials.

	SA Supplier	**Preparation process**	
	Fresh	Frozen	Dried
Quality	0.98	0.88	0.72
Shelf-life	67%	89%	95%

Table 6-1 Quality and Shelf-life for the different cases

The cost for each case is shown in table 6.2, but exact numbers cannot be shown for confidentiality reasons. Instead, the ratio shows the differences between each case. We assume the adding of a preparation stage with dried raw materials as a bench-mark, as it is the cheapest process amongst the three different cases. The other two cases (frozen raw material and fresh raw material shipped from South America) are different and the ratios are shown in table 6.2. The costs have been summarised in the table below.

	SA supplier	**Preparation process**	
	Fresh	Frozen	Dried
Costs	Shipment, port, supply and availability	Inventory and preparation process	Inventory and preparation process
	1.21	1.18	1

Table 6-2 Cost of the different cases

This is over a one-year time horizon, and since the seasonality issue only lasts for 10 weeks throughout the whole year, the shelf-life does not cause an issue. Having much better quality compared to a 21% cost increase may be a better choice in the long run in regards to the fresh supply from South America. The profitability of using dried raw materials is 3.5%, compared to the frozen option at 2.2% and fresh raw material from the South American supplier, which is only at 2%. It is important to remember that this calculation is made under the assumption of demand being flat, which may not be the case if a lower quality product is used. Also adding to this, we must consider the limited inventory capacity, which may result in some demand shortfalls.

6.1.4 Recommendations

Based on the discussions and results in the previous section, adding another supplier from South America to the model in order to overcome seasonality is feasible, even with limitations in regards to shipment capability. This is because quality is a key feature in order to maintain demand. Using fresh raw materials for the soya milk production, even if linked to a long shipment time, will result in a better quality final product. Also, it will result in a lower cost compared to the manufacturing system with the preparation process.

The new supplier has to commit to supply and ship a given amount of fresh soya beans for 2.5 months between week 20 and 26, as well as week 38 and 42. This will pave the way for a potential increase in profit by only 2%, but the company benefits by meeting the demand all year round and by maintaining a good quality end product, which could result in maintaining a flat demand.

Further analyses could be carried out by researching the costumer behaviour, and how the demand would be affected if low-quality soya beans (from the local supplier) were used. Should this not be sufficient, lower quality soya beans could be used during low season.

6.2 Industrial Case 2: Multi recipe and ingredient product, soup

This case study is an extension of the previous one in Chapter 5. This is a much larger problem, as not only are the raw materials seasonal, but there are also seasonality issues in regards to the demand.

In this section, we consider soup for the second industrial case study. Four different types of soups are being considered, namely potato and leek, peas and mint, tomato, as well as mixed vegetable soup. Each soup has a number of different ingredients, with most of them being subject to seasonality issues.

Different raw materials have different supply prices and shipment costs. Also, in this section there are a number of different raw materials, which are subject to seasonality issues compared to only one raw material (soya beans) in the last cast study. The cost is therefore much higher.

Recently, the company has conducted a feasibility study in order to investigate possible ways of overcoming the seasonality issue. Taking into account the number of different recipes and the seasonality of the supply and demand, the options to consider are third party suppliers and the integration of a preparation process by drying (air or freeze), freezing or blending them. However, due to confidentiality reasons, the manufacturing, inventory, production and final product costs, as well as the product prices, are not being shared. By optimising the quality and energy consumption for each stage after adding the preparation process, we can meet the seasonal demand with a good final product quality at the minimum possible cost.

6.2.1 Problem specifications

As mentioned above, the company is investigating ways to compensate for seasonality shortages in regards to the supply and demand. The objective is to meet on-shelf consumer requirements in regards to quality and quantity, with minimal waste in regards to natural resources, energy, nutritional values and cost. However, the company's main objective is to deliver high quality soup products whilst maintaining product safety by adding a preparation process to the raw materials in terms of the existing production line in order to increase their shelf-life. Below is the list of factors, which have been considered as part of this case study:

- Water evaporation during the preparation process
- The quality of the product and keeping the microbial content below the legal level
- Energy consumption of the process and storage
- The shelf-life of raw and processed materials
- Recipes, ingredients and required raw materials
- Seasonal demand and supply
- Waste production at each state due to the quality of the material and its shelf-life.
- Costs (purchase, processing, disposal and storage): as mentioned due to confidentiality this is not shared, but the ratios have been taken into account and described as part of this case study
- Capacity, utilisation and plant shut-down.
- Cooking value: this is measured at the cooking stage in order to control the quality of the product.
- Retort: sterilisation process and measuring the F-value for the microbial content, destroys 90% of the bacteria.
- The packaging and filling process.

All of these factors are highly sensitive towards variations in the raw materials, recipes and process degrees of freedom, as well as in regards to the conditions, the process time and the temperature.

The figure below (6.3) illustrates the manufacturing process. The quality indicators for nutrient degradation, texture changes and enzyme activation have higher z-values than the microbial inactivation reactions. The z-value is the temperature change required to control the microbial content for quality purposes. In order to achieve a better quality product, a shorter process time and a high temperature is advised; this is because the z-value for the microbial content is lower than the rest of the quality indicators. Therefore, analysing the quality at every stage has become a very important factor.

First stage:

For fresh raw materials, the initial quality is assumed to be 1 and the purchase cost comes from the supplier. This is not known, but the assumption is that the further away the supplier, the more costly the raw material will be due to shipment costs.

Second stage:

A preparation process is added in order to increase the shelf-life of the raw materials and to overcome supply seasonality problems.

The preparation process includes freezing, air-drying and freeze-drying. Quality degrades at this stage and is measured by the linear and blending quality models that have been generated. The parameters for the generated models are calculated using zero- and first-order kinetic models.

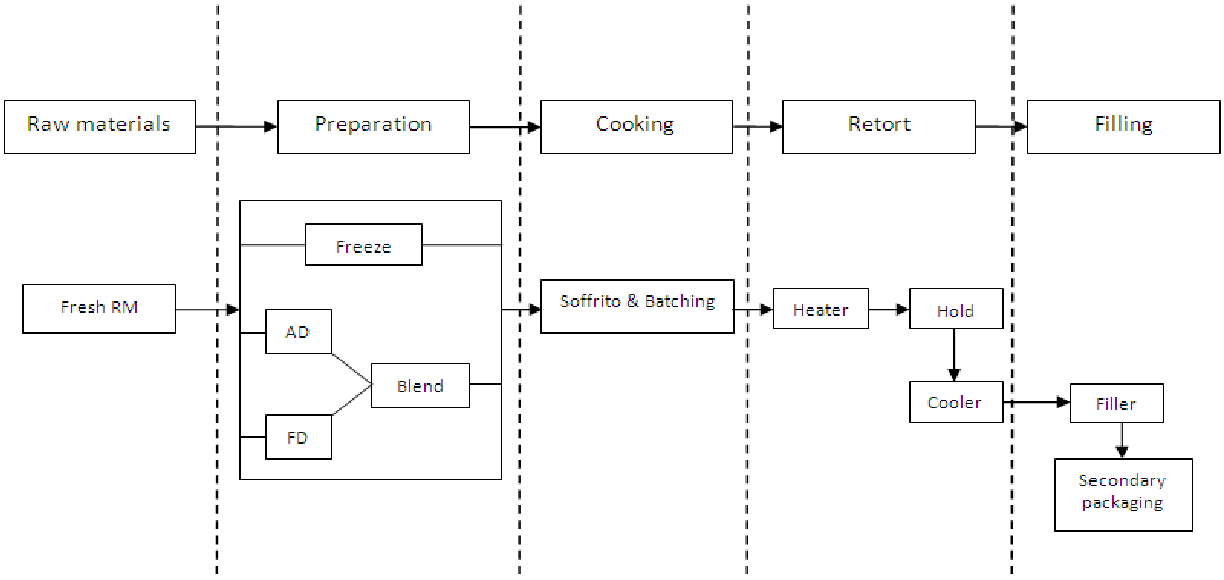


Figure 6-3 Multi-recipe /supply and seasonal soup manufacturing system

Third Stage:

The cooking stage, known as the soffrito and batching process, depends on the recipe. Here, a "cook value" is used to calculate the parameters for the generated models. In addition to the process time and temperature, this stage is very sensitive in regards to the recipe and the raw materials.

$$C = \int_0^t 10^{\frac{(T-T_r)}{Z_c}} dt \qquad (6.1)$$

where C is the cook-value,
T is the process temperature
T_r is the reference temperature,
Z is the temperature change required to affect a 10-fold change in the rate of microbial/quality change (table 6.3)

Component	Approximate range of z-value (°C)
Microbial Spores	7 to 12
Vegetative cells	4 to 8
Vitamins	10 to 50
Enzymes	25 to 30
Proteins	15 to 37
Sensory factors	25 to 47
Texture softening	25 to 47
Colour	25 to 47

Table 6-3 Z-Value

Fourth Stage:

This is the sterilisation stage, where retort technology is used. For safety reasons, the major quality indicator is the microbial content. A certain level of microbial content is legal, which is F_0=3, however, there is a risk in terms of the company taking on extra precautions relating to the amount of bacteria in the food product. Therefore, the temperature for the retort stage varies between 125.3^{0}C to 125.9^{0}C. The minimum quality allowed is set to the microbial content indicator, as the safety issues and other indicators have been optimised with regard to the temperature range and the given process time changes.

Three processes have been integrated into this stage: Ohmic heating followed by holding and then cooling.

The F_0 value is measured by the equation below, where:

T is the temperature of the process

T_r is the reference temperature, this is 121.1 with a z-value of 10 for the sterilisation provided by this equation called F_0.

Z is the temperature change required to affect a 10-fold change in the rate of the microbial/quality change (table 6.3)

$$F_0 = \int_0^t 10^{\frac{(T-T_r)}{z}} dt \tag{6.2}$$

F_0 is used for safety, the microbial content and the legal bacteria level.

Fifth Stage:

This is the packaging stage, and two different processes have been integrated: filler and secondary packaging. This stage only has a small effect on the quality of the final product.

6.2.2 Problem solution

As mentioned above, the aim of the project is to deliver a high quality soup product, whilst maintaining product safety, overcoming seasonality problems and by optimising wastage and energy usage. A preparation process is added to the existing production line, in order to increase the shelf-life of the raw materials.

The quality of each ingredient can vary in different ways. The chosen indicators are very sensitive towards variations in the raw materials, recipes and process conditions.

A number of quality indicators have been considered, with the two most important ones being nutrient content and microbial content (following the retort stage, microbial content has to at least fall into the legal value, F_0=3).

The waste produced during the preparation process is relatively high in regards to dried materials. Only 10% of the fresh raw materials are at a high quality level and a waste rate of 25% is produced.

Quality

- Temperature, time and Z-Value, for quality checks at every stage
- The minimum quality acceptable to costumers for all indicators is a constraint, which is an input for the model.
- We have assumed that only one product goes through the preparation and manufacturing process at any one time and that the quality degradation of the main ingredients (i.e. in

potato and leek soup, potatoes and leeks are considered to be the main ingredients) plays a major role in regards to the total quality degradation of the final product.

Energy

- Energy per tonne for each task
- Energy for tasks during every stage
- Energy consumed during inventory stage per day of storage.
- Maximum energy.

Below is the energy usage and quality degradation data for this case study. Four products with four different recipes have been considered. However due to confidentiality, the exact data cannot be disclosed and only ratios have been used.

Figures 6.4 and 6.5 show the energy usage and quality degradation for each process for the composite soup products. It comes as no surprise, as shown in figure 6.4, that the energy usage during the freezing process is much higher than during the drying process. The drying process uses a 60 to 80˚C process temperature with 1 to 12 hours of processing time. The freezing process, on the other hand, uses the same processing time, but the process temperature is -40 to -70˚C.

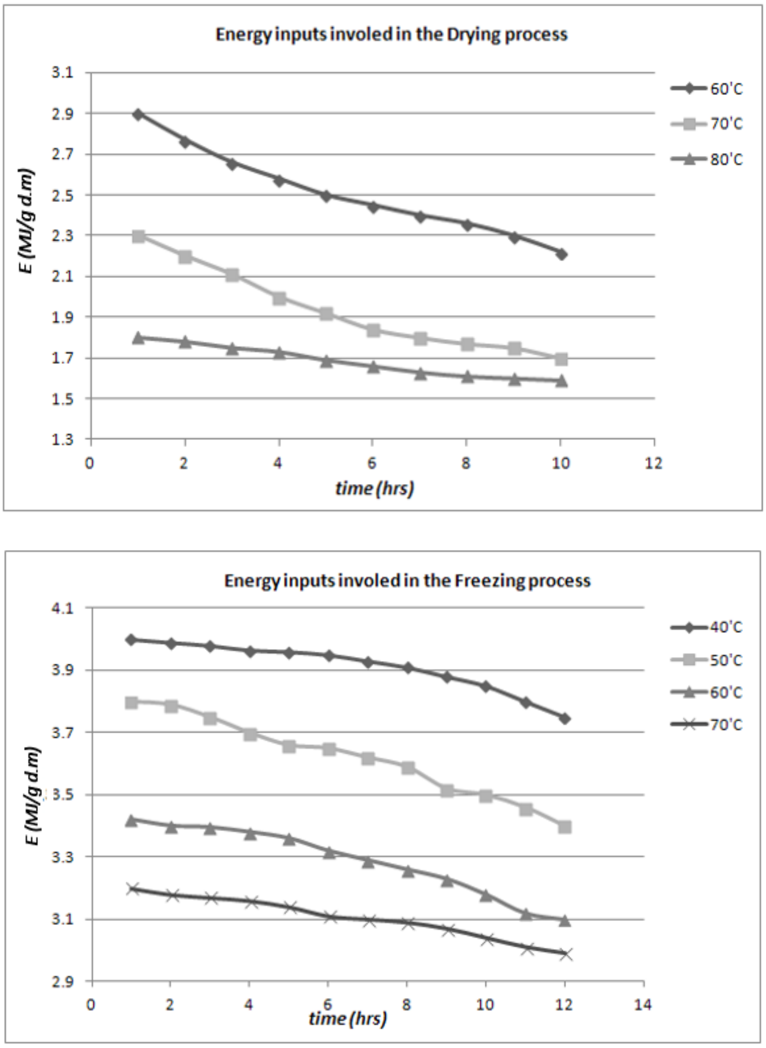


Figure 6-4 Energy Usage, with the top being the drying process and the bottom being the freezing process

Due to internal restrictions at Unilever, the preparation process cannot last longer than four hours. Figure 6.5 therefore only shows the quality degradation for the two processes with a process time between one to four hours.

As shown in figure 6.5, the quality for the drying process is lower than for the freezing process. This is because the freezing process can retain more nutrients, which results in a better quality product.

Figure 6.6 compares the quality degradation for all four products using the three processes in one graph. Here, it is easier to see the quality differences in each product, given that the quality of the final product is a key factor for Unilever products.

The air-dried and freeze-dried materials could be blended together at a later stage, in order to optimise the quality and energy consumption.

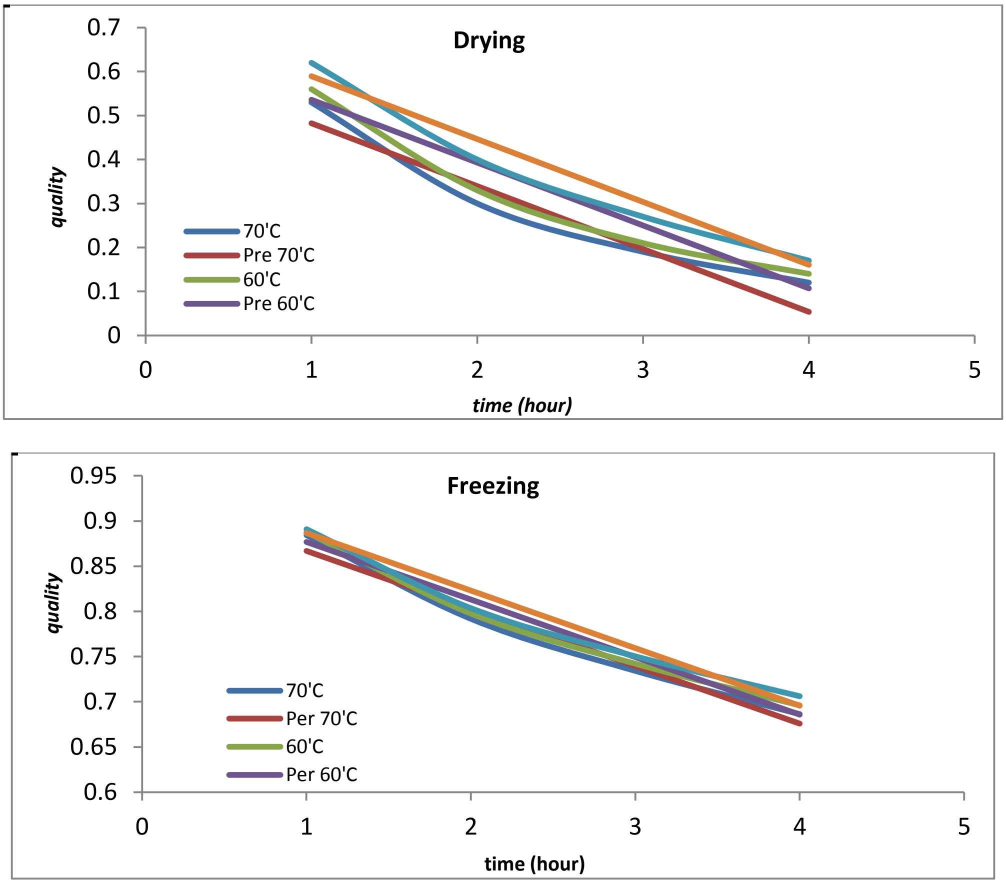


Figure 6-5 Quality degradation for drying on top and at the bottom for freezing

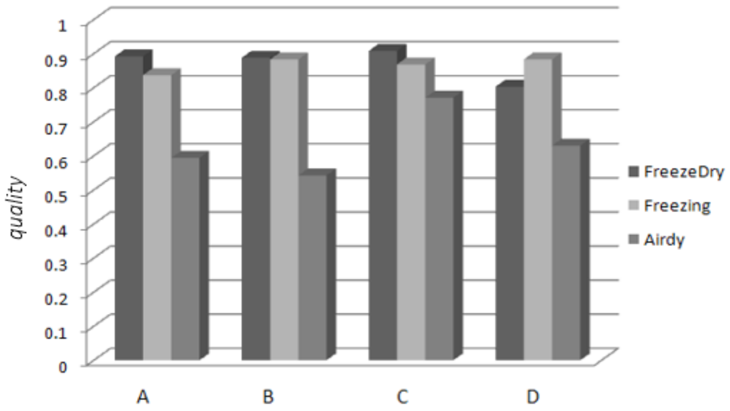


Figure 6-6 Quality comparison between the air- and freeze-dry process, as well as the freezing process across all four products

The table below shows the percentage of blending for the four products. In order to achieve this, the following constraints and assumption are being considered.

- The drying process cannot be higher than four hours (due to Unilever restrictions) and there is no inventory before feeding the dried materials into the blending stage.
- The weighting of the quality is higher than that for energy, as the quality is more important than the energy (weightings presented by Unilever).
- There is only one product in the process at any one time

	Air-Dry	Freeze-Dry
product a	40%	60%
product b	60%	40%
product c	30%	70%
product d	20%	80%

Table 6-4 Blending percentage for each product

Figure 6.7 shows the quality degradation for each raw material (from a to f) during the blending stage. In order to measure the quality of the product, a composite quality indicator for all of the ingredients of the product is being considered.

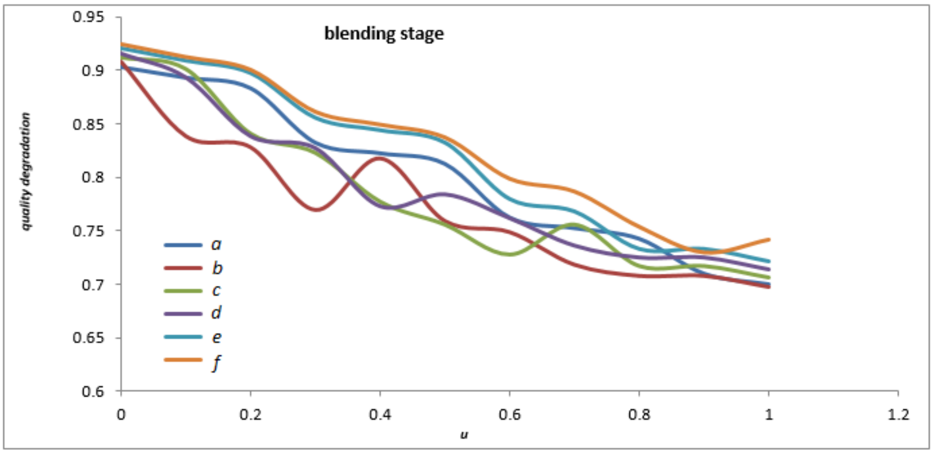


Figure 6-7 Quality degradation at the blending stage for different raw materials

Figure 6.8 compares the freezing process with the drying process after blending for all four products. Clearly, the freezing process still results in a better quality product, but at this stage the energy consumption is applied. The weighting of the energy consumption is lower than that for quality, as proposed by Unilever.

6.2.3 Potential modifications

As mentioned before, the company is investigating ways of overcoming seasonality issues for both supply and demand.

Due to confidentiality reasons, there is insufficient data on third-party suppliers in regards to using fresh raw material from different locations in order to overcome the seasonality problems. This is also very complex, as we are dealing with a number of recipes and raw materials, which all need to be supplied. Also, by having both demand and supply as variables with seasonality issues, the best modification to the current system is the adding of a preparation process.

Figures 6.5 and 6.6 show the quality degradation after each process, approximately 42% for air-dry, 15% for freeze-dry and 18% for the freezing process. However, we can benefit from the blending stage following the drying process, which is also shown in the previous section. Figure 6.7 and table 6.4 show how we can mix the materials from each drying process in order to achieve better quality materials and a lower energy consumption process.

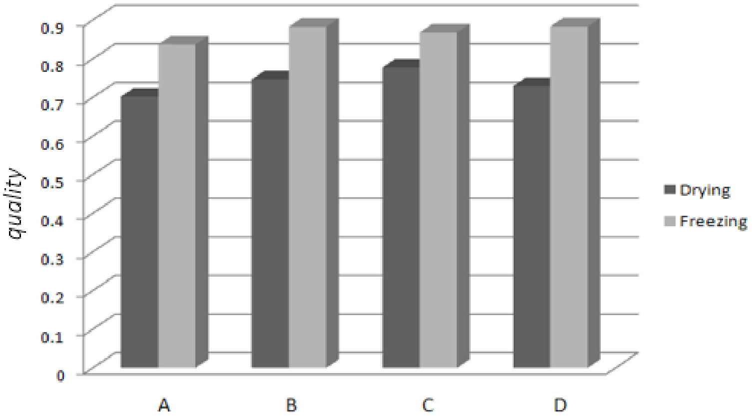


Figure 6-8 Quality comparison between the drying (after blending) and freezing process across all four products

6.2.4 Recommendations

The overall recommendation is to integrate a preparation process into the existing manufacturing system, and to simultaneously optimise the planning and recipe design with regards to quality monitoring. Although the integration of this step is costly, it will allow for the raw materials to undergo either a drying and/or freezing process depending on the recipe, before entering the cooking stage. Also, this stage will benefit the system by using both drying and freezing processes and by blending them together, if necessary.

This will allow the company to choose an appropriate preparation process by knowing what quality end product they can expect. In average, there is a quality degradation of 18% following freezing and a 30% degradation following drying after the blending stage. Energy usage for the freezing process, on the other hand, is almost double that of the drying process, which would result in a more costly process (before even considering the inventory and manufacturing costs).

6.3 Comments

In this chapter the industrial collaborator existing system is being compared with our model. All the data in this chapter are provided by the industrial collaborator. In this chapter we show in the first case study where there is a single seasonal raw material the existing system works better if the source of raw material changes to South America for the required period of time.

The second case study however suggest a preparation process adds a huge benefit to the system. This is because there are number of seasonal raw materials that needs to be taken into account. It would be very expensive and time consuming to source them elsewhere, therefore drying or freezing them will benefit us more.

Chapter 7

Conclusions and Recommendations for Future work

7.1. Summary and main contributions of the thesis

In food industry supply chains, product quality is a major concern for manufacturers. Quality is a function of cost and therefore a function of the end user price. Quality is also a function of demand and therefore a function of revenue. In this thesis, we have quantified quality and have measured it for every stage by providing a measure, which correlates with the degrees of freedom process. Energy, on the other hand, is a variable factor, which plays a key role in regards to the cost minimisation problem. In this work, we have managed to identify the relation between quality and energy using the degrees of freedom process. By using this relation, we have modelled quality and energy together in order to simplify the optimisation problem.

Three different preparation processes have been considered as part of this work, namely freezing, air-drying and freeze-drying. For the drying process, an additional blending stage has been added. This stage allows us to blend the products from the air- and freeze-dry process together. Also, a model has been generated for this stage, in order to determine the fraction at which they should be blended in order to achieve a product with optimum quality and energy usage.

The parameters and input data for these models stem from experimental data from different literature sources. We have used several models to calculate the parameters and input data.

In this work, we have been trying to simplify the optimisation problem. The quality model introduced and used here, linearises the non-linear quality models. However, in this linearisation, some of the characteristics are lost. Therefore, a correction constraint (equations 4.16 - 4.20) has been applied. This constraint allows us to gain back some of lost characteristics and also increases the accuracy of the results.

Novel solution algorithm

In order to solve this problem, we have developed a deterministic supply chain model. Initially, a single supplier is assumed with a multi-state manufacturing system. The deterministic model is applied in order to optimise the quality and energy usage with a cost minimisation for the production and inventory stages. The constraints 4.9 to 4.27 are used in this model. This model is very useful for measuring the quality and energy usage for each stage, re-adjusting if necessary, and for integrating it into a whole supply chain for long-term planning. This model has been developed using an MILP mathematical model. The main reason for MILP is that it gives us the flexibility of using both integer and linear modelling for this problem, where both are necessary (the model in chapter 4 uses a number of integer variables).

For this model, the following key objectives are considered:

- Relate the material's output quality to the input quality for the next process

- Relate the quality of the material to the degrees of freedom process
- The ability to propagate quality indicators through the process: state quantity
- Maintain model linearity
- Relate the energy usage to the quality model

In order to solve this model, decomposition and hierarchical methods are used based on mathematical programming. In this solution technique, we first establish which variable is the most significant decision factor, and then build a reduced decomposition hierarchical model in order to reduce the solving time.

We then develop a long-term planning formulation for supply chain networks with multiple sites, which applies to the supply chain model throughout the whole system in order to overcome common food manufacturer problems in regards to seasonality. Our model suggests which supplier to choose (at what price for quality raw materials, which location etc.), which preparation process to use (freezing, air-dry, freeze-dry or a combination of air- and freeze-dry), as well as how long they should be stored in inventory for and at what temperature. It also suggests how to cook, mix and pack them. In order to achieve these results, a direct approach is used with the following assumptions:

- The materials which satisfy the consumer quality requirements leave the task and the leftovers are considered to be waste, and added to the disposal cost.
- A single, aggregated supplier of raw materials (this does not affect the core problem being modelled).
- Only one manufacturing system is considered at a time.
- Product storage and inventory is available at every stage.
- Negligible changes in quality and energy consumption during the inventory state after the preparation process.
- A short inventory stage after the cooking process, which does not affect the quality of the product and does not disturb the shelf-life constraint.
- The packaging process only affects the cost and not the quality of the product due to a very short processing time after the cooking process.
- The fraction of each batch leaving the inventory (β) is assumed to be 1.

This is shown in chapter 4 and 5 and determines the production plan and the degrees of freedom process, as well as inventory policies, the product quality for each task, the product quantity for each task and the final product quality and quantity.

These models and assumptions are then put to test in two real world case studies. The results show that with a few amendments (e.g. legal microbial level, company agreed prices and location amendments), this model can be applied.

7.2. Recommendations for future work

In the future, more accurate results could be achieved by having more detailed supply chain structures, where more constraints and criteria are added to the model. Also, this model could be run for profit maximisation rather than for cost minimisation. Profit maximisation considers the total number of sales and revenue, together with cost minimisation. In the profit maximisation model, price, cost and quality could be considered.

7.2.1. More detailed supply chain structures

In this work, a single raw material supplier (hence fixed input quality per season) and a single distribution centre have been assumed. In the future, this work should be extended to multi-supplier and multi-distribution systems.

Detailed supply chain model:

The supply chain system could use a hierarchical solution method in order to optimise all of the necessary sub-systems in the model. This system consists of five system elements to be modelled, namely manufacturing, inventory, logistics, tactical supply chain network optimisation and strategic supply chain network optimisation systems. This model starts with the manufacturing and inventory system in a simple single option in a tactical horizon. However, this model could be extended to a more detailed supply chain model, and it could also be extended to a strategic horizon in future (long-term planning) to lead to a more comprehensive analysis and results.

Detailed Supply Chain Model with Multiple Stages and Multiple Options

Whilst the above analysis mainly deals with simple representative and single stage models, real industrial processes use multi-supplier, multi-stage and multi-option supply chain models. Future researchers could extend the model and the analyses to more complex cases. This work could be extended to multi-supplier, multi-objective, multi-optional and multi-consumer models, as discussed below.

Although multiple suppliers add another level of complexity to the model, it is more realistic and practical in an industrial world. A supply chain model and inventory model with multiple suppliers and its contribution to supply chain management has already been reviewed by Minner (2003). This paper shows that the multi-supplier model produces a model with flexibility in regards to sourcing and raw materials, as well as a possible cost and shortage reduction in raw material. In our case, multiple suppliers might offer material at different qualities and prices, and the system could optimise procurement.

Multiple objective supply chain models give us the option to analyse the model in more detail; they also generate more comprehensive results compared to the single objective model. An example of this has been provided by Sabri (2000), who developed an integrated multi-objective supply chain model to be used simultaneously for both strategic and operational supply chain planning. The model developed in the paper aided in the design of an efficient, effective, and flexible supply chain system and evaluation of competing supply chain networks. This multi-objective model has been developed, so that the decision analysis is adapted to include a performance measure.

To conclude this subsection, the model could be extended to a multi-supplier system in order to increase flexibility and to reduce shortages of raw material and multi-objectives in order to generate a more comprehensive result, multi-stage in order to cover the model in more detail, as well as a multi-customer model. Most multi-stage and multi-objective models focus on a single customer, which is not a practical industrial approach. Khouja (2003) has developed a three-stage supply chain model with many customers. He has solved the model with three inventory coordination mechanisms between chain members for cost minimisation. He has discovered that some of the inventory coordination mechanisms, depending on the customer, result in lower production and transportation costs.

Logistics system

The quality model has been implemented on a quantitative level as part of a single option manufacturing and inventory system. After extending the model to a more detailed supply chain and multi-optional model, and after then populating it with real system data to fit into the industrial world, a next step could be to implement this original and unique model into a logistics system. In order to consider the process as a whole in a supply chain system, the transportation and logistics costs and methods must be included. There are various industrial and scientific papers on cost minimisation, which use almost similar methods. However, we are introducing a new model for the logistics system, which controls the quality of the shipped product at each stage and which could even mix transportation paths in order to provide the best quality product at each location by considering the quantity, and by having the right amount of products at each location. The shipment paths should be used for processing types, and at the blending stage these quality type checks should be accepted by the local consumers, as well as achieving the required quantity. In this implementation, a detailed supply chain model with multi-stages and multi-options (e.g. different logistics conditions and durations) is being used. For instance, the multi-customer model will affect this system much more than the manufacturing system, just as the multi-supply model affects the manufacturing system more compared to the logistics system.

Trienekens and Zuurbier (2008) state that quality assurance will dominate the process of production and distribution in food chains in future. This also means that product flows with different quality attributes can be directed to different logistical distribution channels (with different environmental conditions) and/or different customers (with different quality demands) in the supply chain. In fact, one of the keys to SCM for the food industry is an integrative view on logistics and product quality, which has been labelled ‘‘quality controlled logistics’’ by Van der Vorst *et al.* (2007). The quality of the dried products suffers a minor change in logistics, but it is a major change in the case of fresh raw materials. For frozen materials, the logistics system has a small effect on quality, but it is significant in terms of energy consumption.

Detailed supply chain modelling and optimisation:

A multi-supplier system adds a negotiation factor, which can lead to cost reduction and higher flexibility. The objective is to find the “best” supplier with minimum supply and purchase costs, whilst considering raw material quality and how this quality will be affected by processing.

In order to solve this, most papers use mostly fuzzy or hybrid modelling, but a hierarchal AHP model may result in a better solution in regards to warehousing and logistics.

Consider a manufacturing system with m suppliers. Each of the suppliers has *max* and *min* throughputs and fixed costs. And the manufacturing system has a *max* capacity and minimum input quantity at which the manufacturing system becomes cost-inefficient.

Objective: different suppliers have different quality raw material, but all of them need to meet all of the constraints at minimum cost.

$$Min\left(\sum_{s,t} Supply_{st}.PurchaseCost_s\right) \tag{7.1}$$

System constraints: ordinary linear programming constraints and no deviation variables. These constraints cannot be violated, thus they are called hard constraints

Resource constraints: goal equations or soft constraints (deviation variables)

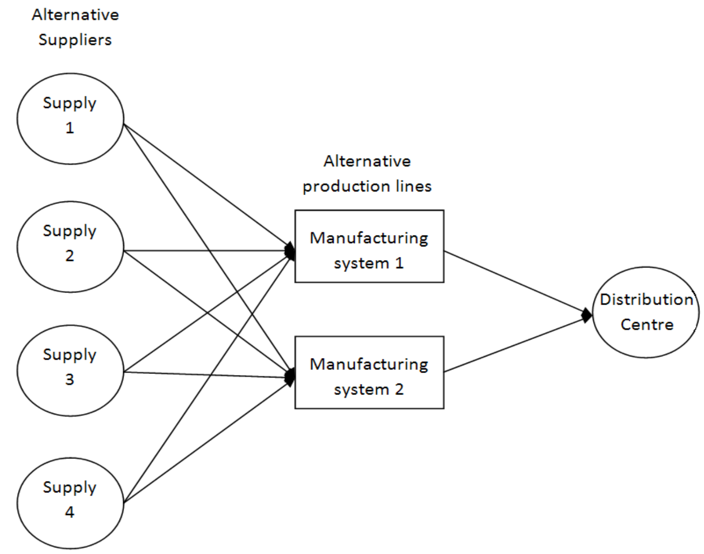


Figure 7-1 Multi-supplier manufacturing system

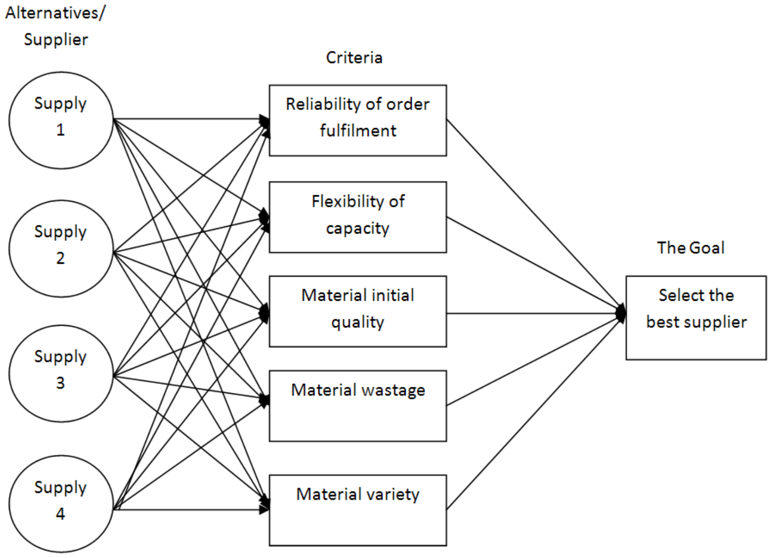


Figure 7-2 A hierarchy of supplier prioritisation

AHP priority constraints are akin to resource constraints. Deviation variables of the priority levels are dependent on the overall AHP priority ranking. AHP compares the suppliers for two of the criteria with regards to the set goals at a certain time. After the comparisons, the AHP priorities ranking determines the priority level.

$$\tau_m = amount\ of\ products\ delivered\ from\ supplier\ m\ to\ maufacturing\ site \tag{7.2}$$

$$\psi_m = \begin{cases} 1\ if\ total\ one\ of\ the\ crteria\ is\ disturbed \\ 0\ otherwise \end{cases} \tag{7.3}$$

$$\upsilon_m = \begin{cases} 1\ if\ supplier\ m\ is\ chosen \\ 0\ otherwise \end{cases} \tag{7.4}$$

$$w_m = \begin{cases} 1\ if\ both\ \psi_m\ and\ \upsilon_m\ are\ 1 \\ 0\ otherwise \end{cases} \tag{7.5}$$

Constraints:

(1) Ensures that the number of suppliers selected is less than or equal to the suppliers available.

$$\sum_m v_m \leq m \tag{7.6}$$

(2) Determines which supplier has been selected

$$\tau_m - Mv_m \leq 0, \forall m \tag{7.7}$$

(3) Determines, which supplier has an allocation of production, which is less than the quantity required.

$$\tau + M\psi_m \geq cap^{min}, \forall m \tag{7.8}$$

(4) Raw materials provided must be less than or equal to the capacity and more than the minimum quantity. Minimum quantity is the quantity below which the system becomes not cost efficient.

$$Cap^{min} \leq PR \leq Cap^{max} \tag{7.9}$$

(5) The raw material must have an initial quality larger than the minimum quality assigned initially.

$$q^{min} \leq q \tag{7.10}$$

(6) Material variety

$$PR \geq PR_{required} \tag{7.11}$$

(7) Material wastage

$$PR_{Waste} = 0 \tag{7.12}$$

(8) Which one of the suppliers can deliver all of the criteria

$$w_m - \psi_m - v_m = -1, \forall m \tag{7.13}$$

7.2.2. Profit optimisation

The last subsector and the models developed in this thesis focus on cost minimisation. But cost minimisation does not necessarily mean a positive profit. Ultimately, profit maximisation will be more relevant for end users, who may not wish to meet all of the possible demands. Therefore, the main objective should be profit maximisation.

Profit is a function of cost and demand and demand is a function of price and quality.

$$Profit_{s,t} = f(Cost, D_{s,t}) \tag{7.14}$$

$D_{s,t} = f(price, q)$, where q is the quality (7.15)

$$Max\ [profit(price, q)] \tag{7.16}$$

Price, Demand and Quality Optimisation

In this work, cost is minimised for a product, which has an acceptable level of quality and a production line with minimum energy consumption. The quality may have a direct effect on demand, and therefore on the profit, especially in the food manufacturing sector.

$$Profit = TotalRevenue - TotalCost \tag{7.17}$$

Revenue is a function of sales. Revenue is calculated by multiplying price and quantity. Quantity is directly affected by demand and is a function of demand. Price, on the other hand, is often a quadratic function of quantity (Kerimar 2007).

$$Revenue = price.Q \tag{7.18}$$

$$price = a.Q^2 + b.Q + c \tag{7.19}$$

Where Q is the quantity (demand), a and b are small numbers and c is a constant. Figure 7.3 shows how the price may change as a function of quantity.

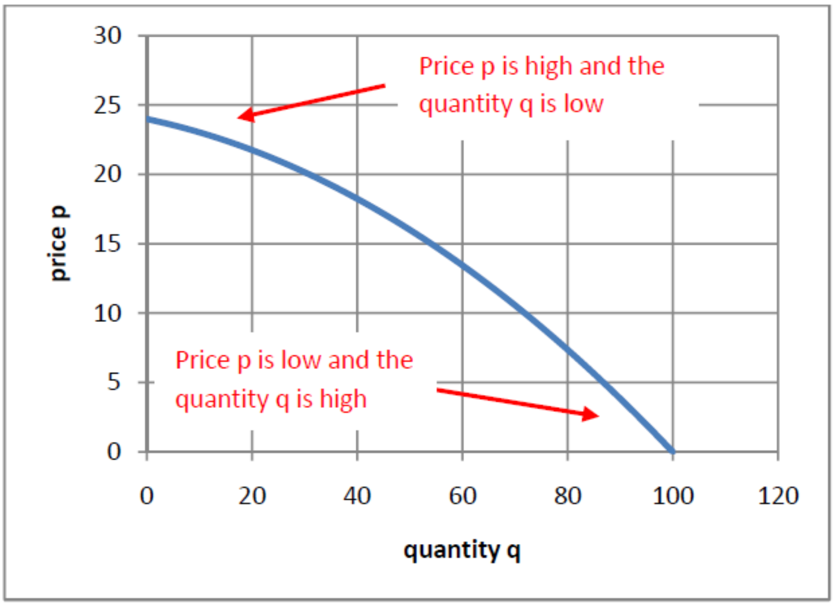


Figure 7-3 Price as a function of quantity

Kerimar 2007 has introduced a, b and c as follows, which could help to find an optimised solution for the model.

$$a = 5.35 * 10^{-5}, b = 3440 * 10^{-5}, c = 414.5$$

Integrating 7.19 into 7.18:

$$Revenue = (a.Q^2 + b.Q + c).Q \tag{7.20}$$

Quality is the other variable in this work. Quality, however, has a direct relation to the price (a better quality product is set at a higher price). Depending on the location, this could mean that the optimal solution will change. For a location with the majority of the population earning a low income, lower quality products may be more popular. This means that we can tackle this problem in two ways.

First, we can optimise the model with a given and constant quality set for different locations in order to optimise the demand locally and to use equation 7.20 and/or 7.14 in order to optimise it, and to later run regression tests for a general solution.

Or else use equation 7.21 for a more general solution.

$$q_{ind}^{j} = e^{\theta_{ind}^{j}(p^{j}-\pi_{ind}^{j})} \tag{7.21}$$

Where q_{ind}^{j} is the perceived quality of the product *j* by individual *ind*, and $q_{ind}^{j} \geq 0$, p^{j} is the price of the product *j*, θ_{ind}^{j} is the information coefficient, the extent to which individual *ind* interprets quality information from p^{j} and $\theta_{ind}^{j} \geq 0$ (0 if the individual disregards quality information from p^{j}) and π_{ind}^{j} individual *ind*'s reference price for product *j* (Ding *et al.* 2010).

Re-adjusting the 7.22 equation:

$$\ln(q_{ind}^{j}) = \theta_{ind}^{j}(p^{j} - \pi_{ind}^{j}) \tag{7.22}$$

$$p^{j} = \frac{\ln(q_{ind}^{j})}{\theta_{ind}^{j}} + \pi_{ind}^{j} \tag{7.23}$$

Integrating equation 7.21 into 7.18 will give us a revenue model as follows:

$$Revenue = (\frac{\ln(q_{ind}^{j})}{\theta_{ind}^{j}} + \pi_{ind}^{j}).Q \tag{7.24}$$

This can be optimised for the revenue in order to maximise sales or to integrate it into 7.17 in order to optimise it for profit maximisation and/or cost minimisation and revenue maximisation.

Applying the given equations (7.17 – 7.24) to the current multi-objective model will generate a complexity in the model and make it difficult to solve. However, the use of a hierarchical solution method or piecewise linear approximations could simplify this and help to identify an optimum solution.

7.3. Comments

The model proposed in this work should be applied to the logistics system as well, so that both manufacturing and logistics systems are run together for an optimum solution covering the entire supply chain. Furthermore, this model could be updated to a detailed supply chain system, which integrates multi-supply, distribution and demand for more accurate results. An AHP hierarchy solution algorithm should be used to consider all of the criteria, as well as adding flexibility in order to simplify the model. Finally, in order to optimise the profit with three proposed correlated variables only one objective should be employed.

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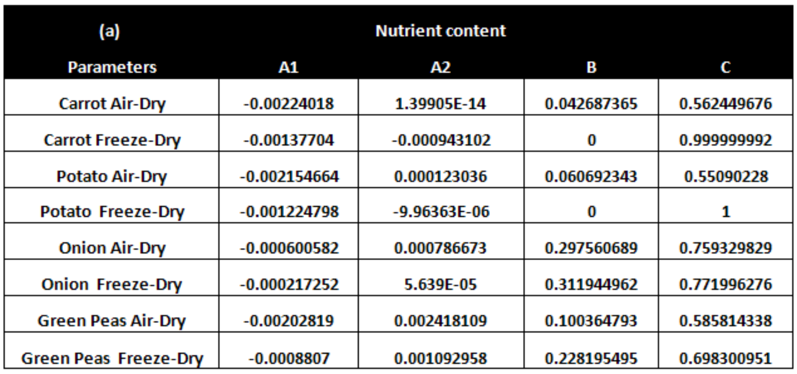
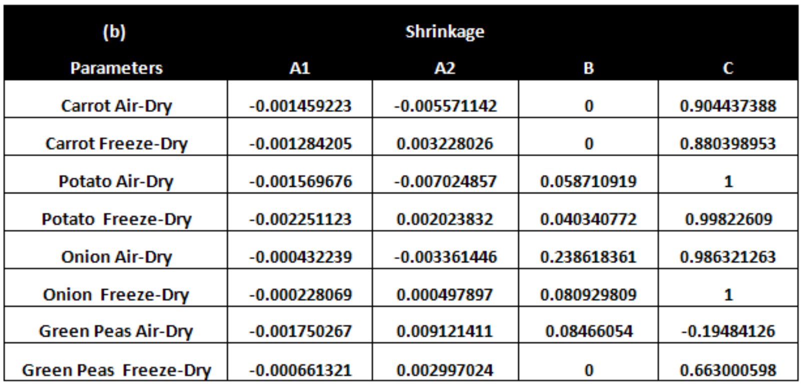
Appendix

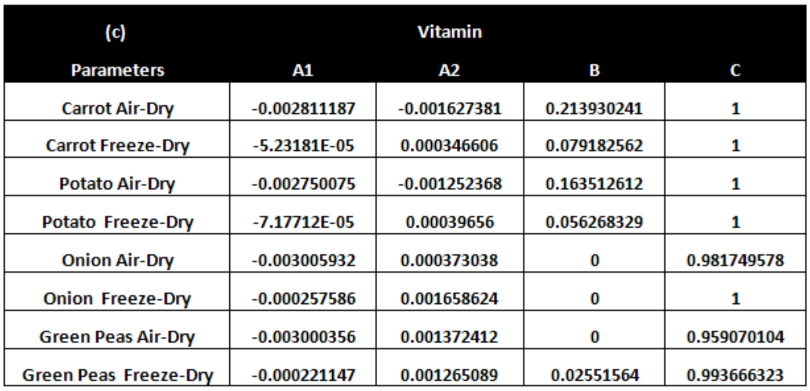
In this appendix tables are shared to show the parameters of the quality model for different quality indicators.



(a)	Nutrient content			
Parameters	**A1**	**A2**	**B**	**C**
Carrot Air-Dry	-0.00224018	1.39905E-14	0.042687365	0.562449676
Carrot Freeze-Dry	-0.00137704	-0.000943102	0	0.999999992
Potato Air-Dry	-0.002154664	0.000123036	0.060692343	0.55090228
Potato Freeze-Dry	-0.001224798	-9.96363E-06	0	1
Onion Air-Dry	-0.000600582	0.000786673	0.297560689	0.759329829
Onion Freeze-Dry	-0.000217252	5.639E-05	0.311944962	0.771996276
Green Peas Air-Dry	-0.00202819	0.002418109	0.100364793	0.585814338
Green Peas Freeze-Dry	-0.0008807	0.001092958	0.228195495	0.698300951



(b)	Shrinkage			
Parameters	**A1**	**A2**	**B**	**C**
Carrot Air-Dry	-0.001459223	-0.005571142	0	0.904437388
Carrot Freeze-Dry	-0.001284205	0.003228026	0	0.880398953
Potato Air-Dry	-0.001569676	-0.007024857	0.058710919	1
Potato Freeze-Dry	-0.002251123	0.002023832	0.040340772	0.99822609
Onion Air-Dry	-0.000432239	-0.003361446	0.238618361	0.986321263
Onion Freeze-Dry	-0.000228069	0.000497897	0.080929809	1
Green Peas Air-Dry	-0.001750267	0.009121411	0.08466054	-0.19484126
Green Peas Freeze-Dry	-0.000661321	0.002997024	0	0.663000598



(c)	Vitamin			
Parameters	**A1**	**A2**	**B**	**C**
Carrot Air-Dry	-0.002811187	-0.001627381	0.213930241	1
Carrot Freeze-Dry	-5.23181E-05	0.000346606	0.079182562	1
Potato Air-Dry	-0.002750075	-0.001252368	0.163512612	1
Potato Freeze-Dry	-7.17712E-05	0.00039656	0.056268329	1
Onion Air-Dry	-0.003005932	0.000373038	0	0.981749578
Onion Freeze-Dry	-0.000257586	0.001658624	0	1
Green Peas Air-Dry	-0.003000356	0.001372412	0	0.959070104
Green Peas Freeze-Dry	-0.000221147	0.001265089	0.02551564	0.993666323

(d)	Colour			
Parameters	**A1**	**A2**	**B**	**C**
Carrot Air-Dry	-0.000527876	0.000621895	0	0.905096679
Carrot Freeze-Dry	-6.47816E-05	0.000890631	0.097167961	1
Potato Air-Dry	-0.000374406	0.000793711	0	1
Potato Freeze-Dry	-0.000235329	0.001610469	0.11292307	0.9498693
Onion Air-Dry	-0.001210027	0.003388088	0	0.369133323
Onion Freeze-Dry	-0.001662565	0.005233546	0.055061912	0.732701392
Green Peas Air-Dry	-0.002064598	0.001383767	0.1	0.79374142
Green Peas Freeze-Dry	-0.001729644	0.003598404	0.190198961	0.780541729

(e)	Texture			
Parameters	**A1**	**A2**	**B**	**C**
Carrot Air-Dry	-0.002012952	0.002809118	0	0.357456002
Carrot Freeze-Dry	-0.000233822	-0.001156	0.03315162	0.994537649
Potato Air-Dry	-0.002149102	0.002663764	0.037894146	0.363037377
Potato Freeze-Dry	-0.00021504	-0.001284791	0.031631461	1
Onion Air-Dry	-0.000180927	0.003225977	0.13511832	0.448604083
Onion Freeze-Dry	-0.000528573	0.001419357	0	1
Green Peas Air-Dry	-0.001135767	0.001661032	0	0.5
Green Peas Freeze-Dry	-0.000628547	0.001521996	0.2	0.570435748

(f)	Microbial degradation			
Parameters	**A1**	**A2**	**B**	**C**
Carrot Air-Dry	0.000768799	1.26093E-10	0.659225125	0.177571799
Carrot Freeze-Dry	0.00117638	8.79105E-11	4.84865E-10	0.815532635
Potato Air-Dry	0.000683048	9.18559E-12	1.00664E-09	0.950077841
Potato Freeze-Dry	0.001106162	7.87786E-11	4.84865E-10	0.834683098
Onion Air-Dry	0.000770948	9.18559E-12	1.00664E-09	0.926105115
Onion Freeze-Dry	0.001228086	7.87786E-11	1.48996E-09	0.801431033
Green Peas Air-Dry	0.00074881	9.18559E-12	1.00664E-09	0.932142856
Green Peas Freeze-Dry	0.001106162	7.87786E-11	4.84865E-10	0.834683098

Table A-1 quality linear model parameter for (a) Nutrient Content (b) Colour intensity (c) Shrinkage (d) Texture (e) Vitamin and (f) Microbial content degradation.

Correction factor		Nutrient	Content			(a)
Data point	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Carrot	0.007900123	-0.007559575	-0.011332386	-0.015010855	-0.005244001	-0.003057081
Potato	-0.00096912	-0.011258954	-0.017979189	-0.021583643	-0.013818546	-0.005379089
Onion	0.000135835	-0.001988556	-0.011533267	-0.010361137	-0.000155766	0.002010361
Green Peas	-0.001366944	-0.003777419	-0.006187893	-0.004982656	-0.002572181	-0.000161707

Correction factor		Colour	intensity			(b)
Data point	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Carrot	-0.001749804	-0.004275216	-0.00711438	-0.005694798	-0.003228968	-0.002489386
Potato	-0.001851004	-0.002778091	-0.002802395	-0.003493367	-0.002753786	-0.002729482
Onion	0.018844494	-0.005020713	-0.011984505	-0.010412726	-0.003027255	0.004263328
Green Peas	-0.012224224	-0.013149404	-0.013370509	-0.013841252	-0.013778661	-0.012520147

Correction factor		Shrinkage				(c)
Data point	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Carrot	0.013872679	0.008176625	-0.001356458	-0.004842237	0.002690442	0.007367489
Potato	0.023345558	0.00545578	-0.020010931	-0.020220176	0.006988937	0.015167248
Onion	0.040297235	0.016470881	0.006862096	0.000586644	0.025746332	0.033021783
Green Peas	-0.000282218	-0.017061978	-0.020621498	-0.022401257	-0.018841738	-0.006835791

Correction factor		Texture				(d)
Data point	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Carrot	0.005115004	-1.69212E-05	-0.007106768	-0.012901124	-0.000155436	0.003194654
Potato	0.009098379	-0.001547531	-0.005230187	-0.009906581	-0.00289199	-0.000243896
Onion	0.015784978	0.00586734	-1.6966E-05	-0.004792452	0.00225852	0.011436159
Green Peas	0.005596438	-0.004116651	-0.006410106	-0.016589862	-0.00405714	0.000102982

Correction factor		Vitamin				(e)
Data point	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Carrot	0.000102728	-0.005547885	-0.014365165	-0.018607138	-0.010123191	-0.001039245
Potato	0.001810897	-0.00065639	-0.003357011	-0.012240034	-0.001272126	-0.00010608
Onion	0.006272732	-0.000173724	-0.00312018	-0.005200496	-0.003587373	0.004853048
Green Peas	0.015404365	0.009804711	-0.001678392	-0.001395174	0.011671262	0.013537814

Correction factor		Microbial	degradation			(f)
Data point	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Carrot	-0.0173896	-0.00727611	0.02172674	-0.000533783	-0.010647273	-0.014018437
Potato	-0.016014667	-0.005999425	0.000677402	-0.002661012	-0.009337839	-0.012676253
Onion	-0.018801028	-0.012057111	-0.004448098	-0.000643592	-0.008252604	-0.015861617
Green Peas	-0.014065176	-0.005892261	0.020743155	0.021278572	-0.008727677	-0.013563093

Table A-2 quality blending model parameter (correction factor) for (a) Nutrient Content (b) Colour intensity (c) Shrinkage (d) Texture (e) Vitamin and (f) Microbial content degradation.

M	Nutrient content	Colour Intensity	Shrinkage	Texture	Vitamin	Microbial degradation
Carrot	-0.030355097	-0.00651	-0.034189055	-0.023030466	-0.025545455	0.022568645
Potato	-0.030618391	-0.007060909	-0.041546091	-0.022409376	-0.025318182	0.020726199
Onion	-0.008420914	-0.028986987	-0.010681818	-0.009090909	-0.028409091	0.02289075
Green Peas	-0.02644641	-0.036590909	-0.028181818	-0.020090909	-0.028636364	0.02155

Table A-3 quality blending model parameter (M) for Nutrient Content, Colour intensity, Shrinkage, Texture, Vitamin and Microbial content degradation.