Designing food supply chains- a structured methodology: A case on Novel Protein Foods

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This work is dedicated to my family

Abstract

This thesis proposes and implements a structured methodology to aid in chain design and the evaluation and decision making processes that accompany it. It focuses on how to design the entire chain from start to finish, so that the consumer gets a product that he/she wants, *i.e.* concentrating on product attributes rather than on the delivery of the product. The novel protein food (NPF) case from the PROFETAS program was used to develop the methodology. Two attributes of quality were investigated with the qualitative model. Some insights obtained from this model were: the generic supply chain for a food product constitutes the following links: primary production, ingredient preparation/processing, product processing, distribution and retailing and consumer processing. This entire chain from primary production up to and including consumer processing influences the final product; but the relative contribution of the links varies according to the goal for which the chain is being designed and optimised. Chains have to be designed for a specific end product as the chain pathway changes and the relative contribution of the links changes with the product. Chain design also changes with the goal. A linear programming model was developed to design a supply chain for the NPF with lowest cost of manufacture. Exergy analysis was used to study the environmental impact of the NPF chain. These models were combined with multiple criteria decision making (MCDM) to give a structured methodology to aid in the design, evaluation and decision making processes of chain design. Variables in each link of the chain were screened to generate potential supply chains (alternatives) and these were evaluated with two MCDM models and ranked. The goals used to evaluate the alternatives are the quality of the product, the cost and the environmental load. The most important factor in the choice of these models was the ease with which they could handle a mix of quantitative and qualitative information, quantify the qualitative information and generate an overall value for each alternative and generate a preference order. The methodology was successful in focussing the decision makers' attention to the issues on hand. The stepwise process made the decision making process transparent and easy to review and audit.

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Chapter 1

Introduction

1. Introduction to thesis

1.1. Background

In the late eighties, the World Commission on Environment and Development (WCED), also known as the Brundtland Commission, published a report that stressed the significance and value of sustainable development. It defined sustainable development as that which can meet the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). This led to many initiatives in this field. In the Netherlands, the Sustainable Technology Development (STD) program was launched (Weaver *et al.*, 2000). One of the focal points of this program was the production and consumption of protein rich foods. Studies were conducted and this led to the multidisciplinary program PROFETAS (PROtein Foods, Environment, Technology and Society).

PROFETAS, started in 1999, aimed to investigate whether a shift from animal protein to plant protein in the western diet would be socially acceptable, environmentally sustainable and technologically feasible. Studies conducted earlier showed that the conversion of protein in feed grains to animal protein is inefficient. Depending on the type of animal and production conditions, on average, six kilograms of plant protein is needed to yield one kilogram of animal protein (Pimental & Pimental, 2003, Smil, 2000). As a large percentage of the grain grown today is utilised to feed meat producing animals, a reduction in the consumption of meat and a consequent increased consumption of plant based food would be, in theory, more efficient. However, instead of a shift to a vegetarian diet, the idea of promoting plant based meat replacers, novel protein foods (NPFs) was recommended because it was hypothesised that consumer acceptance was crucial. One of the main conclusions of the STD program was that meat replacers or NPFs would be a feasible option only if they did not imitate whole cuts of meat but instead replaced ingredients in meals (constituents of soups, pizzas, snacks etc.) Initial findings showed that the present products did not satisfy consumers, primarily with respect to taste and texture (Elzerman, 2006); so a new, pea based, environmentally and economically sustainable product of good quality was suggested as a potential meat replacer.

The environmental scientists in the PROFETAS program investigated and developed performance indicators to measure environmental impact of the shift to a partial plant based diet. Findings suggested that the pea based chain is 5-6 times better than the pork meat chain. However, the research concentrated on the primary production of both chains and did not take into account the environmental load that would result from processing the pea to make a NPF (Aiking *et al.,* 2006). A team of social and consumer scientists investigated issues connected with protein politics, international regulations on meat substitutes, consumer diets and preferences, acceptability of vegetarian meals and market and social trends in food consumption habits. It was found that consumers would prefer meat replacers to have the same colour and flavour as meat and take the place of meat in their meals (Elzerman, 2006; Hoek, 2006). It was also discovered that health and environmental issues were not important issues to change over to meat replacers for current meat eaters (Hoek, 2006). Food

technologists and chemists studied the technological properties of pea proteins and possible methods to make the NPFs (O'Kane, 2004; Heng *et al.,* 2004).
It was at this stage that the need for a structured methodology to develop this new product was felt. An efficient system that would look at the requirements of the consumer and society, incorporate this into the design and deliver it to the users was required. In the case of the NPF, a product that was economical, environmentally friendly, tasted good and had a meat like texture had to be developed. *An 'efficient chain design methodology' that would deliver this product had to be developed.*

1.2. The thesis

This thesis is titled: Designing food supply chains- a structured methodology: A case on Novel Protein Foods. A supply chain (SC) is a sequence of connected actors or events or a system that sources, makes and delivers a product to a consumer effectively and efficiently. To ensure this, designs are needed. In the case of a SC, some of the design elements are where to produce and process raw materials and manufacture the product, *i.e.* location decisions; what varieties of raw material and what technologies to use to manufacture the product; how much to make, how to price the product etc. In the case of a food supply chain (FSC), emphasis on what attributes the product should have *i.e.* nutritional value, microbial safety, taste, are also important. In other words, designing is all about planning- looking at requirements and *deciding* what is required. To facilitate this decision making process and to be objective about choices, a structured methodology or a set of working rules becomes essential. The methodology was applied to a case on pea protein based meat replacers (novel protein foods, NPFs).

1.3. The need for a new methodology

Supply chain management and chain design have been the focus of many studies and have been researched widely. It has been realised and accepted that the design and analysis of all the links in the supply chain have to be coordinated to achieve efficient management (Wang *et al.*, 2004). Traditionally, supply chain management refers to managing a supply chain to meet end-customer needs through product availability and responsiveness, on-time delivery etc. Usually, the chain starts at the supplier and ends at the retailer or the consumer and costs are minimised over these links of the chain (Beamon, 1998; van der Vorst *et al.*, 1999; Wang *et al.*, 2004). Research has been centred on production and inventory management, scheduling, distribution and transportation logistics. Commonly used optimization methods are linear and non-linear programming, goal programming, metaheuristics and discrete event simulation. The supply chain metrics or performance indicators or objectives considered are mostly quantitative in nature. The Supply Chain Council (SCC) developed and endorsed the Supply-Chain Operations Reference-model (SCOR), a process reference model that is the cross-industry standard diagnostic tool for supply-chain management. SCOR enables users to address, improve, and communicate supply-chain management practices within and between all interested parties (SCC, 2005). This model endorses for main performance categories- delivery reliability, flexibility and responsiveness, costs and assets- to measure SC performance.

Van der Vorst *et al.* (1999) presented a method to model the dynamic behavior of supply chains (SCs) and proposed alternative designs by using discrete event simulation. They used design variables and points of uncertainty to create alternative scenarios. Some of the performance indicators that they used to measure SC performance were holding costs, costs of logistics, delivery reliability of producers, remaining product freshness and product assortment. Wu and Grady (2001) used a network based approach to SC design. In both cases the evaluating criteria were quantitative. Wang *et al.* (2004) used the analytical hierarchy process and pre-emptive goal programming to relate product characteristics to SC strategy. They used SCOR's supply chain metrics to select the best supplier but did not study or design the rest of the chain.

Some studies have looked at decision making tools to study and evaluate chain designs. Bovea and Wang (2002) used quality function deployment (QFD) with multiple criteria decision making (MCDM) models to evaluate pre selected product concepts. The method derived indices for the evaluating criteria with QFD and incorporated those into the MCDM models. Qualitative data was easily handled. The alternatives used were preselected and the method does not propose a way to generate and select alternatives. The effect of only product design and not the entire chain on the evaluating criteria was studied. Bevilacqua *et al.* (2004) used MCDM to chose an optimal blanching – freezing system. This is a localized study in the processing link and did not take into account the effect of the rest of the chain on the product. All the criteria considered were quantitative in nature.

Zak *et al.* (2002) studied the redesign of a distribution system with MCDM. They started with the existing chain, studied it and created different scenarios or alternatives by making changes to the old chain. Balcomb and Curtner (2000) used MCDM to aid in the planning stage of designing buildings. Vital decisions are made at this stage and using a comprehensive tool helps to set priorities, performance targets and ensure that all important issues are considered.

Food supply chains are different from other supply chains. Attributes of the product such as the taste, texture and nutritional level are very important to the consumer and could influence the success of the chain as much as traditional supply chain metrics can. Qualitative performance indicators like consumer acceptance and the taste of a product need to be taken into account along with structural decisions like the location of processing facilities and transportation modes.

The chain design methodology for the NPF needs a comprehensive and complete method that can take into account:

- qualitative and quantitative data
- multiple and conflicting goals
- consumer preferences
- the generation of alternatives when they are not obvious
- the screening of alternatives when there are too many
- product attributes along with regular SC metrics
- that supporting models may have to be developed to measure criteria in the chains, especially qualitative criteria

- that all goals or metrics are not equally important; also in the case of multiple stakeholders, relative importance may be different to the different parties involved

1.4. The gap

A search of the literature reveals that there are methods that do some of the above tasks but not all simultaneously. A new method needs to take into account all the choices available to the decision makers or developers and aid in decision making. Thus, the need for a decision making methodology that integrates multiple and conflicting goals, both qualitative and quantitative in nature, generates and screens alternative chain designs and evaluates them on the basis of the goals became imperative. The methodology has to find a means to measure objectives or goals like environmental load and cost in the chain and a way to ‘measure’ or evaluate quality, along with decisions regarding processing and manufacturing locations. The method has to use product attributes as chain design goals and not commonly used SC metrics. Another important factor that has to be considered is that the relative importance of goals or objectives in the chain design is different to different actors and links in the chain.

1.5. The hypothesis

To be able to design a successful supply chain for a food product which has social and consumer specified attributes, it is necessary to

1. concentrate on the attributes of the product rather than only the delivery of the product
2. take into account the effect of all the links and variables in the chain
3. simultaneously consider all the attributes/goals/objectives of the product and hence of the chain design.

To this end a structured chain design methodology is necessary.

1.6. The research questions

This thesis proposes and implements a structured methodology to aid in chain design and the evaluation and decision making processes that accompany it. It focuses on how to design the entire chain from start to finish, so that the consumer gets a product that he/she wants, *i.e.* concentrating on product attributes rather than on the delivery of the product. The novel protein food case from the PROFETAS program was used to develop the methodology. The questions that arose were:

1. What constitutes the entire supply chain of a food product?
2. Is it product specific?
3. What is the meaning of ‘design’ in the context of a supply chain?
4. How are the attributes of the product and therefore the SC goals chosen?
5. How are multiple, often conflicting goals integrated or balanced?
6. Is there a way to deal with a mixture of qualitative and quantitative data and goals?
7. How can the level of achievement of the goals be measured in a chain?
8. What constitutes an optimal or best chain design?

1.7. The outline of the thesis

Chapter 2 of the thesis presents a qualitative methodology for efficient chain design. The chapter focuses on some quality attributes of NPFs and how to measure them in the SC. It also looks briefly at the cost and environmental load aspects. Chapter 3 describes and uses linear programming to design a FSC with cost of manufacture of the product as the goal. Chapter 4 puts forth the concept of exergy analysis as a means to measure environmental load of a SC and calculates the exergy load for a NPF chain and compares this to a pork meat chain and a pea soup supply chain. Chapter 5 describes the theory of MCDM. Chapter 6 describes the application of MCDM to chain design and along with the measuring techniques used in the preceding chapters, presents a quantitative methodology for chain design. Chapter 7 is the general discussion. The calculations and other supporting material for the work done in this thesis are compiled in appendices.

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Chapter 2

Qualitative methodology for efficient food chain design

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2. Qualitative methodology for efficient food chain design

2.1. Introduction

Consumer demands for better and cheaper products, together with the technological developments and open markets have changed the production, trade and distribution (*i.e.* the supply chain) of food products beyond recognition (Trienekens & Omta, 2001). Many studies have been done on food supply chain modelling (van der Vorst, 2000) and management processes in chains (Trienekens, 1999). Work has also been done on calculating the environmental load of production chains using Life Cycle Analysis LCA (Andersson & Ohlsson, 1999). Quality function development is used to aid product developers to link preferences of consumers to the food product (Costa *et al*., 2001). However, the studies by van der Vorst and Trienekens focus on optimising the logistic aspects of supply chain performance; the studies on LCA, on the environmental load only and QFD does not consider the entire supply chain. The design of food supply chains (Figure 2.1) for products that have good quality are not expensive and environmentally friendly, right from primary production to the consumer is a challenging task. There are many pathways to obtain each product and many links (actors) and sub-links. Present optimization tools concentrate on individual aspects rather than on the entire chain. It is important to have a tool that can take into account multiple goals for a product. Methodologies that are able to handle this complex process of designing supply chains have not yet been developed. This paper seeks to remedy this problem by presenting the qualitative part of an approach to develop a methodology for multiple-goal food chain design by looking at two goals (quality and environmental load) independently of each other.

A chain is a network of autonomous and named organisations that co-operate to produce a product. The relationship between the organisations can vary from direct linear to complex network forms (van Dalen, 1994). It is a consecutive sequence of events or activities that prepare a product for the end user (Tijskens *et al.,* 2001). The participating enterprises form a network that mutually co-operative and the enterprises are inter-dependent not only for their raw materials but for services and information. Porter (1980) defined a value chain—consisting of five operations that together prepare a commodity for a specific consumer: production/inbound logistics, production, outbound/distribution logistics, marketing and sales.

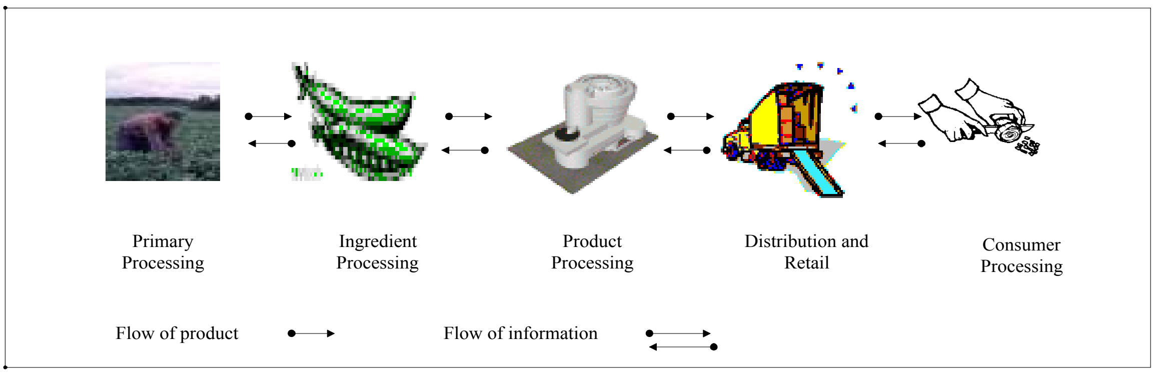

Figure 2.1: The food supply chain

The main fact that differentiates food supply chains from other chains is that there is a continuous change in the quality from the time the raw materials leave the grower to the time the product reaches the consumer. The quality of a food product—the end result of a food production and distribution chain-is more than just the intrinsic qualities of the purchased product. When a buyer is faced with a range of products, he/she finds a balance between, among others, personal preferences, the assumed properties of the product, the preferences of the end user of the product and the cost of the product (Tijskens *et al.*, 2001). Another important fact to be taken into consideration is the health and safety aspects of foods, especially for new products, both in the long and short run.

Food supply chains are rapidly moving towards globally inter-connected systems with a variety of relationships. A number of products from markets all over the world are increasingly available to consumers; making these products accessible at competitive costs is the focus of much research today. Knowledge from food process technology, operations research, environmental science, marketing and business economics has to be combined to enable the design of such chains.

2.2. Definitions and boundary conditions

Supply chain: a possible pathway to manufacture and deliver a particular product to a consumer
Attributes: the product for which the chain is being designed will have desired attributes that the consumer wants, *e.g.* good mouth-feel, attractive colour.
Goals: The attributes are used to select the goals to evaluate and optimise the chain. The goal may be very specific and measurable like low product price. In some cases the goal may not be directly measurable, *e.g.* good quality. In such cases it must be further defined. *e.g.* good quality can, for example, be defined as good texture.
Performance indicator (PI): The performance indicator is a measurable characteristic that is related to the goal under consideration. It is used to judge the effectiveness or efficiency of the chain with respect to the target attributes that the consumer desires, *e.g.* water holding capacity of the protein as a measure of texture (Zayas, 1997; van Oeckel *et al.,* 1999). A PI should have the following properties (Caplice & Sheffi, 1994):

- Easily measurable: essential that the PI can be objectively measured or calculated
- Valid: it has to be related to the goal and the attribute already chosen
- Useful: easily understood by all the parties using it
- Economic: the benefits of using the PI should outweigh the cost of data gathering, analysis and reporting

Control variables: These are the independent variables whose value can be adjusted to obtain the target PI so as to realise the attributes, *e.g.* processing temperature, feed composition. Table 2.1 elaborates on these definitions with examples.

Boundary conditions:

- Consumer demands should be met. The chains are therefore traced backwards, *i.e.* described from what the consumer wants back through to primary production.
- The chains are designed for an end product that has specific attributes.

Table 2.1: Definitions and examples

Attributes	Goals	Definition	Performance indicators
Good taste	Good quality	Texture	Water holding capacity, g water/g product
		Flavour	Sugar level, flavour volatiles
		Colour	Carotenoids, chlorophyll, maillard reaction products
		Nutritive value	Anti nutritional factors, cholesterol, levels of essential amino acids, level of ANF
Cheap	Low cost	Low selling price	Euro/g, Euro /kg
		Low cost price	Euro/g, Euro /kg
Does not harm the environment	Low environment load	Low energy use	Joules/g product, Joules/ kg product
		Less waste generated	Kg waste/ kg product
		Exergy analysis	Exergy input, Exergetic efficiency

2.3. Methodology

The design of a methodology with an overall view is complicated as there are many variables, pathways and goals that have to be optimised. If there are multiple goals, the issues with trade offs will arise. This paper deals with the goals (quality and environmental load) separately to present the issues and challenges involved with each with the aid of case studies on novel protein foods. The goal of low cost is investigated in a separate study (Apaiah & Hendrix, 2005) and the three goals, quality, costs and environmental load, will be integrated in future work.

First a qualitative model is developed. For a given product, goals and production chains are chosen and the relationships between the performance indicators of the goals and the control variables are determined. The important relationships are identified. A quantitative model is then developed and different optimisation approaches and sensitivity analysis are used to design the chain quantitatively. Figure 2.2 illustrates the steps that have to be taken according to the methodology by the chain designer.

<u>Part 1: The qualitative model</u> (Figure 2.2)

1. Identify the product for which the chain is to be designed.
2. a. Identify the attributes that the consumer desires in the product *e.g.* good mouth-feel, healthy, cheap.
   b. From consumer studies assign minimum acceptable scores or a range of scores to these attributes.
3. From the attributes identify the goal that will be used to evaluate the chain- good quality, low cost, low environmental impact. *Continue by choosing one goal, e.g. good quality.* Define the goal. C*hoose one definition, e.g.* Texture.

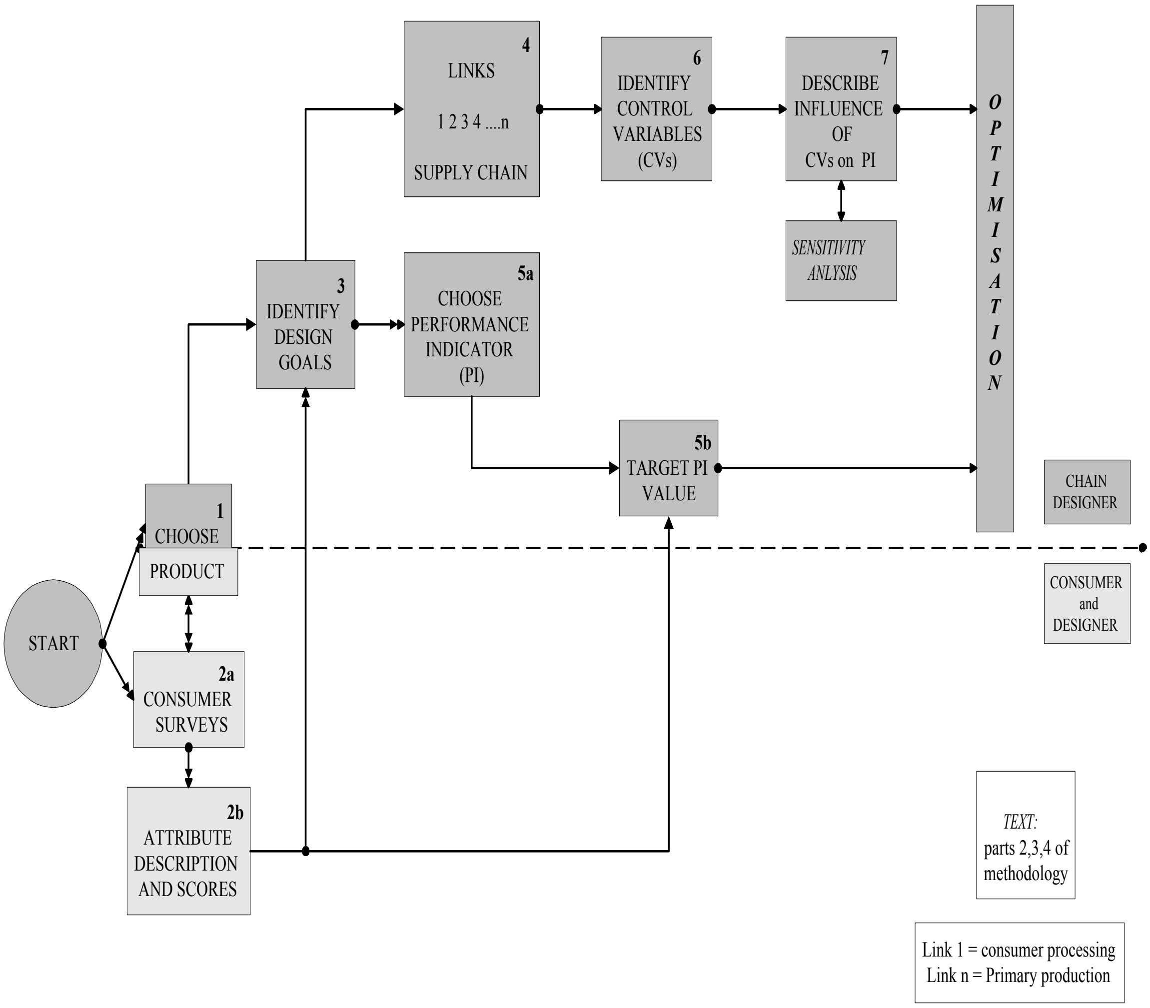

Figure 2.2: Methodology to derive the model

4. Define all the links in the chain required to obtain the product from primary production to the end-user. It is possible that multiple chains will be obtained for the same end product. *Choose a chain for which maximum information is available.*
5. a. Choose a performance indicator that is relevant to the attribute and goal under consideration.
   b. A product with a minimum/range of attribute scores can be related to a target value for the PI.
6. Identify all the control variables (process variables) of the chosen chain that are relevant to the chosen PI.
7. Identify and define all the relationships between the PI and the control variables starting from the consumer end of the chain and going back to primary production.

Part 2: Identifying the important relationships

Many of the relationships between the control variables and the PI defined above may not be relevant for the chosen goal. It is therefore important to make necessary assumptions and eliminate all irrelevant relationships before the quantitative model can be developed.

Part 3: The quantitative model

The identified relevant relationships from above are described in greater detail, preferably mathematically.

Part 4: Sensitivity analysis and optimisation of the chain

The quantitative relations are used to find values for the control variables over all the links in the chain such that the overall performance is optimal. Sensitivity analysis will be done to evaluate the variation in the output of the model to changes in the input data, parameters and assumptions.

Table 2.2: Process and farm value*

Product	Retail price, $/kg	Marketing margin, $/kg	Farm value, $/kg	Farmer's share, %
Potato	8.37	6.92	1.45	17.37
Frozen French fries	2.31	2.09	0.22	9.52
Potato chips	7.40	6.83	0.57	7.74
Lettuce	1.63	1.23	0.40	24.32

*www.ers.usda.gov (2000)

As this paper deals with the qualitative model, it focuses on Parts 1 and 2. An analysis of the cost of a generic food product is presented to exemplify this methodology. This is followed by the case studies.

Product: *A processed food product*
Attribute: Inexpensive product
Chain: Generic processing

- Consumer processing
- Distribution/retailing
- Product processing
- Ingredient processing
- Primary production

Goal: Low cost
Performance indicator: Food dollar, cents/food $
Target cost: As found from consumer studies
Since the chains are traced backward from the consumer through to primary production, the last activity before consumption, consumer processing is called link 1 and primary processing is the final link (link n).

Figure 2.3 shows the distribution of the consumers' food dollar between the links of the chain for a generic processed food product (Kohls & Uhl, 1998). This Figure however, gives only the distribution of the food dollar and not the actual cost to the consumer. The actual cost of the product at each link depends on the final retail price of the product (Table 2.3a and b). From this table, it can be seen that as the degree of processing for the product increases, the farm share will decrease and the marketing share (processing) will increase. However, if a minimally processed or fresh product has to be transported over a large distance to the market, the farm value will decrease and the marketing (transportation) share will increase (as in the case of lettuce in Table 2).

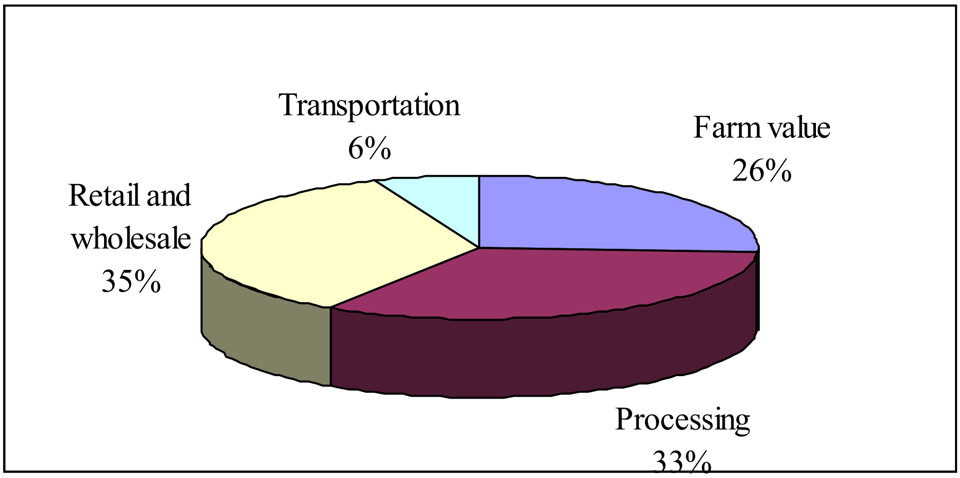

Figure 2.3: Distribution of the food dollar (Kohls & Uhl, 1998)

This information shows the importance of the chain approach and the contribution of the links to the final cost of the product. Missing information that is relevant to the study can easily be identified *e.g.* how the price of the product can be influenced by the control variables at each link in the chain. A possible PI for studying the price of the product can be the 'value-added' at each link. This question will need to be studied in detail to be able to understand the impact of the valued added at each link to the total cost of the product and to the goal of minimising costs. A case study on cost of novel protein foods can be found in Apaiah and Hendrix (2005).

2.4. Case study-novel protein foods

2.4.1. Introduction

The case material presented in this study was collected in the framework of PROFETAS. PROFETAS is a multidisciplinary research project in the Netherlands that aims to investigate whether a shift from animal protein to plant protein in the western diet is socially acceptable, environmentally sustainable and technologically feasible. It was hypothesised that the current food production and consumption pattern has a strong impact on the environment and natural resources. Meat production in particular is not appealing from an environmental point of view because of the inefficient conversion of protein in the feed into protein in the slaughtered animal. The non-meat protein products presently on the market do not meet the expectations of most consumers and thus cannot be considered realistic alternatives to meat. The prospects for replacing meat-derived ingredients by non-meat ingredients- Novel Protein Foods (NPF) are more promising (www.profetas.nl).

There are several reasons why the non-meat products currently available have not been very successful. The texture, taste and the price of these products limit their popularity. Manufacturers of these products have to be aware, that for such products to be successful, important criteria (from the consumers' point of view) in the development of NPFs (based on plant proteins) are the texture and price but from society's point of view, it is the environmental load and sustainability of the products that matter. The design of a successful supply chain is therefore an important task.

Case study A is an in depth analysis of the qualitative model investigating the goal of quality. Case B looks at the goal of lowering environmental load for two products, a NPF and pea soup. The two products are made from the same raw material but are very different because of the processing they undergo.

2.4.2. Case study A

Product: *A texturised product pea-based similar to Tivall™ Vegetarian Mincemeat*
Attribute: Good mouth-feel
Chain: The five main links in the supply chain for the NPF are:

- Consumer processing
- Distribution/retailing
- Product processing- Extrusion
- Ingredient processing- air classification and milling
- Primary production

Goal: Good quality
Performance indicator: Water holding capacity (WHC) and Protein content (PC)

Food quality can be defined in many ways. However, a large contributor to the quality of a food is its texture *i.e.* the sensation the food imparts to the mouth as the food is bitten, chewed and swallowed (Rosenthal, 1999). The critical importance of food texture to optimal food quality depends on the relationship between food texture and processing operations. Food texture as experienced during consumption is difficult to measure as it is subjective and depends on a consumer's perception. Juiciness is an aspect of texture that can be measured by the water holding capacity of the product (www.ansci.uiuc.edu/meatscience).

The water binding capacity (WBC) of a protein is defined as: grams of water bound per gram of protein when dry protein powder is equilibrated with water vapour at 90–95% relative humidity. The water holding capacity (WHC) is more important in food applications than WBC (Fennema, 1996). WHC refers to the ability of a protein to imbibe water and retain it against gravitational force within a protein matrix. This water refers to the sum of bound water and hydrodynamic water and physically entrapped water. The contribution of the latter is more than the first two together. It has been found that WHC is positively correlated with WBC of a protein. Thus, WHC was chosen as the PI. The water hydration capacity (or water absorption or water uptake or water holding or binding) is defined as the maximum amount of water that 1 g of a material will imbibe and retain under low speed centrifugation. This method is not affected by the solubility if the material (AACC method 88-04, AACC (1995)).

Target value: Consumer sensory panels assign a minimum acceptable sensory score to the mouth-feel; this translates into a target water holding capacity of WHC0, g/g product (after consumer processing). The protein content of meat and meat ingredients is usually between 20 and 30%. As these novel protein foods are targeted to replace meats and meat ingredients in a consumer's diet, they should have comparable protein content; the target protein content will be called PC0, g/g product (wet basis).

Identifying the control variables and relationships: The relationships between the PIs and the control variables in the links were found through literature studies, internet searches and consultation with experts. The information obtained was qualitative, quantitative, and heuristic and in some instances, it was not possible to define the relationships.

Tables 2.3a and b show the results of the investigation of the influence of the control variables on two PIs, *i.e.* the WHC and the crude protein content (PC) as they are traced from Link 1 (consumer processing) to Link 5 (primary processing). In each link, the PI is influenced by the control variables of that link *e.g.* after Link 4 and before Link 3, the product had a WHC=WHC3. After link 3, the value changes to WHC4. This is due to the effect of the control variables of extrusion processing on the water holding capacity of the product.

Identifying important relationships: Many of the relationships between the control variables and the PI defined are not relevant for the goal of quality.

Link 1: The storage time before use has no effect on the WHC of the product because it is assumed that the product is used before the 'use before date' and the WHC after link 3 is optimised for this period.

Link 2: The storage time and temperature during retail and distribution does not affect the WHC of the product as it is assumed that the product is sold before the 'use before date' and it is stored below 4 °C.

Link 4B: The process variables in this link do not influence the PIs and therefore are not taken into account (Tables 3a and b).

Waste is generated at each link of the chain. As it does not affect the quality of the product, the waste is not taken into consideration in this case.

Observations: After an extensive investigation of several months, it was clear that it was not possible to describe satisfactorily all the relationships between the PI and the control variables. Some links have more influence on the PI than the others. When the goal is quality, consumer processing and product processing have the greatest effect on the PI. However, it is important to note that the other links also contribute to the product quality (in this case study quality refers to the product texture). In Link 2 it was assumed that the product was stored below 4 °C and was used by the 'use before date'.

Table 2.3a: Control variables and their effect on the performance indicators

Value of PI before the link					Target value PI after link
	LINK 1	Consumer processing			
	Control variable	WHC	PC	Comments	
WHC1, PC1 (PC1= PC0)	Storage time before use	No change if used before critical date	No change		WHC0, PC0
	Cooking method	No information	No information	PC decreases if boiled (soluble protein may leach) 34*	
	Cooking temperature	Changes	No change		
	Cooking time	No information	No information		
	Time for consumption	expected to decrease	No change		
	LINK 2	Distribution and retail			
WHC2, PC2 (WHC2=WHC 1 PC2=PC0)	Temperature	No change if temperature below 4°C	No change		WHC1, PC1 (PC1= PC0)
	Time	No change if used before critical date	No change		
	LINK 3	Product processing-Extrusion			
WHC3, PC3 (PC3=PC0)	Screw speed (F)	Increases with increase in F 36	No change	WHC = 2.09 – 0.023D + 0.0007F + 0.004I - 0.0041 B + 0.0002DB – 0.00014 DI 36	WHC2, PC2 (WHC2=WHC 1, PC2=PC0)
	Barrel temperature die end (B), middle (I)	Increases with increase in B 36	No change		
	Moisture content of the feed (D)	Decreases with increase in D 36	No change		
	Feed composition	Changes 36	Changes		
	Product temperature	Increases 8,14,15, 20,24,37,40	No change		

Link 4

* number is the reference for the text

Table 2.3b: Control variables and their effect on the performance indicators (contd.)

Value of PI before the link					Target value PI after link
	LINK 4A	Ingredient processing- Air classification and milling			
	Control Variable	WHC	PC	Comments	
WHC4A, PC4A	Classification speed (x)39	As the protein content increases, WHC will increase 15,26,27	Increases	PC = 4.7055x + 8.0018, R2 = 0.935739	WHC3, PC3 (PC3=PC0)
	Cut point (decrease)10,11		Increases		
	Vane angle (low)		Increases 22		
	% particles below 16 mm		Increases		
	Protein content of pea seed = x 14.5 –28.5 %		Increases	PC = 1.4x + 20.322	
	Protein content of non-starch portion = x		Increases	PC= 1.863x-47.833 25	
	Mesh size % particles under 16 □m 13,18	As the protein content increases, WHC will increase15,26,27	Increases		
	Number of passes (Low)		Increases		
	Temperature	Increases till a specific value of NSI 8	No change		

	LINK 4B	De-hulling			WHC4A, PC4A
WHC4B, PC4B	No influence on WHC and PC		Increases29		

	LINK 5	Primary production			
WHC5, PC5	Variety	No information	Influences6,19,38		WHC4B, PC4B
	Harvest maturity	Changes21	Changes		
	Solar energy	No information	No information		
	Inoculation	No information	No information		
	Fertilization	No information	No information		

If these two conditions are violated, the quality of the product will deteriorate rapidly. A technologically 'good' product can be obtained after link 3 (product processing); however, if the consumer overcooks the product or uses it after the recommended date, the quality obtained after Link 3 will be lost.

Looking at Table 3a and b from the chain perspective, it can be seen that the target value of PC0 is achieved after Link 4 (PC3=PC0). Product processing, distribution and retail and consumer processing (if cooked using recommended directions) will not affect the protein content of the product. In the case of water holding capacity, the target value is almost achieved at the end of product processing and will reach the target value after Link 1. The control variables in consumer processing (after which the PI reaches the desired value) influence the texture of the product greatly and therefore can 'make or break' the product.

2.4.3. Case study B

Case B is based on a study by Steen (2002) where two products made of the same raw material are compared on the basis of their exergy requirement. This study is interesting from the chain designer's perspective. It can be viewed as two different product chains with the same goal: low environmental load as measured by exergy requirement. The highlights of the analysis, following the qualitative methodology outlined above, are presented below.

Product 1: *A texturised product pea-based similar to Tivall™ Vegetarian Mincemeat*
Attribute: Environmentally friendly
Chain: The links are the same as in Case A
Goal: Low environmental load
Performance indicator: Exergy input (MJ/kg product) and exergetic efficiency
Target value: Lower exergy input and maximum efficiency.

Product 2: *Pea soup (minimally processed product)*
Attribute: Environmentally friendly
Chain: The four main links are:

- Consumer processing
- Distribution/retailing
- Ingredient processing- Sorting and packaging
- Primary production

Goal: Low environmental load
Performance indicator: Exergy value, (MJ/kg product) and exergetic efficiency
Target value: Lower exergy input and maximum efficiency.

Performance indicators and target value: Indicators of environmentally sustainable development are increasingly important. They provide concrete measures of effectiveness and hence, accountability. Indicators are used to measure the state the environment is in. There are numerous environmental indicators: animal populations; plant condition; air, water and soil quality, emissions of carbon dioxide, -all these change in response to pressures on the surrounding environment.

Exergy is defined as the amount of work that can be obtained from an energy source *i.e.* the quality of an energy source. The concept of exergy is based on the First and Second Law of Thermodynamics (Szargut *et al.,* 1988). In contrast to energy, exergy is exempt from the law of conservation. The main objectives of the analysis are to identify the causes and calculate the magnitude of exergy losses (Szargut *et al.*, 1988). An exergy balance applied to a process or a whole plant, tells us how much of the available work (or exergy), supplied as the input to the system under consideration has been consumed (irretrievably lost) by the process (Kotas, 1995).

Exergy can be used as a PI to evaluate the chain for environmental impact. Exergy inputs for the various links can be calculated and the links that require the highest inputs can be identified and the total chain can be redesigned and optimised. The environmental impact can also be assessed by calculating the exergetic efficiency of a chain. A chain with high exergetic efficiency will have a lower impact on the environment. There are many ways to calculate exergetic efficiency (Equation 2.1)

$$Eff = \frac{Ex_{out}\,product}{Ex_{in}\,total} \tag{2.1}$$

where Ex_{out} product = Exergy value of the produced end product (MJ), Ex_{in} total = Total of all exergy inputs in the production chain (MJ)This equation calculates exergetic efficiency only on the basis of the desired product. All by-products are considered to be wastes. This equation calculates exergetic efficiency only on the basis of the desired product. All by-products are considered to be wastes.

Observations: Figure 4 shows the exergy inputs into the NPF chain and the pea soup chain. In the case of the NPF, a highly processed product, the highest inputs are required in the processing link (50%) and in the consumer processing link (26%). The pea soup chain has the largest input from the consumer processing link (long cooking time required to make pea soup) and the next largest contributor is retail followed by primary production. The stage of product processing is completely absent. As the end products are different, the chains for the products are dissimilar and, the relative contribution of the links to the goal of low environmental load is different. For details refer to Apaiah *et al.,* (2006).

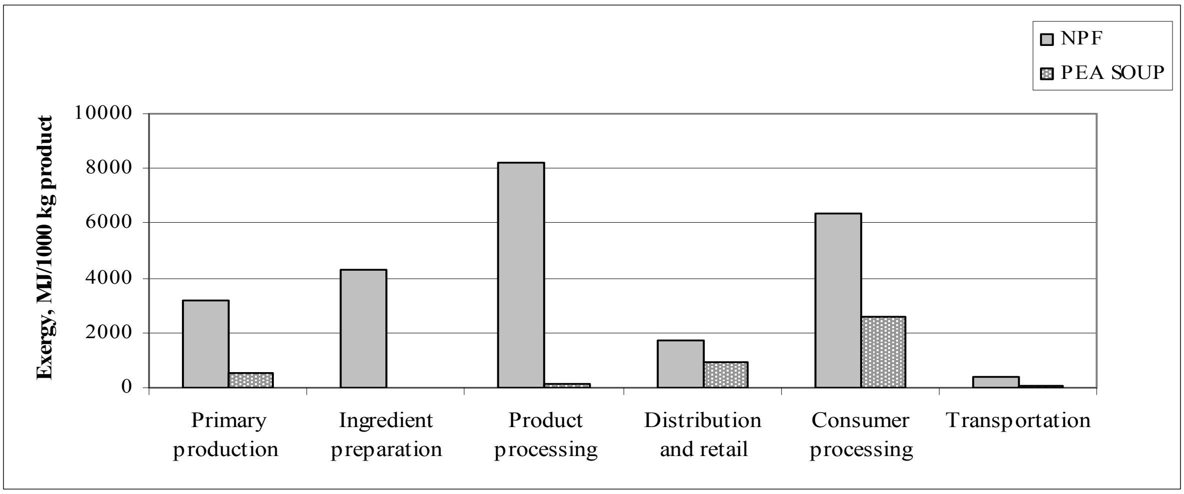

Figure 2.4: Exergy input at each link to get 1000 kg of end product

2.5. Conclusions

Consumers today demand high-quality products in various innovative forms through the entire year at competitive prices. However, there is a growing concern in society and among some consumers about the traceability and environmental load of food products and manufacturing processes. These issues can be better addressed and tackled if there is an efficient method to design food supply chains right from primary production up to and including the consumer. Developing a methodology to design food supply chains for such products therefore becomes a relevant and pertinent concern.

Chains have to be designed for a specific end product as the chain pathway changes and the relative contribution of the links changes with the product. Case study B illustrated that the contribution of the different links was different for the pea soup and novel protein food chains though the goal was the same. This analysis pinpoints the weak links and shows where improvements will have the most impact.

Chain design also changes with the goal. As consumer demand has to be met, it is important to ask the consumer what attributes he/she desires in the product as these attributes are used to select the goals to design the chain. If the goal is high quality, with cost being a non- issue, then technologically advanced and consequently expensive equipment can be used to produce the product and it can be transported to the consumer by air. However, if the goal is a low priced product, care has to be taken while choosing the technologies to manufacture the product and the methods of distribution.

The contribution of the links to the final product also changes with the chosen goal. When the goal is quality, product processing and ingredient processing influence the texture more than the other links; when the goal is minimising costs, distribution and retail play a more important role. However, it is important to remember that even when a ‘perfect’ product is obtained after a link, improper attention at a subsequent link can ruin its quality, increase the environmental load or increase the cost. For example, a product with a satisfactory texture after product processing can be ruined if the temperatures during distribution and retail are not carefully maintained.

The choice of the performance indicator is important as this traces changes to the goal in the chain. The quality of NPFs can be evaluated by their texture, and as water holding capacity (WHC) is a measure of texture, tracing the changes in the WHC of the product as it goes through the chain is a way of monitoring quality changes and optimising the chain for quality. This presents a simplified view of texture and quality, but this is inherent to the fact that a model is not actuality but is an abstraction of reality.

In some cases, it is not possible to describe the relationship between the performance indicator (PI) and the control variables (CVs) satisfactorily. It should be noted however that if more time is spent in investigation and experimentation, the relationships could be determined. What is of importance here is whether the specific relationship is relevant to the goal when considering the total chain (with all links). The relationships are qualitative, quantitative and heuristic. Choosing the relevant relationships and eliminating the others is a critical step. The definition and quantification of the identified relationships may be incomplete and not always accurate. The inclusion of such mixed information into existing optimisation models requires further investigation.

The qualitative model was very useful in recognising the hot spots in the chains. This provided a valuable tool to identify links that need to be optimised together to fulfil the chain requirements. It also gave many other insights as detailed earlier. The development of the quantitative model and the subsequent optimisation of the chain will be the next stage in the methodology. The final stage will consist of integrating the three goals of quality, low cost and low environmental load leading to a true multiple-goal focussed chain design tool.

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Chapter 3

Design of a supply chain network for pea-based novel protein foods

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3. Design of a supply chain network for pea-based novel protein foods

3.1. Introduction

Consumers today demand high-quality products in various innovative forms through the entire year at competitive prices. Society imposes constraints on producers in order to economise the use of resources, ensure animal friendly and safe production practices and restrict environmental damage. These demands, together with the technological developments and open markets have changed the production, trade and distribution (*i.e.* the supply chain) of food products beyond recognition (Trienekens & Omta, 2001).

A supply chain (SC) is an integrated process where raw materials are acquired, converted into products and then delivered to the consumer (Beamon, 1998). The chain is characterised by a forward flow of goods and a backward flow of information. Food supply chains are made up of organisations that are involved in the production and distribution of plant and animal-based products (Zuurbier *et al.*, 1996).

Such SCs can be divided into two main types (van der Vorst, 2000):

- SCs for fresh agricultural products: the intrinsic characteristics of the product remain unchanged and,
- SCs for processed food products: agricultural products are used as raw materials to make processed products with a higher added value.

The main fact that differentiates food SCs from other chains is that there is a continuous change in quality from the time the raw materials leave the grower to the time the product reaches the consumer (Tijskens *et al.*, 2001). A food SC as defined in this paper consists of six links: primary production, ingredient preparation, product processing, distribution, retail and the consumer (Figure 3.1).

Performance measures or goals are used to design SCs or supply networks by determining the values of the decision variables that yield the desired goals or performance levels (Beamon, 1998, Apaiah *et al.*, 2005). The design of the chain or network changes with the goal for which the chain is being designed and optimised. As consumer demand has to be met, it is important to ask the consumer what attributes he/she desires in the product as these attributes are used to select the goals to design the chain, *e.g.* if the goal is quality at any cost, then technologically advanced and consequently expensive equipment can be used to produce the product and it can be transported to the consumer by air. However, if the goal is a low priced product, care has to be taken to minimise production and transportation costs.

The current food production and consumption pattern has a strong impact on the environment and resources and is not sustainable (www.profetas.nl). Meat production in particular is not appealing from an environmental point of view, because of the inefficient conversion of protein in the feed into protein in the slaughtered animal. Novel protein foods (NPFs) are non-meat protein ingredients that are designed to replace meat- based ingredients in meals. The NPFs presently available do not meet the expectations of most consumers and thus cannot be considered realistic alternatives to meat. They are niche products and are expensive when compared to pork. The prospects for replacing meat-derived ingredients by NPFs are more promising. The partial shift from an animal based diet to a plant, specifically pea-based diet may be feasible only if the price of these products decreases. This paper considers an OR approach that can be applied to explore possible chain designs. The interesting question here is whether an NPF based on pea protein is feasible as a price-competitive product, when all essential cost sources are identified.

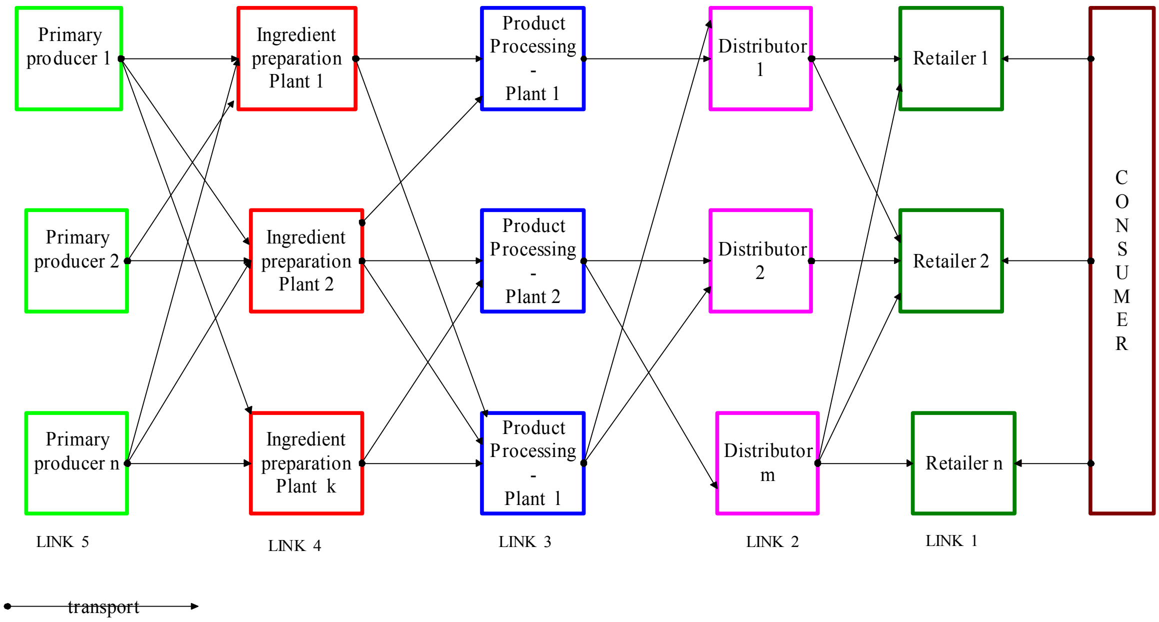

Figure 3.1: Food supply chain

3.2. Case

NPFs based on pea proteins do not currently exist. The proposed product is designed to resemble the vegetarian mincemeat currently available. As mentioned earlier a supply chain consists of two basic processes: 1. Production planning; 2. Distribution and logistics planning (Beamon, 1998). In this study, this is modified as: 1. Production- this includes all the links from primary production to product processing and 2. Distribution- the remaining links. This paper focuses on the first process. The second process of distribution and logistics planning, similar to that of chilled meat products, has been much researched (Chopra, 2003; Jayaraman & Ross, 2003). Designing this part of the chain will not lead to a distinction between the costs of NPF and of the chilled meat Production planning for pea-based NPFs , is a new and unknown area. The aim is to generate scenarios that lead to low costs by designing supply chains with the aid of OR techniques.

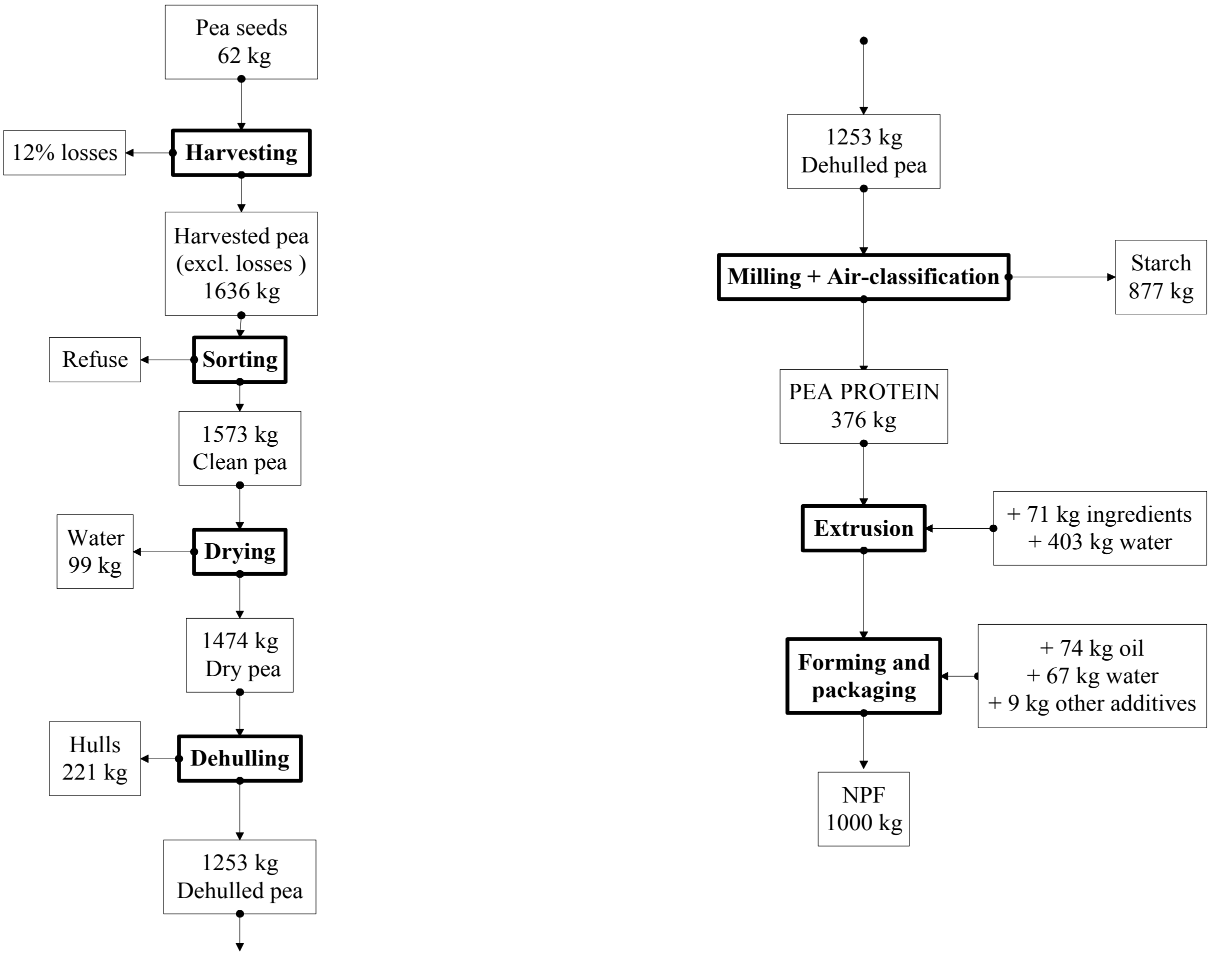

Figure 3.2: Production scheme for NPFs (1000 kg basis)

The supply chain for the first process is divided into three major links: primary production (growing and harvesting), ingredient preparation (milling and concentration of pea protein) and product processing (manufacture of the NPF). The product is designed for the Dutch market. Figure 3.2 shows the production scheme for 1000 kg of the pea-based NPF. The peas are sourced from several locations around the world such as Canada, Ukraine, France and the Netherlands and can be transported by sea, rail, road or barge.

Figure 3.3 illustrates the steps in each link of production. In primary production (PP) plant refuse is the main by-product. In ingredient preparation (ING), the hulls and starch are by-products. Starch comprises about 70% of the dehulled peas and therefore the selling price of the starch (starch is used as a raw material in many applications) is important in the overall cost of manufacture.

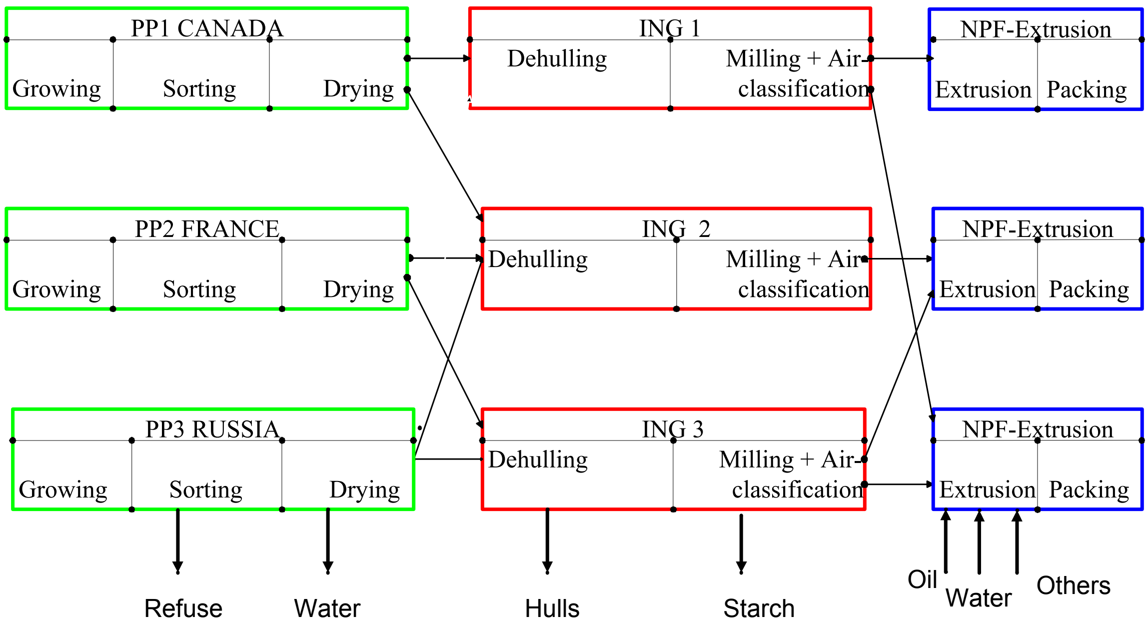

Figure 3.3: NPF production chain

3.3. Model development

The following approach was developed in Apaiah *et al.* (2005). For a given product, goals and production possibilities are identified and the relationships between the performance indicators of the goals and the control variables are determined. The important relationships are identified. A quantitative model is then developed and optimisation approaches and sensitivity analysis are used to design the chain quantitatively.

The paper deals with a long-term exploratory question of the feasibility of pea-based NPFs and therefore considers possible flows and quantities of products, by-products, refuse and production schemes. This deviates from the usual set-up and locations decisions in similar logistics modelling that is used to support decisions for particular companies (Jayaraman & Ross, 2003; Wouda *et al.* 2002). These typically lead to mixed integer linear programming type of models, whereas this paper considers a network flow, a linear programming approach from a long-term perspective.

3.3.1. The qualitative model

According to the methodology presented in Apaiah *et al.* (2005), the relevant aspects to model the underlying supply chain are identified.

Product: A pea-based NPF resembling vegetarian mincemeat
Attribute (as specified by the consumer): An inexpensive product. This product is designed to replace pork meat. The retail price of pork is about €6/kg. The cost of manufacturing is about 38-40% of retail cost (www.ers.usda.com).
Goal: Minimise cost of manufacturing

Chain: An important boundary condition for these chains is that consumer demands should be met. The chains are therefore traced backwards, *i.e.* described from what the consumer wants back through to primary production. The links are: Consumer processing, Distribution/retailing, Product processing- Extrusion, Ingredient processing- milling and air classification, Primary production.
Performance indicator: Value added at each link
Control variables: In this supply chain design problem the following decision variables are considered. Figure 3.4 shows the supply network with the associated variables.

Variables:
PP_i = amount of pea produced at primary production location i
TPI_{ijn} = amount of dry pea transported from location i to facility j via transport mode n
ING_j = amount of ingredient, pea protein concentrate produced at facility j
TIP_{jkn} = amount of protein concentrate transported from facility j to k via transport mode n
NPF_k = amount of NPF produced at facility k
SA_j = amount of starch produced at facility j

Data to evaluate a specific supply chain design includes the following technical and cost coefficients:
wpc_i = whole dried pea cost at location i, €/MT
$tcdp_{ijn}$ = transportation cost of dried pea from PP location i to ING facility j via transport mode n, €/ton
ipc_j = pea protein cost at facility j, €/MT
$tcpp_{jkn}$ = transportation cost of protein concentrate from ING facility j to NPF production facility k, via transport mode n, €/MT
ppc_k = cost of producing the NPF at location k, €/MT
ss_j = selling price of starch from facility j, €/MT
stpt = starch per ton of dehulled pea= 0.7, MT/ MT
npfp = pea protein per ton NPF = 0.376, MT/ MT
ppdp = pea protein per ton of dry transported pea = 0.255, MT/ MT
pwp = percentage of dry pea from total pea produced = 0.805, MT/ MT
demand = total amount of NPF put into the market = 30744 MT;

where:
i = index for PP location (i = 1,2,3…I)
j = index for ING production facility (j= 1,2,3…J)
k = index for NPF production facility (k= 1,2,3…K)
n = modes of transportation (n= sea, rail, road, barge)

The optimisation of the supply network for NPFs in the Netherlands is done using linear programming, similar to work done by Wouda *et al.* (2002). It focuses on finding the lowest cost at which NPFs can be manufactured for a specific market demand; while deciding the location of primary production, ingredient processing and product production areas and modes of transportation by minimising the sum of production and transportation costs (Appendix 3).

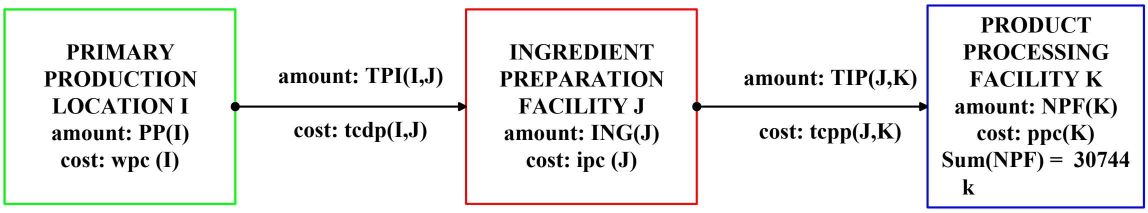

Figure 3.4: Supply network with associated variables and cost coefficients

The market demand: as mentioned earlier, pea-based NPFs are not currently available. The cost of manufacturing a product depends largely on the quantity in question; the larger this amount, the more will be the effect of economies of scale. The research program PROFETAS aims to replace 20% of processed pork consumption by the year 2020. An amount equal to 20% of the processed pork consumed in 2000 is used as the market demand for this exercise (30744 MT).

3.3.2. The quantitative model

A quantitative linear programming model was formulated and implemented using the GAMS software (www.gams.com) to generate various scenarios. As mentioned earlier, the objective is to minimise the sum of the production and transportation costs.
This is:

Minimise:

$$\sum_i wpc_i * PP_i + \sum_i \sum_j \sum_n tcdp_{ijn} * TPI_{ijn} + \sum_j ipc_j * ING_j + \sum_j \sum_k \sum_n tcpp_{jkn} * TIP_{jkn} + \sum_k ppc_k * NPF_k - \sum_j ss_j * SA_j$$

Constraints: The model has some constraints or restrictions for the supply of raw materials and ingredients and the demand of the final product.

The flow in the whole chain is demand driven. The amount of NPFs produced in all the locations should be equal to the demand.

$$\sum_k NPF_k = demand$$

The amount of pea protein transported from all facilities j to facility k by all modes of transportation is equal to the amount of pea protein concentrate in the final NPF.

$$\sum_j \sum_n TIP_{jkn} = npfp * NPF_k \quad \text{for all k}$$

The amount of pea protein transported from each facility j to all locations k cannot exceed the amount of concentrate produced in location j.

$\sum_k \sum_n TIP_{jkn} \le ING_j$ for all j

The amount of pea protein produced at facility j cannot exceed the amount of protein contained in the dry peas transported from all locations to facility j by all modes of transport.

$ppdp * \sum_i \sum_n TPI_{ijn} \ge ING_j$ for all j

The amount of dry pea transported from all locations i to facility j cannot exceed the amount of peas grown in location i minus the harvest losses and refuse (expressed as a percentage of peas grown)

$\sum_j \sum_n TPI_{ijn} \le pwp * PP_i$ for all i

The amount of starch produced as a by-product at each facility j is equal to the percentage of starch in the dry peas transported from all locations to location j by all modes of transportation.

$$SA_j = stpt * \sum_i \sum_n TPI_{ijn} \text{ for all j}$$

3.4. Data acquisition:

The model provides a systematic tool to identify the relevant information required to answer the question: how cheaply can this product be manufactured. This information, called the cost coefficients (defined in section 3.3.1) are:
wpc_i, $tcdp_{ijn}$, ipc_j, $tcpp_{jkn}$, ppc_k and ss_j.

The data was acquired after an extensive search that involved personal and telephonic interviews with experts and companies in the respective areas, internet searches and estimations based on the above. In the model it is possible to specify as many areas/ countries as required to source/manufacture the products. For the purpose of this exercise, four countries were selected to give a diverse range of characteristics. They were: Netherlands (area of interest), France (a major grower of peas in Western Europe), Ukraine (major grower in eastern Europe) and Canada (large grower in the Americas). Table 3.1 shows the primary production data for these countries. The coefficient wpc_i can be calculated from here.

As can be seen from Table 3.1, the yield and the areas under cultivation differ greatly between countries. However the average protein content of the peas is about 22 % and the quality of the peas is similar. It may appear from Table 3.1 that the best option is to choose the country where the cheapest peas are available. However as costs integrate over the entire supply chain, this may not be the optimal strategy. There could be strategic reasons to obtain peas from various sources and to put a limit on the amount of peas from each country.

Table 3.1: Primary production information

	Total production, MT#	Total area, hectares#	Yield, MT/hectare	Export price, €/MT*	Import price, €/MT*
Netherlands	4000	800	5.0	473	147
France	1,700,000	334,119	5.088	154	231
Ukraine	746,800	540,007	1.383	129	337
Canada	1,492,600	719,071	2.076	160	401

*http://apps.fao.org; # www.statpub.com

The next information of interest is the transportation costs ($tcdp_{ijn}$) from the primary production locations to the protein production location. The details are summarised in Table 3.2 (Personal communication). It was not possible to obtain costs for rail transport and in some cases for internal transport in certain countries. As a result these costs were not considered in the model. However they could be included later and lead to a reduction in total transportation costs.

Table 3.2: Transport cost in €/MT

	Sea	Rail	Barge	Truck
CANADA.CAN *				
CANADA.FRA	55.02			
CANADA.UKA	55.02			
CANADA.NLD	55.02			
FRANCE.CAN	55.02			
FRANCE.FRA				
FRANCE.UKA	50.9		21	20
FRANCE.NLD			13.5	16
UKRAINE.CAN	55.02			
UKRAINE.FRA	50.9		21	20
UKRAINE.UKA				
UKRAINE.NLD	50.9		21	20
NETHERLANDS.CAN	55.02			
NETHERLANDS.FRA			13.5	16
NETHERLANDS.UKA	50.9		21	20
NETHERLANDS.NLD			5	10

* CANADA, FRANCE, UKRAINE, NETHERLANDS are the primary production locations; CAN, FRA, UKA, NLD are the ingredient preparation locations

The next coefficient is the cost to make the pea protein (ipc_j) at the different locations. The cost per ton of pea protein are summarised in Figure 3.5 (web addresses).

The process of manufacturing pea protein involves dehulling, followed by milling and air-classification. Pea hulls and starch are by-products that are important because they have a high resale value: the cost of cereal starch is € 70/tonne and the price of pea hulls is € 108/tonne (raw fibre).

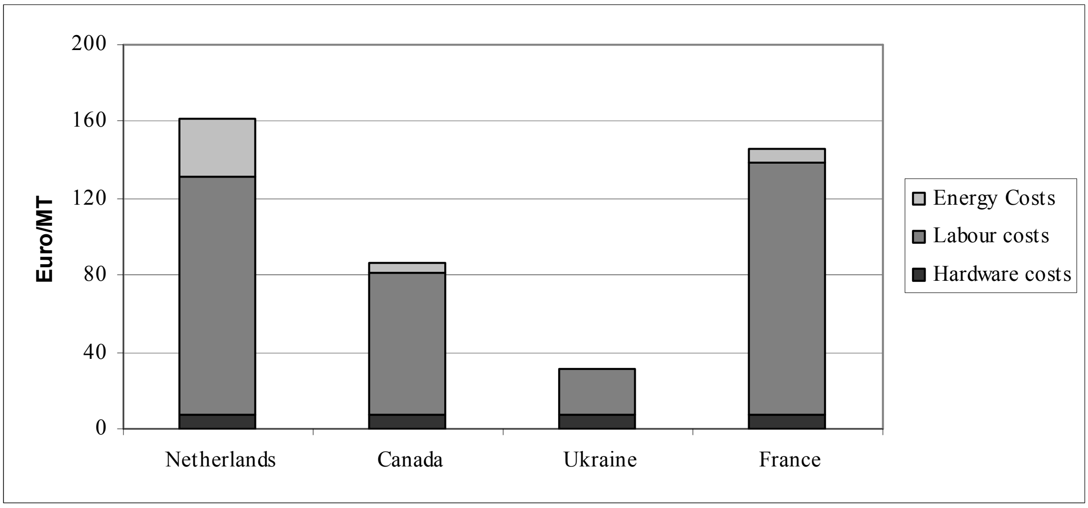

Figure 3.5: Ingredient processing costs per MT of NPF

The fourth coefficient of interest is the transportation cost from the ingredient processing facilities to the NPF production locations ($tcpp_{jkn}$). The costs are the same as those in Table 3.2. However, in reality, there may be some differences if the locations lie further apart than assumed in the previous case. Moreover, in the model NPF production facilities were limited to the Netherlands and France because of the time it would take to transport the product from Canada or the Ukraine to the Netherlands. The cost of refrigerated transport was found to be so high that those options were not explored further.

The cost of manufacturing the NPF (ppc_k) in France and the Netherlands are estimated as being € 19.82 and € 17.84 per ton respectively (web addresses). The differences arise because of the higher energy costs in the Netherlands. The selling price of starch (ss_j) was calculated as a world average of € 70 per ton.

3.5. Scenarios

The model can be used to develop scenarios. The scenarios that arise depend on the constraints that are part of the model. The exploration was limited to two cases. In the first case, no additional capacity constraints were added and the optimisation reduces to a simple shortest path problem that identifies the cheapest supply chain in the network. In the second case, giving an upper limit for the primary production sources simulated the strategic consideration of obtaining peas from several sources.

Scenario 1: there are no constraints on the amount of pea that can be sourced in each primary production area. This therefore results in a single flow/chain with the model choosing the cheapest route through all the links. Figure 3.6 illustrates this chain. The optimal path is then to source the peas in the Ukraine, make the pea protein there and then transport it by truck to the Netherlands.

Scenario 2: Simple upper limit capacity constraints were used. The model specifies the amount of pea that can be sourced from each location. This is done to ensure a supply from all sources so as not to be dependent on any one country. The flow changes from a single chain to a network (Figure 3.7). The final product is made in the Netherlands and the pea protein is made in the Ukraine. The model calculated that the optimal path is to source the peas in all the countries, transport them by various means to the Ukraine to be converted to pea protein and then transport the protein concentrate by truck to the Netherlands. The estimated costs apparently show that this is cheaper than setting up an additional processing facility in the Netherlands to process the pea sourced in the Netherlands.

Figure 3.6: Scenario 1: Uncapacitated network

Cost comparisons: Figure 3.8 illustrates the difference in total costs for the two scenarios. Scenario 1 has lower total costs (for the first part of the supply chain) and therefore a lower product cost. This is because there are no constraints on capacities and the model chooses the cheapest path of manufacture. Initial estimates show:
Scenario 1: cost per ton of product = € 216/MT
Scenario 2: cost per ton of product = € 273/MT

The cost estimations are limited to that for the main ingredient, the pea and the concentrate made from the former. The procurement costs for the other ingredients like oil, functional ingredients and flavours are not considered here. However it is known from preliminary calculations, that the inclusion of these costs would still limit the production cost per MT of the product to below € 1000. Further value is added with the inclusion of the costs of the second part of the supply chain – packaging, distribution and retail.

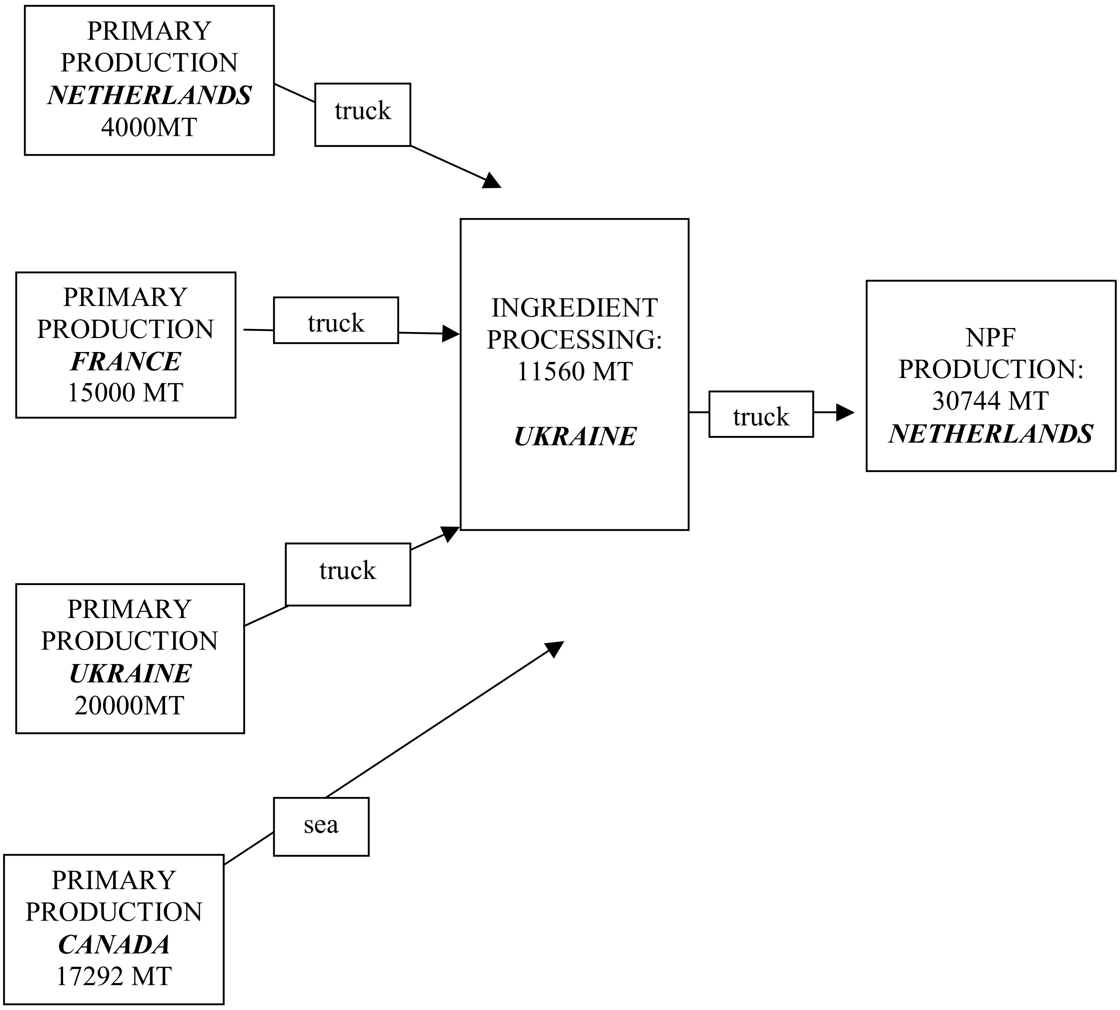

Figure 3.7: Scenario 2: Capacitated network

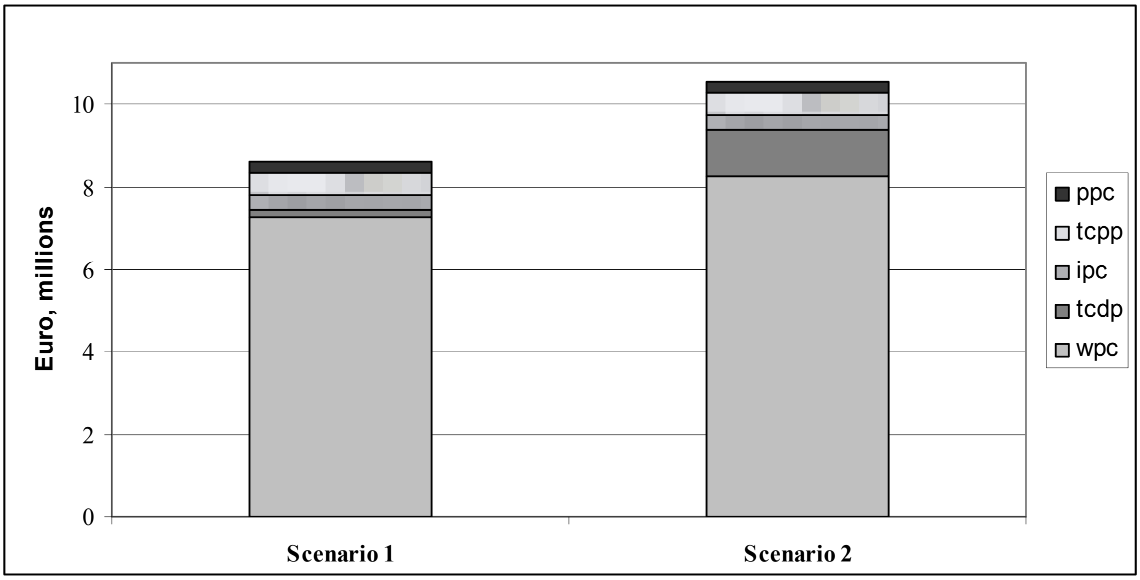

Figure 3.8: Total cost of Scenarios- value added at each link

As mentioned earlier, NPFs are targeted to replace pork meat in the consumer's diet. The retail cost of pork meat is about € 6/kg and the cost to make pork meat is about 38-40 % of this value (www.ers.usda.com). It can be seen from above that the cost of manufacture of NPFs is much below this Figure. This answers the question posed at the beginning of section 4- how cheaply can this product be manufactured.

3.6. Conclusions

This paper presents a systematic method to design a supply network for a particular product with a specific goal. The OR linear programming model is a tool that can be used to generate and evaluate different scenarios that are based on differing constraints. The model also provides a methodical way assist in the collection of relevant information.

Acknowledgements

The authors would like to thank Joris Sprakel and Bas Toonen for all their help in data acquisition. They would also like to thank Dr. A.R. Linnemann and Dr. M.A.J.S van Boekel for their comments and suggestions.

3.7. Appendix 3

GAMS Model formulation (ton = MT)

Model 1: Uncapacitated
Sets
I Primary production locations / CANADA, FRANCE, UKRAINE, NETHERLANDS /

J Ingredient preparation facilities / CAN, FRA, UKA, NLD /
K NPF production facilities / fran, neth /
N Modes of transportation / sea, rail, barge, truck / ;

PARAMETER
wpc (I) cost of production of dry pea at location I in euro per ton
/ CANADA 160, FRANCE 154, UKRAINE 129, NETHERLANDS 147 /
ipc (J) cost of making the pea protein ingredient at location J in euro per ton
/ CAN 86.7, FRA 145.7, UKA 31.69, NLD 161.9 /
ss(J) selling price of starch in euro per ton
/ CAN 70 , FRA 70, UKA 70, NLD 70 /
ppc (K) cost of producing the NPF at location K in euro per ton
/ fran 19.82, neth 17.84 / ;

Table tcdp(I,J,N) transport cost, €/MT

	sea	rail	barge	Truck
CANADA.CAN				
CANADA.FRA	55.02			
CANADA.UKA	55.02			
CANADA.NLD	55.02			
FRANCE.CAN	55.02			
FRANCE.FRA				
FRANCE.UKA	50.9		21	20
FRANCE.NLD			13.5	16
UKRAINE.CAN	55.02			
UKRAINE.FRA	50.9		21	20
UKRAINE.UKA				
UKRAINE.NLD	50.9		21	20
NETHERLANDS.CAN	55.02			
NETHERLANDS.FRA			13.5	16
NETHERLANDS.UKA	50.9		21	37.5
NETHERLANDS.NLD			5	10

Table tcpp (J,K,N) transport cost, €/MT

	sea	rail	barge	truck
CAN.fran	55.02			
CAN.neth	55.02			
FRA. Fran				
FRA. Neth			13.5	16.0
UKA.fran	50.9		21	20
UKA.neth	50.9		21	20
NLD. Fran			13.5	16
NLD. Neth			5.0	10.0

Scalar
Stpt starch per ton /0.7/
npfp pea protein per ton npf /0.376/

```
        ppdp          pea protein per ton of dry transported pea /0.255
        pwp           percentage of dry pea from total pea produced /0.805/
        demand        total amount of NPF put into the market /30744/;

 Variables
         PP(I)          amount of pea produced at primary production location i
         TPI(I,J,N)     amount of dehulled pea transported from location i to  j
         ING(J)         amount of ingredient pea protein concentrate produced at facility j
         TIP(J,K,N)     amount of pea protein concentrate transported from facility j to k
         NPF(K)         amount of NPF produced at facility k
         SA (J)         amount  of starch produced at J
         Z              total costs     ;

Positive Variable PP, TPI, ING, TIP, NPF ;

 Equations
        cost          define objective function
        supply(K)     observe supply limit at j
        demand        satisfy demand at market j
        sup(J)        supply from location j
        supl(I)       supply from location i
        sta (J)       starch limit
        deli(J)       delivery to ingredient production            ;

  cost ..             z    = E = sum(I, wpc (I)* PP(I)) + sum((I,J,N), tcdp(I,J,N)*
                      TPI(I,J,N))+ sum(J, ipc (J)* ING(J)) + sum((J,K,N),tcpp(J,K,N)*
                      TIP(J,K,N))+ sum(K, ppc(K)* NPF(K)) - sum(J, ss(J)* SA(J))   ;

  supply(K) ..        sum((J,N)$(tcpp(J,K,N) gt 0), TIP(J,K,N))  =e= npfp* NPF(K) ;
  demand ..           sum(K, NPF(K))  =e= demand ;
  sup(J) ..           sum((K,N)$(tcpp(J,K,N) gt 0), TIP(J,K,N))=l= ING(J) ;
  deli(J)..           ppdp*sum((I,N)$(tcdp(I,J,N) gt 0), TPI(I,J,N))=g= ING(J) ;
  supl (I) ..         sum ((J,N)$(tcdp(I,J,N) gt 0), TPI(I,J,N))=l= pwp* PP(I);
  sta(J) ..           SA(J)=e= stpt* sum ((I,N)$(tcdp(I,J,N) gt 0), TPI(I,J,N));

  Model model1 /all/ ;
  Solve model1 using lp minimizing z;
  Display PP.l, pp.m, TPI.L, TPI.M, ING.L, ING.M, TIP.L, TIP.L, NPF.L, NPF.M;
```

Capacitated model:

Model 2: Capacitated
The capacitated model is similar to the uncapacitated model. The capacity constraints added are for the primary production of peas.
The extra parameter is:

```
 PARAMETER
 ppu (I) upper limit for primary production in MT
```

```
/ CANADA      20000, FRANCE      15000, UKRAINE      20000, NETHERLANDS
4000  / ;
```

The upperbound for the production is also declared as a positive variable.

```
 Positive Variable PP, TPI, ING, TIP, NPF ;
                PP.UP(I) = ppu(I) ;
```

3.8. References

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Personal communication
Product-agency Pulses, cereals and seeds, Netherlands
MSC Shipping Rotterdam, Netherlands
Shortsea, Netherlands
Vd Bosch, Erp, Netherlands

Vd Linde Rotterdam, Netherlands
Zijdehand Moerkappelle BV, Netherlands

Web addresses
www.fao.org
http://www.alberta-canada.com
http://www.euireland.ie
www.cbs.nl
www.nuon.nl
www.edf.fr

Chapter 4

Exergy analysis: A tool to study the sustainability of food supply chains

Radhika K. Apaiah, Anita R. Linnemann & Hedzer J. van der Kooi

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4. Exergy analysis: A tool to study the sustainability of food supply chains

4.1. Introduction

At the turn of the 19th century, the earth's population was one billion. Over the next 100 years this number almost doubled and today it is more than 6.4 billion (US Bureau of the Census). It is only obvious that these growing numbers of people require increasingly larger amounts of food and fuel to meet their needs. However, there is an increasing awareness in the industrialized world that the present food production and consumption patterns were far from sustainable and had a heavy environmental burden (Pimentel *et al.*, 1999; Tilman *et al.*, 2001). To reduce the negative effects caused by these trends and to avoid sub-optimisations, systems analysis studies are needed; starting with simple products and as knowledge is gained and the methods are improved, shifting to more complex products and whole diets (Andersson & Ohlsson, 1999).

The World Commission on environment and development defined sustainable development as meeting the [human] needs of the present without compromising the ability of future generations to meet their own needs''. The relationship between sustainable development and the use of resources, fuel, food, land, water is very significant (Dincer & Rosen, 2004). It became obvious that using resources more efficiently would reduce the environmental impact of emissions. This was called energy conservation (Rosen & Dincer, 2001). However, an examination of thermodynamic principles reveals that the focus on energy conservation as a strategy is at best incomplete and at worst wholly incorrect. As energy is converted from one form to another, it is neither lost nor destroyed. It does, however, ''lose a certain quality which can be described as its ability to do work'' (Torrie, 1981). For example, the heat in exhaust air and warm water has low quality, while electric energy has high quality. As conventional energy analysis fails to recognize this distinction, wasteful policies are often implemented. The amount of work that can be extracted from a fuel source in principle is actually larger than the amount of work that is actually produced from the fuel (Simpson & Kay, 1989).

This available energy or available work or quality of energy is called exergy. It measures the ability of a source to produce useful work. Exergy is therefore a thermodynamic unit that gives a numerical value to energy quality. It can also be defined as a physical concept that quantities the usefulness or value of energy and material (Wall, 1977, 1986). Exergy is thus the maximum amount of work that can be extracted from a system (any specified collection of matter under study).

The concept of exergy is based on the First and Second Law of Thermodynamics (Szargut *et al.*, 1988). In contrast to energy, exergy is exempt from the law of conservation. In real processes, exergy input always exceeds exergy output. This is due to exergy destruction, also called irreversibility or lost work. Every real process has exergy losses leading to the reduction of the useful effects of the process or to an increased consumption of inputs from where the product was derived. The difference between exergy destruction or irreversibility and exergy waste or exergy flow to the environment is important.

Simpson and Kay (1989) illustrate the concept with the following example. The water at the top of a waterfall has gravitational potential energy due to its height above a gorge. This energy is transformed into kinetic energy as the water drops over the falls. The kinetic energy of the falling water can be used to produce work. The original gravitational potential energy that the water possessed at the top of the falls is converted to heat energy and also into sound energy – the roar of the falls. The water at the bottom of the falls is one eighth of a Celsius degree warmer than the water at the top per 100 m difference in height. This heat energy is caused by the friction of the water molecules colliding against one another and against the rocks. The total amount of sound and heat energy at the bottom of the falls is exactly equal to the total amount of gravitational potential energy at the top of the falls. The essential difference between the two forms of energy is that the high quality concentrated gravitational potential energy at the top of the falls can be harnessed to perform work – to run an electric generator for example – whereas the low quality sound energy and heat energy at the bottom is too dispersed to be of use.

Exergy analysis is a relatively new technique based on the above concept (Kotas, 1986). An exergy balance when applied to a process or a whole plant shows how much of the available work potential supplied as the input to the system under consideration has been consumed (irretrievably lost) by the process. It enables the determination of the location, types and magnitudes of wastes (streams that still contain exergy) and losses (exergy is irreversibly lost).

Life cycle assessment (LCA), which is a method for analysis and assessment of the environmental impacts caused by production systems, is commonly used for such analyses (Andersson, 2001; Guinee, 2002). The components of exergy analysis are more or less the same as in LCA. A drawback of LCA is that incomparable factors like global warming, acidification and ecotoxicity are taken together to generate one final Figure for environmental impact. The major difference between the methods however, is that exergy analysis takes all energy forms (food/fuel) into account with respect to their ability to do work in a physical sense (Dincer & Rosen, 2004). Thus conversion factors between electricity, natural gas, diesel, etc. are not needed.

A supply chain (SC) is an integrated process where raw materials are acquired, converted into products and then delivered to the consumer (Beamon, 1998). It is thus a possible pathway to manufacture and deliver a particular product to a consumer (Apaiah *et al*., 2005). The chain is characterised by a forward flow of goods and a backward flow of information. Food supply chains are made up of organisations that are involved in the production and distribution of plant and animal-based products (Zuurbier *et al*., 1996). Such SCs can be divided into two main types (van der Vorst, 2000):

- SCs for fresh agricultural products: the intrinsic characteristics of the product remain virtually unchanged and,
- SCs for processed food products: agricultural products are used as raw materials to make processed products with a higher added value.

A food SC as defined in this paper consists of six links: primary production, ingredient preparation, product processing, distribution, retail and the consumer (Figure 4.1).

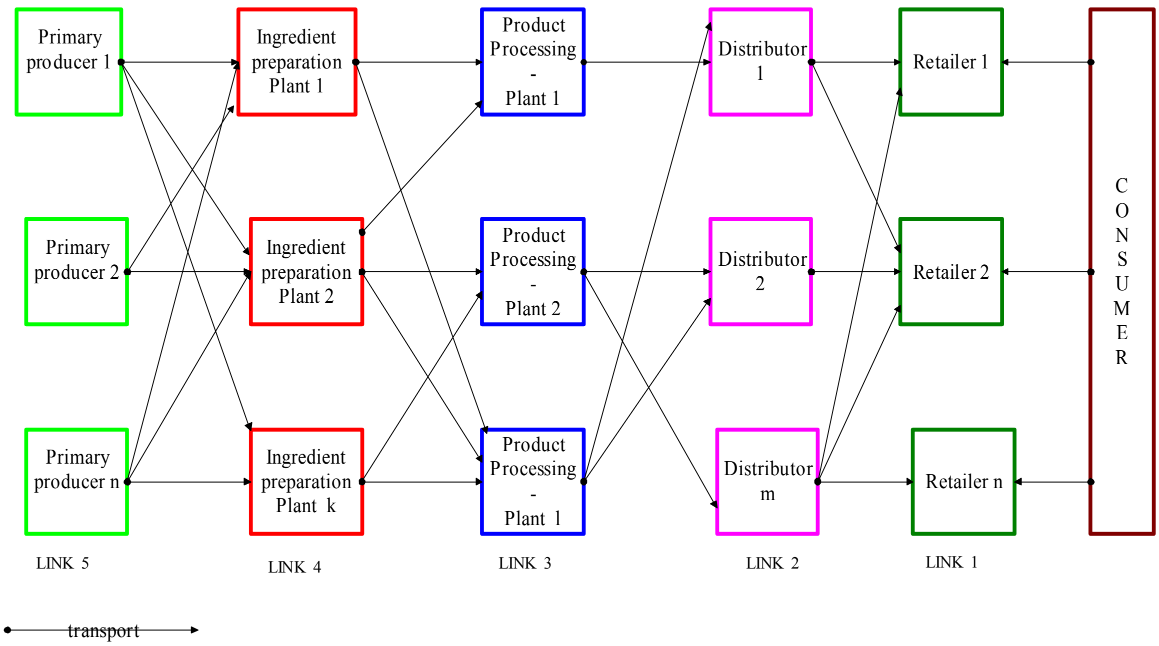

Figure 4.1: Food supply chain (from Apaiah & Hendrix, 2005).

Exergy analysis has been used successfully in the chemical industry (Cortez & Larson, 1997; Morris, 1991; Szargut *et al.*, 1988). It has been applied in the food industry in many areas (Fang *et al.*, 1995; Iibuchi *et al.*, 1982; Midilli & Kucuk, 2003; Rostein, 1983; Tekin & Bayramoglu, 1998, 2001). However these studies are limited to exergy analysis and optimisation of a product/ process in one factory. However a factory is just one link in the supply chain of a product. The chain has to be studied in its entirety to avoid local and sub-optimisations.

This study was done within the framework of PROFETAS. Meat production in particular is problematic because of the inefficient conversion of protein in the feed into protein in the slaughtered animal. As a result of this inefficiency, growing environmental impacts and the competitive element between food and feed crops, the possibilities to optimise the sustainability of the protein production and consumption chain are immense.

This paper explores the potential of using exergy analysis as a tool to study and compare the environmental sustainability of the entire supply chain of food products and identify opportunities to reduce their environmental impact. Three products were chosen: Novel Protein Foods (NPFs) – a pea-protein based product that is designed to replace meat-based ingredients in a consumer's diet; pork mince as the animal protein source because of the absence of secondary products like milk or eggs and its similarity to the NPF; and pea soup as it represents the simplest way of using peas as a food. Exergy inputs and outputs of the various streams, products and processes are calculated for the entire supply chain of a product. Exergy is measured in Mega Joules/unit of product and therefore a clear and objective overview is created. The evaluation of the product and its chain is therefore less disputable in exergy analysis. Resource intensive processes can be indicated easily and the improvement is a logical result. Engineers can optimize production processes to consume fewer resources like raw materials and fuel, and produce less emission and waste with the help of design tools like exergy analysis (Schijndel *et al*., 1998). Such analyses can be applied to the supply chain of existing and profitable products or can be applied to aid in the design of supply chains for new products. However in the latter case exergy analysis would have to be combined with some form of cost analysis to make the product cost competitive as well as environmentally friendly.

4.2. Methodology

4.2.1. System boundaries and assumptions

The system comprises the chain that is under study. Secondary chains *e.g.* the supply chain for the fertilizer production plants or the chains for the manufacture of a machine or transport vehicle are not included in the system. However, the cumulative exergy input necessary to produce a fertilizer and the exergy of the fuel used to run the machines are included as input in the relevant links.

The supply chains of the three products – pea-based novel protein food (NPF), pork meat and pea soup – were studied. The pork chain was chosen as it is a commonly utilised source of meat protein. It is well known and documented. The pea soup was included because it represents a chain where unprocessed peas are used almost directly for human consumption. The pea-based NPF is designed to resemble the vegetarian mincemeat currently available. NPFs based on peas do not exist yet. The supply chain and production schemes (Figure 4.2) are based on similar products available in the market.

The supply chains for the products are described in detail (Figures. 4.3–4.5). Common inputs for the three chains are diesel, natural gas, electricity, fertilizers and pesticides (not shown in Figures). All inputs to make the functional unit *i.e.* raw materials, fertilizers, and fuels are accounted for. All outputs and wastes at each link are also given in more detail in Appendix 4.5.

Chain 1: The pea-based NPF chain. The supply chain for NPF product is a theoretical one and is based on chains of similar meat substitutes on the market (Figure 4.3). The actors/links for which most information is available were chosen to create the chain.

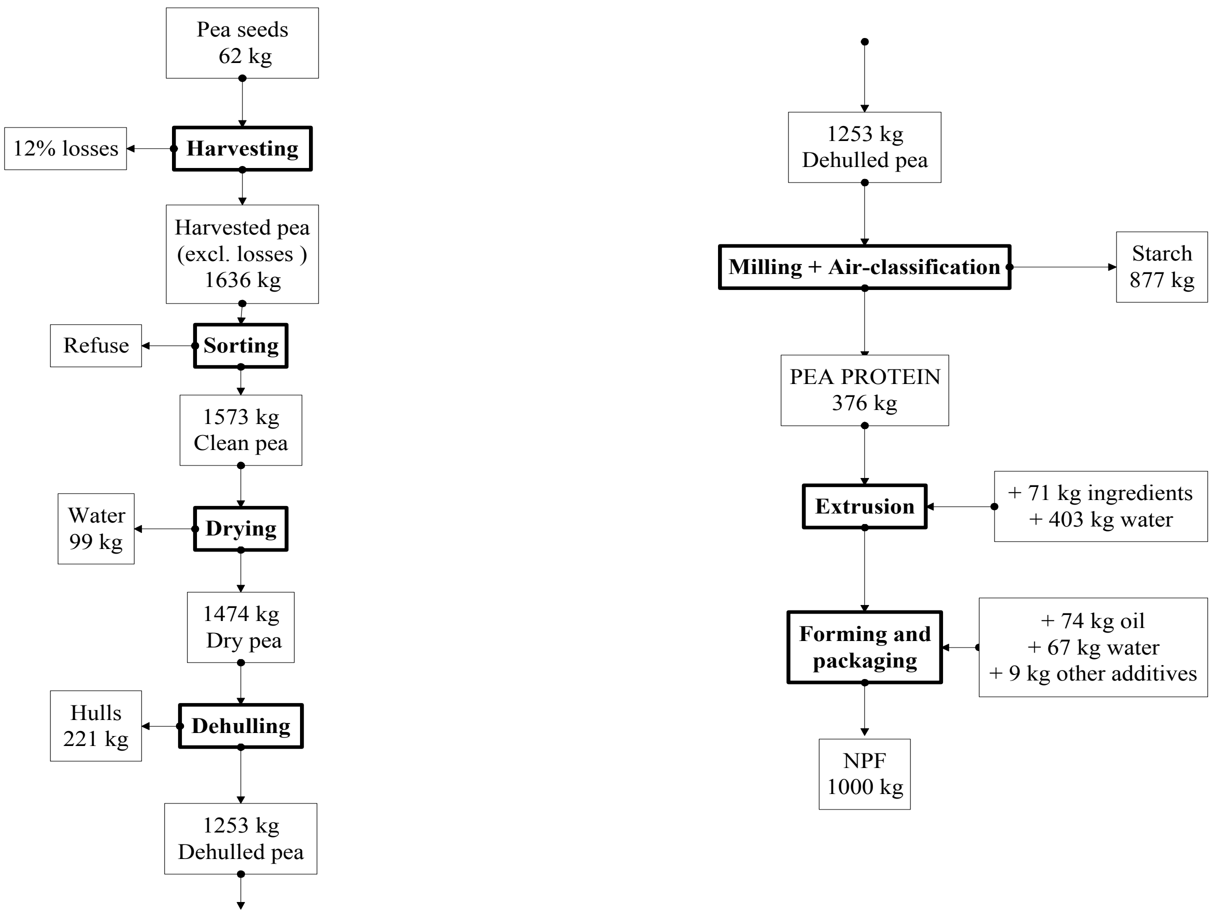

Figure 4.2: Production scheme to make 1000 kg of NPF

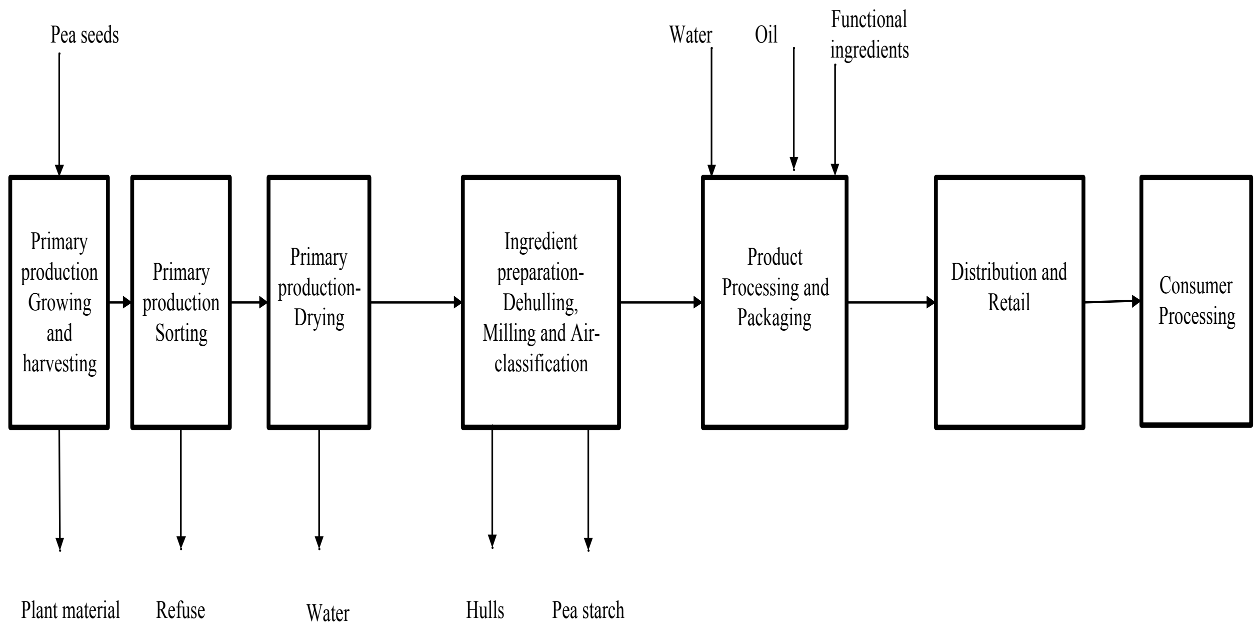

Figure 4.3: NPF supply chain

Chain 2: The minced pork meat production chain. The minced pork meat sector has a relatively simple supply chain in comparison with other more complex meat products. Like the NPF chain, this chain can be divided into links (Figure 4.4).

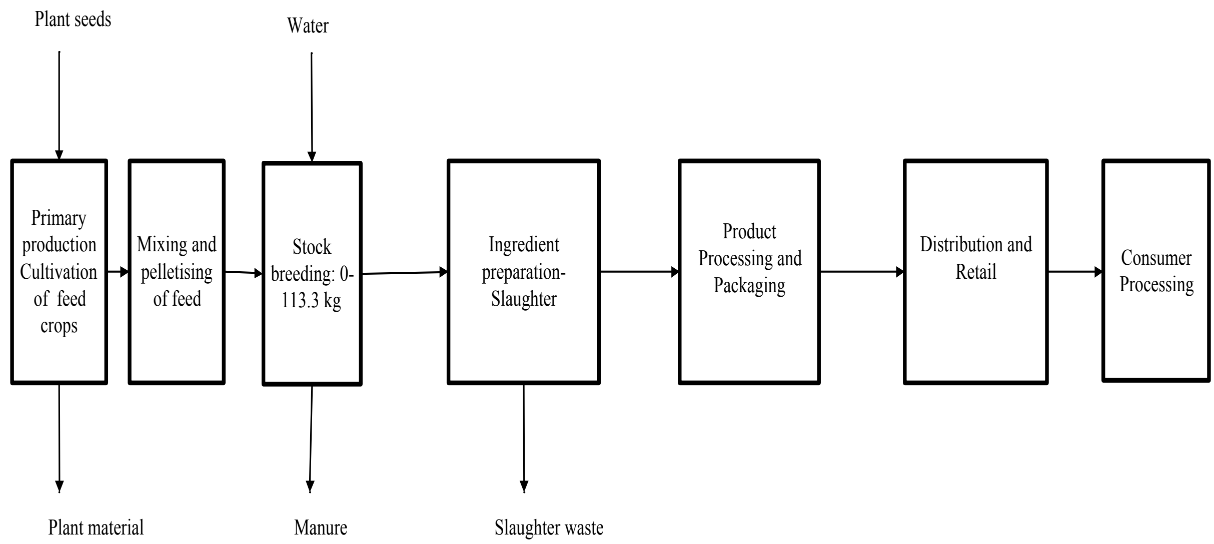

Figure 4.4: Pork meat supply chain

Chain 3: The pea soup chain. This chain represents a simple use of the pea, in terms of both product processing and consumer processing (Figure 4.5).

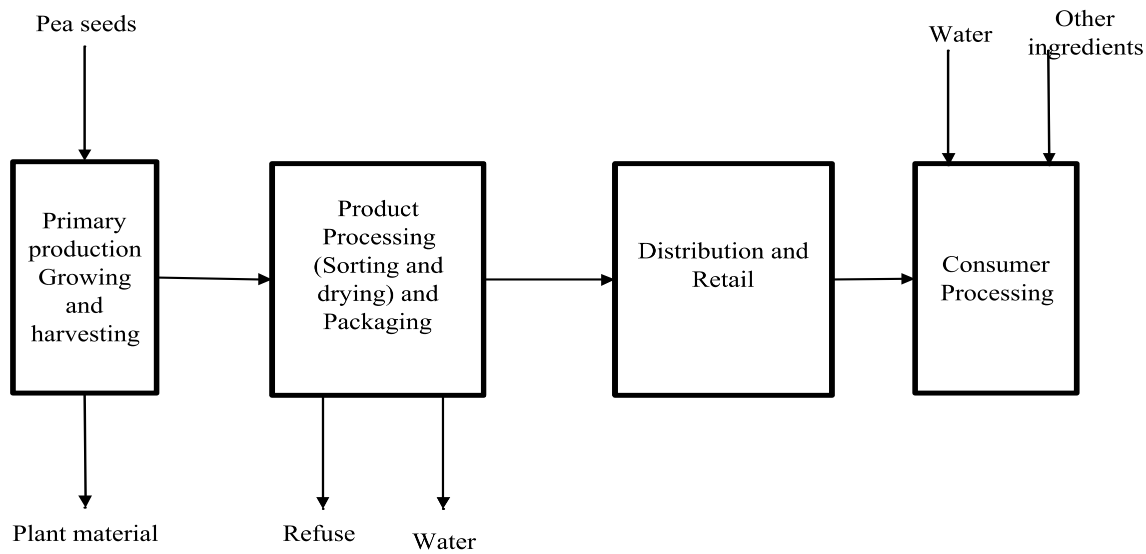

Figure 4.5: Pea soup supply chain

4.2.2. The functional unit

A comparable end product is necessary to genuinely contrast different food chains for their environmental impact. This is called the functional unit (FU), which in this case is 1000 kg of end product (NPF mince, pork meat, pea soup). The NPF and pork meat have similar nutritional compositions, but the pea soup is dissimilar. As mentioned earlier, the pea soup chain was included to demonstrate a simple use of the pea. The exergy content and requirements of products and processes respectively were calculated as shown below.

The chemical exergy, at standard conditions, of substances containing several elements can be calculated by using the chemical exergy values of the elements together with known values of the Gibbs energy of formation at the same reference conditions. This method has been mainly used for the exergy calculation of fertilisers. The chemical exergy of complex chemicals that are not listed by Szargut *et al.* (1988) can be estimated by using group contribution methods based on information about their molecular structure to determine absolute entropy values and enthalpy of formation values at standard conditions and then to determine the Gibbs energy of formation values (Reid *et al.,* 1977). The exergy value can also be calculated by using the Group Contribution Method of Szargut *et al.* (1988). This method has been mainly used for the exergy calculation of pesticides and packaging materials. Schenk (2001) gives a detailed description of the methods and their formulas. Sample calculations have been included in Appendix. The Gibbs energy of formation can also be estimated directly for organic compounds, gases and liquids with the method developed by Krevelen and Chermin (1952). The chemical exergy can then be calculated by using the sum of the products of the stoichiometric coefficients of the elements in the formation reaction and the exergy value of the elements, and the Gibbs energy of formation value at the same standard temperature and pressure, this can be called the Element Method.

4.2.3. Exergy balance for a process

$$Ex_{in}\,total = Ex_{out}\,product + Ex_{out}\,waste + Ex_{out}\,losses \tag{4.1}$$

where Ex_{out} product is exergy value of the desired end product (MJ); Ex_{in} total is total of all exergy inputs in the process (MJ); Ex_{out} waste is exergy value of outputs other than the desired product; Ex_{out} losses is exergy losses due to the irreversibility of the real process.

Equation 4.1 gives the exergy balance for a process. This is applied to each link of the chain to determine how much of the input exergy is used to produce the desired end product and how much is lost as wastes and losses. Tables 4.1a and 4.1b present a sample calculation of the exergy balance for the ingredient preparation link in the manufacture of NPFs.

Table 4.1a: Input data for the ingredient preparation link in the NPF chain for one FU

Process name/ product	Mass, kg	Exergy, MJ	Exergy chem., [MJ/kg]	Total Exergy chem., MJ
Harvested peas	1635.68		18.19	34334.69
Sorting				4.42
Drying				3934.95
Dehulling				159.16
Milling				197.92
Air classification				9.02
Total input				38640.15
Sorting				
Electricity		4.42	1.00	4.42
Drying				
Electricity		70.66	1.00	70.66
Natural gas		3680.28	1.05	3864.29
Total input				3934.95
Dehulling				
Electricity		159.16	1.00	159.16
Milling				
Electricity		197.92	1.00	197.92
Air classification				
Electricity		9.02	1.00	9.02

Table 4.1b: Output data for ingredient preparation link in the NPF chain for one FU

Process name/ product	Mass, kg	Exergy, MJ	Exergy chem, [MJ/kg	Total Exergy chem, MJ
Pea concentrate	376		20.90	7854.12
Intermediates				
Refuse peas	62.91		18.19	1144.49
Product	1572.77		18.19	28612.24
Drying				
Water	99		0.53	52.25
Product	1473.68		19.47	28689.02
Dehulling				
Hulls	221		18.19	4021.45
Product	1252.63		19.47	24385.67
Milling				
Product	1252.63		19.47	24385.67
Air classification				
Coarse fraction	876.84		18.32	16064.60
Product	376		20.90	7854.12

4.3. Results and discussion

4.3.1. Comparison of chains: Inputs and outputs

Figures 4.6 – 4.8 describe the chains in different ways. What goes into the chain, where it enters the chain and what the output is becomes very clear when all outputs and inputs are converted into exergy values (measured in MJ/ 1000 kg of product). Problem areas can easily be recognized and the potential for optimisation can be identified.

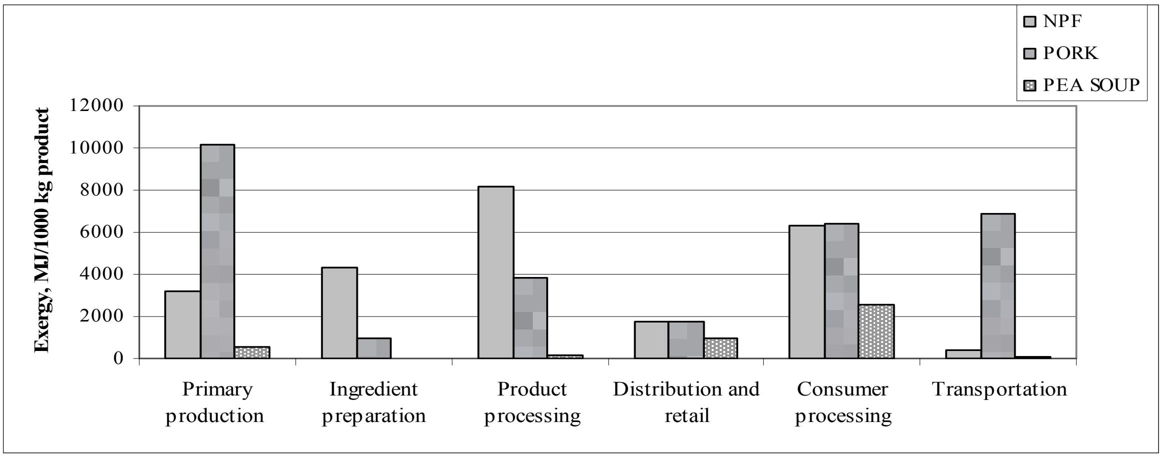

Figure 4.6: Comparison of exergy input between the three chains

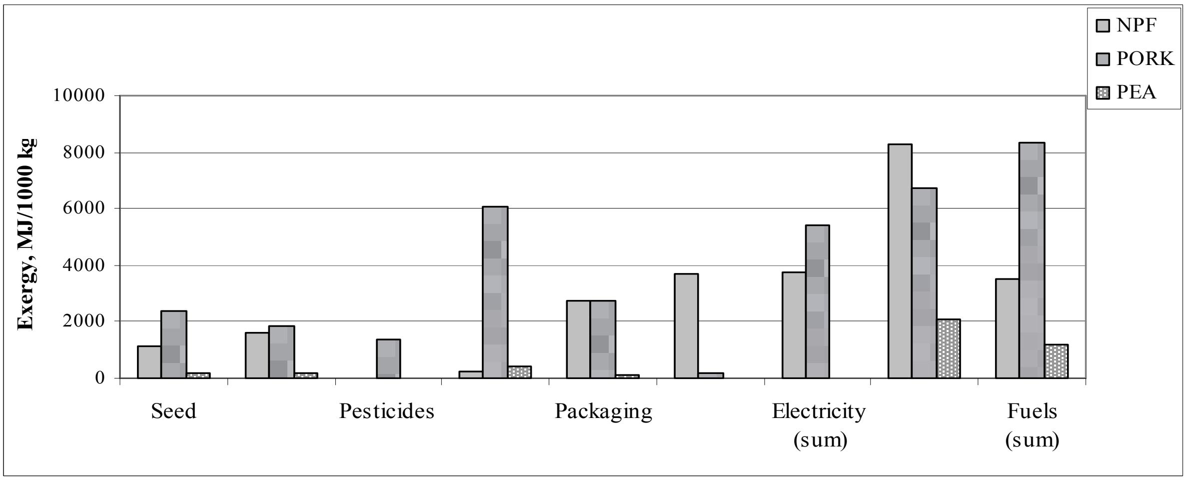

Figure 4.7: Exergy input per stream

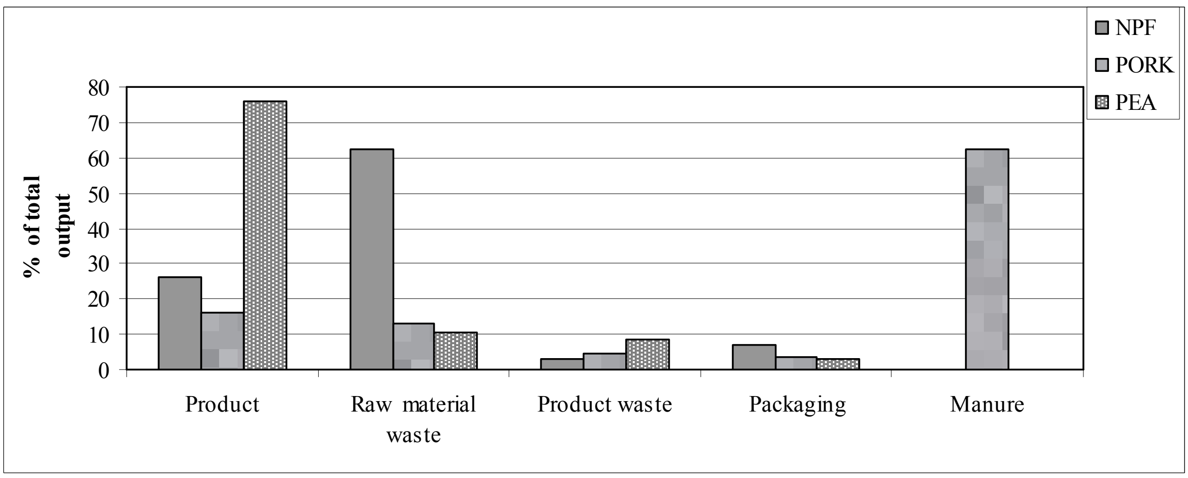

Figure 4.8: Exergy output per stream

Figure 4.6 shows the exergy input per link for the three chains. The exergy required for primary production in the pork chain is very high when compared to the other chains. This is due to the inefficient conversion of plant protein from the feed to animal protein in the pig. Ingredient preparation is an exergy intensive process in the NPF chain as the peas have to be sorted, dried to reduce moisture, dehulled, and milled. The protein in the pea .our has then to be concentrated. In comparison, slaughtering is the only process in the corresponding link of the pork chain and therefore requires less exergy. The link of ingredient preparation is absent in the pea soup chain. Product processing is an important link in the NPF chain as the concentrated protein from the preceding link is made into an edible form. The process considered here is extrusion. The exergy input for this and packaging the product is considerably more than what is required to form the product in the pork meat chain (mincing and packing the mince). In the pea soup chain this link involves only sorting and packaging the peas.

Distribution and retail for both the NPF and the pork mince are similar. The products have about 50% moisture and therefore have to be transported and stored under refrigerated conditions and therefore require more exergy input than the dry peas.

Consumer processing is the last link considered here. This includes shopping, storage and cooking. This results in an exergy input 453 MJ/1000 kg functional unit (Table A4.5, Appendix 4) (Velthuizen, 1996). The exergy input for the pork meat is similar. Both the NPF and pork mince need to be refrigerated as they have a moisture content of about 50%. It is assumed that the consumer handles the NPF the same way as pork meat, so 80% is frozen before consumption (Velthuizen, 1996). This results in an exergy input of 1475 MJ per 1000 kg functional unit.

Cooking the product is the last step. Natural gas provides the required energy. The consumer can cook the NPF and pork mince in different ways. It was assumed that the product is pan-fried; Figures are based on this method of cooking. This results in an exergy input of 4.2 MJ per kg product that is cooked for 30 min on a 2 kWh burner (Velthuizen, 1996). The pea soup chain again differs from the others at this link. The exergy input for storage is less as the peas can be stored under ambient conditions. However, it is important to remember that the exergy consumption in this link is very variable and difficult to control as it depends on individual consumers.

The exergy input for transportation is highest in the pork chain. It is assumed that 50% of the crops used in pig feed are transported over 10,000 km by barge (ocean) and 50% by truck over 100 km (Berg *et al*., 1995) to the Dutch pig feed factories whereas the peas required for the NPF and pea soup are assumed to be transported on average over 100 km only.

Figure 4.7 shows the various streams that enter each chain. The inputs of electricity, diesel (fuel) and natural gas are for the entire chain. The seed input is largest in the pork chain; a large amount of feed is required to get one FU pork meat because of the inefficient conversion of plant to animal protein. The NPF chain has the largest input of extra ingredients, while the pork meat chain has the highest drinking water input.

Figure 4.8 compares the outputs of the three chains. As mentioned earlier, high exergy sources like fuel, raw material etc are used to create a desired product. However only part of the input exergy goes into the desired product – part of it goes into waste streams (the environment) and the rest is irreversibly lost. The largest output in the pea chain is the desired product whereas in the NPF chain it is the raw material waste with the desired product a far second. The largest output in the pork meat chain is manure with meat only 15% of the total output.

4.3.2. Comparison of chains: Efficiency analysis

The chains can also be compared on the basis of their efficiency. There are many ways to calculate exergetic efficiency. The chosen efficiency parameter (Equation 4.2) focuses on the conversion of energy in the process. A process is most sustainable when it uses the exergy of its inputs efficiently, since production can be carried out with a minimum input of exergy and material resources (Lems *et al.,* 2002).

$$Eff = \frac{Ex_{out}\,product}{Ex_{in}\,total} \tag{4.2}$$

where Ex_{out} product is exergy value of the desired end product (MJ); Ex_{in} total is total of all exergy inputs in the production chain (MJ)

Exergy from a process can be lost in two ways – losses due to the irreversibility of real processes and losses due to waste streams. Both these exergy losses contribute to the inefficiency of a process. The exergy of waste streams can be considered useful when the products are used in other processes/chains. In this analysis, waste steams are not recycled or used in other processes or products. Emissions to the environment were not included in this study as the aim here is to show the efficiency of the chain on the basis of the desired product only. Eq. (2) thus calculates exergetic efficiency on the basis of the desired product.

An important issue that was encountered was whether to include renewable natural resources like sunlight and rainfall in the inputs. The amount of solar energy is based on the land requirement for the feed crops and pea crop. The land required to grow feed crops for 1000 kg of pork meat is 2.4 times the land needed to grow peas to make 1000 kg NPF. The calculated efficiencies are very different with the two approaches. When the renewable resources are included the efficiencies of the NPF, pork and pea chains are 0.2%, 0.09% and 0.48%, respectively. Figure 4.9 shows the total exergy input/output of the three chains when natural resources are not included. Now, the efficiencies are respectively 42.3%, 40% and 78%. The NPF chain is 1.2 times more efficient than the pork meat chain when only controllable inputs are included but is twice as efficient when natural resources are incorporated. Similarly the pea chain is 1.8 times better than the NPF chain when controllable inputs are included but 2.3 times better otherwise.

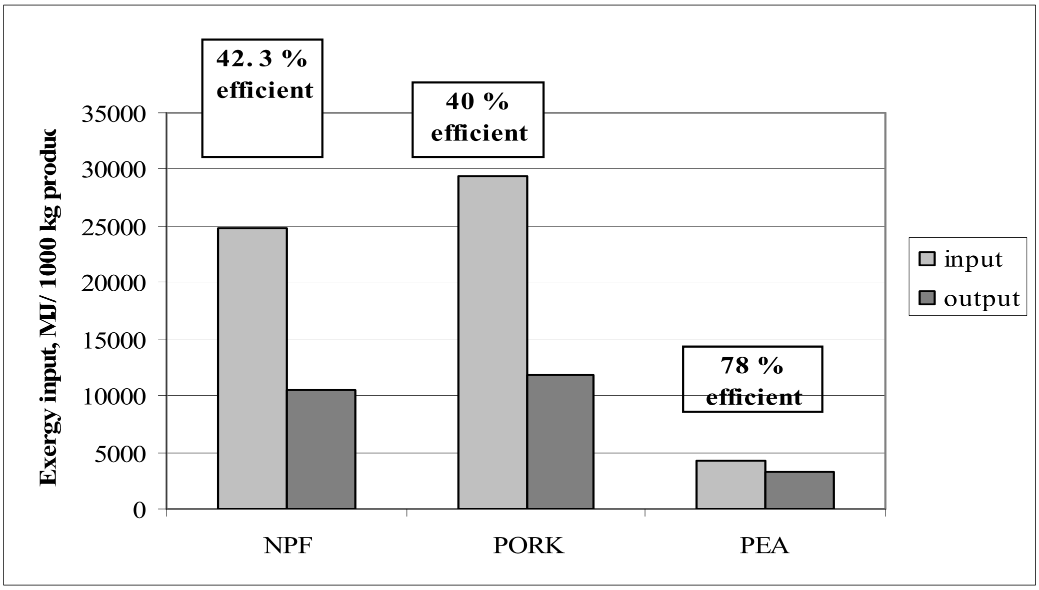

Figure 4.9: Exergy of inputs and the corresponding exergy of outputs (products) based on no natural resources

These results are interesting as it was expected that the NPF chain would be much more efficient than the pork meat chain. The large amount of processing required to convert the dry pea into the final product is partially, responsible for this. Also, the existing pork meat chain is optimal and the NPF chain is a hypothetical one with room for improvement.

4.3.3. Problem areas in the chains

Exergy analysis can help identify problem areas in chains and aids in identifying losses and inefficient uses of natural resources.

NPF chain:

- Ingredient preparation and product processing were identified as exergy intensive links in this chain.
- Exergy consumption in the consumer processing link can be very variable.
- Ingredient input into this chain is high.
- Electricity, natural gas and diesel use is high because of the intensive processing required.
- Only 42% of the input exergy goes into the desired product, raw material waste is high.

Pork chain:

- Primary production and transportation are exergy intensive links.
- Exergy consumption in the consumer processing link can be very variable.
- Seed input is high because of the inefficient conversion of plant to animal protein.
- Drinking water input is high.
- The largest output is manure with the pork mince being only 15% of the total output of this chain.

4.4. Conclusions

Exergy analysis is a useful method to study the impact of supply chains of food products on the environment. The analysis requires an in-depth input–output analysis of the links of a chain. This involves some investment of time but once this is done, results are visible and conclusions can easily be drawn, as was shown in the present paper. Efficiencies based on exergy, unlike those based on energy, are always measures of the approach to ideality, and therefore provide more meaningful information when assessing the performance of food chains. All inputs and outputs are measured in one covering unit, the Joule, making the method simpler to use. This method pinpoints the links where the exergy destruction takes place. It is therefore possible to investigate these links in detail and perform an improvement analysis to minimise this destruction.

The analysis also shows that supply chains of products that are relatively simple, minimally processed, derived from local ingredients and sold in domestic markets have a low exergy requirement. In reality, such products are few. Processed "value added" products are more exergy intensive – these products are more profitable to the manufacturers and more popular with consumers and the real money in food business comes from these. The supply chains of such popular and profitable products can be redesigned to make the chain more sustainable from an environment perspective – making it possible to deliver a product that performs well and is environmentally friendly.

Exergy analysis is also useful while designing the supply chains for new products. However, in such cases, exergy analysis needs to be extended to include monetary costs. This will make the technique more acceptable to supply chain managers. A detailed study of the chain, as will result from the above analysis, can lead to increasingly environmentally sustainable and profitable products.

Acknowledgements
The authors would like to thank Bas van der Steen for the data and calculations. They also thank Dr. E.M.T. Hendrix and Dr. M.A.J.S. van Boekel of Wageningen University for their advice and comments.

4.5. Appendix 4

Szargut *et al.* (1988) have proposed an idealised model of the environment with three reference states: gaseous and solid reference species in the environment and reference species dissolved in seawater. The exergy values of these reference substances are taken as zero. The solid species are treated as the components of an ideal solution. The standard chemical exergy of a pure reference species is then given by the Equation (A4.1) and listed in Szargut *et al.* (1988):

$$Ex^0{}_{chem,i} = -RT_n \ln x_{i,n} \tag{A4.1}$$

where:
R = gas constant (8.3145 J/mol K)
Tn = standard temperature, usually 298.15 K (K)
xi,n = the conventional mole fraction of the solid and ideal gas reference species in the environment (mol/mol)

Szargut *et al.* (1988) developed an empirical method for the calculation of the chemical exergy of fuels. The method relates the net caloric value (NCV) to the chemical exergy. For each type of fuel a b-value can be calculated which is a function of the atomic fuel composition (see Table A4.1).

$$Ex^0_{chem,i} = \beta_i \cdot NCV_i \tag{A4.2}$$

The β-value can be considered as a quality factor that relates energy to exergy content.

Table A4.1: β-value

Substance	β-value	Reference
Natural gas	1.0500	Schenk (2001)
(Fuel) oil	1.0700	Szargut *et al.* (1988)
(Hard) coal	1.0485	Schenk (2001)
Naphtha	1.055	Szargut *et al.* (1988)
Electricity	1.0000	Szargut *et al.* (1988)

Table A4.2: Chemical exergy packaging

Poly styrene packaging				
Chemical formula		n*[C8H8]		
MW		105.088	g/mole	
Group contribution method (Szargut *et al.*, 1988)				
Group nr.	Amount (#)	Bo chem (KJ/mole)	Total	
2	1	545.27	545.27	
3	1	651.46	651.46	
14	1	466.41	466.41	
15	5	568.28	2841.40	
Exergy Poly styrene			4504.54	KJ/mole
			42.86	MJ/kg

Table A4.3: Exergy values of macronutrients

Protein				
All proteins are assumed to be polymers of alanine (Van den Berg *et al.*, 1998)				
Chemical formula	-(NH-CHR-CO)- with R=CH3			
MW	71	g/mole		
Group contribution method (Szargut *et al.*, 1988)				
	number	Bo chem	Bo chem,total	

Group nr	(#)	(kJ/mole)	(kJ/mole)	
2	1	545.27	545.27	
4	1	752.03	752.03	
29	1	281.36	281.36	
38	1	195.56	195.56	
Exergy Protein			1774.22	
			25.35	MJ/kg

Table A4.4 Exergy balance for the NPF chain

Process	Exergy in	Exergy out product	Exergy loss
Soil preparation	471.00	0.00	471.00
Sowing	1291.27	0.00	1291.27
Growing	5079801.72	37023.90	5042777.83
Growing no-natural resources	2218.60	37023.90	-34805.30
Harvesting	303.87	29756.73	7571.04
Transporting	136.74	29756.73	136.74
Sorting	4.42	28612.24	1148.91
Drying	3934.95	28689.02	3858.17
Dehulling	159.16	24385.67	4462.51
Milling	197.92	24385.67	197.92
Air classification	9.02	7854.12	16540.57
Extrusion	2075.79	9350.14	579.77
Cuttering	2417.27	11639.40	128.00
Shaping	57.14	11639.40	57.14
Packaging	3418.02	14371.70	685.71
Storage and distribution	746.50	14371.70	746.50
Retail	993.99	14371.70	993.99
Shopping	452.74	14371.70	452.74
Storage home	1474.99	14371.70	1474.99
Cooking	4410.00	10475.46	8306.24
Total (no natural resources	24773.37	10475.46	14297.91
Total (with natural resources)	5102356	10475.46	5091881.04

Table A4.5 Calculations for consumer processing of the NPF

1	Average family size in the Netherlands#	2.7
2	Food per person per day#	2708 g
3	Total consumption of food per week	51181.1 g
4	Meat per person per day	99 g (3.7% of 2)#
5	Meat share per week	1871.1 g#
6	Pork meat per week	471.5 g (25.2% of 5*)
7	% NPF (of food consumed)	0.9
8	Exergy of fuel for shopping trip	12.9 MJ
9	Food share in groceries	66.7%
10	Average trips per week	2.69
11	NPF share in trips	0.6%
12	Exergy required	453 MJ per 1000 kg NPF

#(Voedingscentrum, 1998), *(De Koning, pers. comm., 2002)

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Chapter 5

An overview on Multiple Criteria Decision Making (MCDM)

5. An overview on Multiple Criteria Decision Making (MCDM)

5.1. Introduction

Decision making is changing- from a single person to a team to multiple stakeholders, from one criterion- profit to multicriteria situations (Zimmermann, 2000). Many methods have been proposed to aid in the solution of these increasingly complex situations. These can be classified into two main types:

- Multi objective optimization: They assume a continuous decision space and use mathematical programming models to optimise many objectives simultaneously to get the 'best' solution. Compromise solutions or trade offs therefore result.
- Multiple criteria decision making (MCDM): The decision space in these cases is discrete. The models do not try to compute an optimal solution. Instead, many alternatives are proposed and the decision maker ranks them with respect to the criteria. There is no objective statement and therefore no trade offs in the traditional sense as each criterion is ranked according to its importance to the decision maker (Zak *et al.*, 2002).

An inherent property about decision making is subjectivity. MCDM does not dispel this but shows the need and makes the process of making such decisions transparent (Belton and Stewart, 2002). The process of MCDM is divided into three phases- identification of the problem, building the model and finally developing action plans. Multiple criteria models appear quite simple and have often been criticized for being simplistic. However this apparent simplicity does not deny the complexity, but is rather a distillate of the key factors in a transparent and an easy to work with format from which insights can be gained (Belton and Stewart, 2002).

This chapter starts with explaining the terminology found in MCDM literature, the types and classification of the models commonly used, followed by the actual process of MCDM. Three types of models are explained in detail and the differences in approach are illustrated with the aid of an example on location selection.

5.2. Terminology

There are many terms that are used in literature on MCDM. The paragraphs below group these together and explain them.

- Options/alternatives: these are the choices open to the decision maker, *e.g.* which car to choose, where to buy a house
- Criteria: these are the goals or attributes or objectives that the decision maker wants to achieve. They are the means by which the decision maker can evaluate the alternatives, *e.g.* cost of car, mileage. These can be directly measurable *e.g.* cost of a house, indirectly measurable *e.g.* location of the property. In the latter case a performance indicator is required to measure the criterion, while in the former case, the criterion is the performance indicator.
- Criteria weights: the weights represent the relative importance of each criterion
- Scores/value/performance: the alternatives are evaluated with respect to each criterion and scores are assigned to each alternative. Usually the scores have no units; the

evaluation method depends on the MCDM model being used and is described in the sections that follow

- Ranking: Once the weights and scores are obtained the alternatives are graded with respect to all criteria simultaneously. This specific method again depends on the model.

5.3. Classification of MCDM models

The sections below describe the various ways that MCDM models are classified in literature.

- **Based on the approach**

Value measurement models or multi attribute value theory (MAVF): numeric scores are constructed in order to represent the degree to which one option is preferred over another. The scores are initially developed for each individual criterion
Goal, aspiration or reference levels: these are desired or satisfactory levels of achievement of each of the goals. The process then seeks options that are closest in some sense to achieving these objectives.
Outranking methods: here alternative courses of actions are compared pair wise, initially in terms of each goal, in order to identify the extent to which a preference for one over the other can be asserted. This differs from the value function approach because the output of the analysis is not a value for each alternative but an outranking relationship. Alternative A is said to outrank alternative B if there is a strong argument to say that A is at least as good as B and no strong argument to the contrary.

As these models depend on the preferences of the decision maker, they are in general called preference models. These models have two main parts:

- preferences in terms of each individual criterion are found out- the model describes the relative importance of reaching different levels or values for each criterion- values of the performance indicators
- preferences are coupled to give an aggregation model- a model that combines preferences across criteria allowing criteria to be compared to each other.

Figure 5.1 shows a value tree- the broad interests that are at the ‘top’ of the tree are represented at the left of the figure. The criteria are broken down, going from left to right in the Figure. The lowest level criteria are defined in such a way that they are measurable in terms of indicators and the alternatives can be ranked according to them. After preferences have been expressed in terms of the latter, the aggregation step can be applied across all the criteria in a single step or stepwise, aggregating each set that share the same parent at the next highest level.

In some cases, the definition of the criteria may automatically lead to the ordering of the alternatives *e.g.* cost of production. It may seem in this case that the first part of the preference model described above is trivial. However this is not so because MCDM deals with value judgments rather than face value.

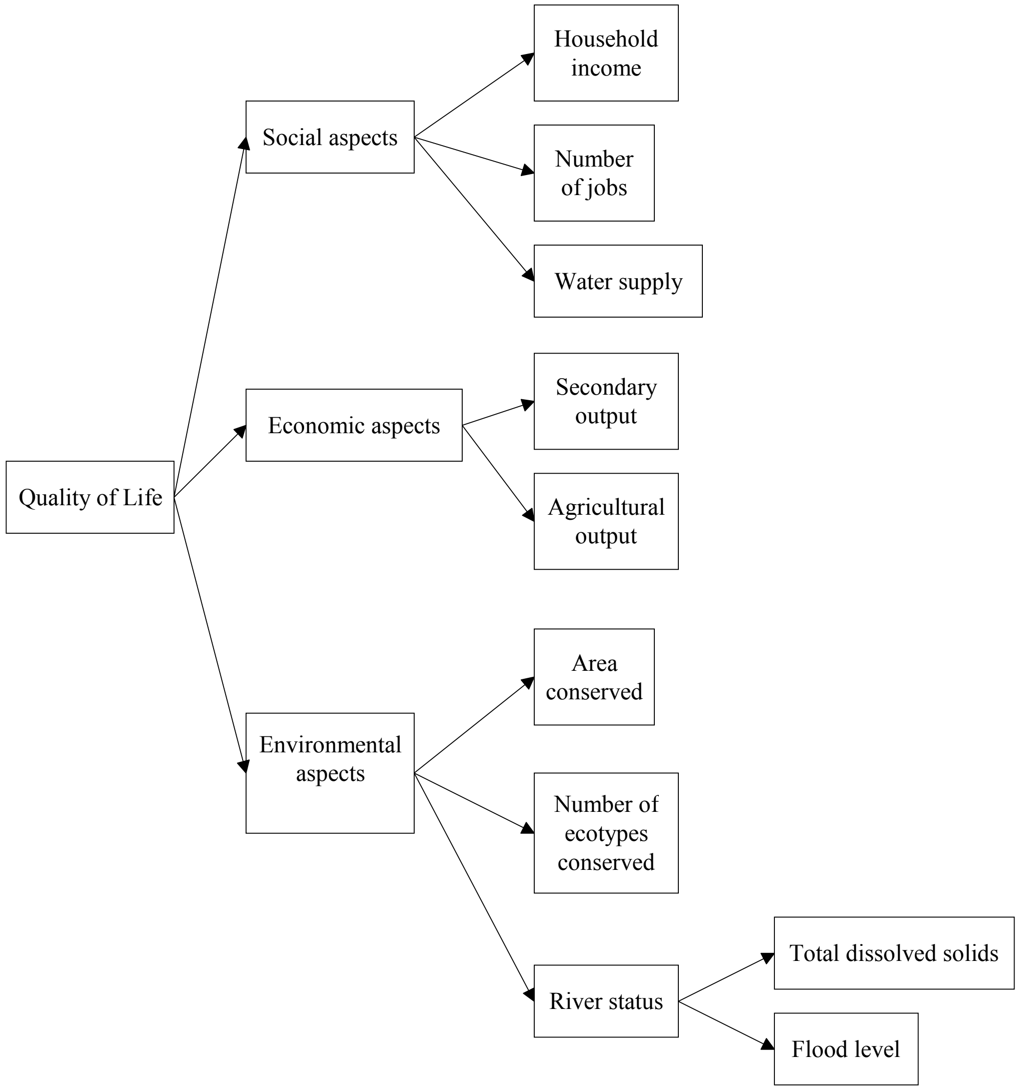

Figure 5.1: A value tree (Belton and Stewart, 2002)

This can be better understood with an example: choosing a location for a new airport. Three alternatives have 4, 6 and 8 company head quarters respectively, in their area. A naïve view would be that going from 4 to 6 is the same as 6 to 8. Non linearities can also arise if there are minimum preference levels or if there are desirable levels of achievement above which improvements have no additional value to the decision maker.

Some criteria cannot be directly measured *e.g.* quality of a food, quality of life in a city, and an ordinal or ordered categorical scale can be constructed to enable the ordering of the alternatives. In some cases however, it may be necessary to specify what aspect of the criterion is to be measured, *e.g.* texture for quality. In both cases, the value of the goal or criterion is called z; the partial preference function and is a measure of the performance of a criterion i, *i.e.* alternative A is preferred to alternative B in terms of criterion i, if zi (A) > zi (B).

- **Type of problem**

One-off decision: the context is more clearly defined. They are more strategic in nature and may need deeper exploration. Examples: location of offices, routing of a new highway.
In the case of repeated decisions, the role of MCDM is more towards setting up of procedures to be followed each time a decision is to be taken rather than to specific decisions in a particular case. It is important to ensure that the methodology can cope well with options that were outside the range of those available on the first occasion.

- **Number of stakeholders**

If the decision maker is a single individual or a group with more or less similar goals, the MCDM process can be used to make a decision without having to justify or debate it. If however the decision makers are a group with diverse interests and objectives, the final decision will involve a political compromise that may not directly be facilitated By MCDM.

- **Type of problematique**

Roy (1996) identified four problematiques, *i.e.* categories of problems (Belton and Stewart, 2002), where MCDM may be useful. The choice problematique: to make a simple choice from a set of alternatives; the sorting problematique: to sort actions into classes or categories such as 'definitely acceptable' or 'may be acceptable' etc.; the ranking problematique: to place actions in a form of preference ordering; the description problematique: to describe actions and their consequences in a systematic manner so that DMs can evaluate these. Belton and Stewart (2002) added two more problematiques to this list:
The design problematique: to search for identify or create new decision alternatives to meet goals revealed through the MCDM process; the portfolio problematique: to choose a subset of alternatives from a larger set of possibilities taking into account the way the alternatives interact with each other.

- **Range of alternatives**

In some cases, the number of alternatives may be small and explicitly defined. Many times however the number of alternatives may be large or infinite and defined in terms of the constraints that the decisions need to satisfy (investment decisions where all possible portfolio of stocks satisfying availability of funds need to be considered).

5.4. The process of MCDM

All MCDM models basically follow the same approach. The general model depicted in Figure 5.2 summarises the process.

1. Generation of ideas
2. Structuring of ideas
3. Model building
4. Determining the relative importance of the criteria
5. Determining the impact of the alternatives on the criteria (scoring)
6. Processing the values to arrive at a ranking for the alternatives
7. Final decision making and review

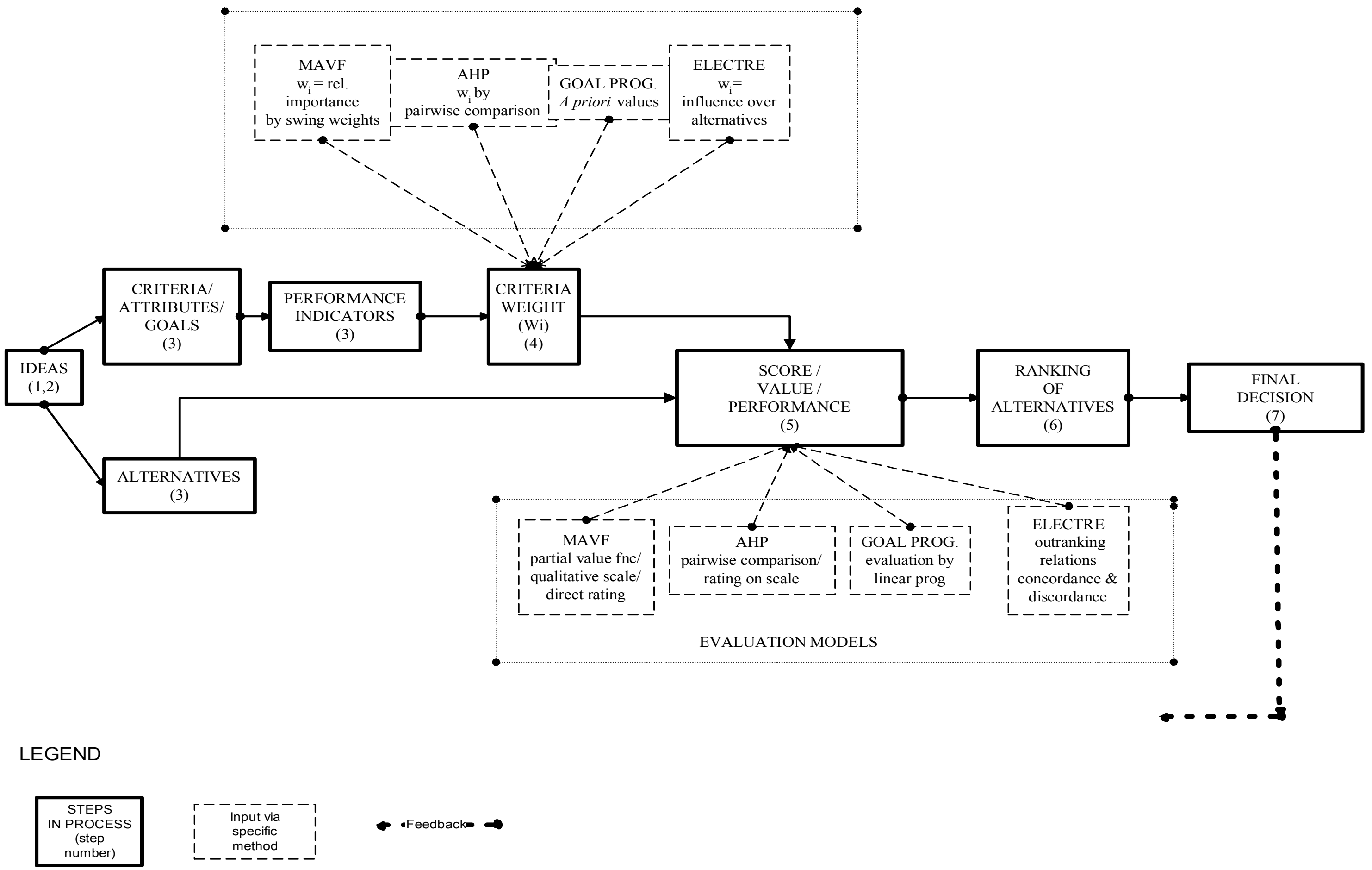

Figure 5.2: The general model (*MAVF- Multi attribute value function; AHP- Analytic hierarchy process; w_i- weight of the i^{th} attribute)

Step 1: Generation of ideas- this is the process of identifying the key concerns, goals, stakeholders, actions, uncertainties etc. The first action here is to identify the issue/issues under consideration and to facilitate the discussion. The ideas that are generated may be written down as the dialogue proceeds or may be summarised later. Details can be easily recoded with the use of 'post-its' or with more sophisticated variants.

Step 2: Structuring of ideas- the ideas that come up from the discussions may be repeated, random and in some cases not relevant. They have to be clarified and grouped together. A formal way of doing this is cognitive mapping (Eden, 2004).

Step 3: Model Building- determining the relevant criteria and alternatives. The key elements of the model framework are (Triantaphyllou, 2000):

i. The model values: criteria, goals, objectives: The identification of objectives/criteria/goals is the basis of all MCDM methods- the difference is in the way they are elaborated and structured. Value function methods focus on creating a value tree (figure 1) or a hierarchy of criteria; outranking methods concentrate on a few, important criteria; multi-objective goal programming also focuses on a few criteria but these have to be measurable on a quantitative scale. There are many factors that have to be considered while choosing criteria.

   a. Value relevance – how is the main concept linked to the goals? For example while choosing a house, size may evolve as a criterion- it may be the number of bed-rooms, the size of rooms, the garden space or the fact that a larger house implies a higher status.
   b. Understandability- the criterion should mean the same to all stakeholders- for example, for the same house situation as above, distance from a highway could be linked to lower commuting time to some stakeholders and increased noise levels to others.
   c. Measurability- all criteria have to be decomposed to the extent where they are measurable in terms of specific performance levels or indicators
   d. Judgemental independence- they should be independent of each other: preference with respect to one criterion should not depend on the level of another.

ii. The alternatives: Alternatives represent the different choices available to a decision maker. In some cases, the number of alternatives may be small and explicitly defined. Many times however the number of alternatives may be large or infinite and defined in terms of the constraints that the decisions need to satisfy (investment decisions where all possible portfolio of stocks satisfying availability of funds need to be considered). If the number of alternatives is infinite only a subset of the whole can be analysed in detail. The selection of this subset becomes a MCDM problem in itself. The analysis then consists of selection of the short lists and then evaluation of the alternatives. In other instances the discovery of alternatives may be an integral part of the study (Belton and Stewart, 2002). The challenge at times may be to find any suitable alternative; at other times the range and complexity of the alternatives may be overwhelming. There is not much literature devoted to this important aspect of MCDM. However the work of Keeney (1992) and Walker (1988) give an overview on the methods to generate alternatives.

Alexander (1979) points out…"Alternative design is a stage in the decision process whose neglect is unjustified in terms of its possible effect on decision outcomes…..if the choices which determine outcomes ….are made informally and intuitively before the evaluation phase begins, then attempts at formalisation and rational evaluation, however praiseworthy, are made in vain." It follows that the generation, evaluation and screening of alternatives are important aspects in MCDM.

The generation of alternatives requires a complete understanding of the problem at hand and it's surrounding situation as well as a great deal of creativity and imagination (Walker, 1988). In the initial stages of the decision process, it is important to specify as large a range of alternatives as possible and include all those that stand any chance of being considered. Alexander (1979) suggests two generation processes- search and creativity.

Search: this assumes that the solution to the problem exists and only needs to be identified. Tactics and strategies can be generated by using the following approaches (Walker and Veen, 1981).

- Review technical report and documents dealing with similar cases
- Talking with experts
- Other interest groups likely to be affected by the decision.

Creativity: Brainstorming is the best known techniques- the group of people should consist of people with different perspectives on the problem and as few restrictions as possible should be placed on the characteristics of the solutions.

When the generation step produces numerous alternatives, the screening and evaluation of these will not be possible within a reasonable amount of time. It is also possible that some alternatives are not worth investigation and many are similar to each other and others are clearly dominated. Therefore the generated alternatives have to be screened. Any good screening policy should possess two properties: it should not miss any good alternative and the number of alternatives it selects should not be large (Walker, 1988). Some other principles that have been used to screen alternatives are: infeasibility- if there is an economical, technical or organizational constraint in implementing the alternative, it is not worth investigating; dominance- if one alternative is clearly dominated by another, the former should not be further investigated. Walker (1988) noted that all screening procedures use one or both of the following strategies: Strategy 1: Bounding the space of promising alternatives: this strategy constraints the space in which 'good' alternatives can be found. If the constraints are chosen well, the strategy can be very efficient. Strategy 2: Using a simplified assessment model: this strategy constructs an extensive set of alternatives and then uses a broad assessment routine to come up with a set of promising alternatives. Data envelopment analysis (DEA) can also be used to screen alternatives.

The theory detailed above is illustrated using an example (italicised) from Belton and Stewart (2002). A company wants to open an office in Europe and wants to choose the location in a *structured manner. Steps 1 and 2 were performed as described earlier and the key issues were identified. Step 3, which is building the model, was then done as shown below.*

Step 3:
Criteria for the choice

- *Costs*
- *Attractiveness of location*
- *Ease of operations*
- *Communication links*
- *Size of local market*
- *Do personnel from the US want to relocate there?*

Goals for the decision

- *Staffing issues*
- *Business potential*
- *Ease of operations*

The value tree then is:

- *Staffing issues* → *Availability of staff*
  - → *Attractiveness to US staff* → *Accessibility from the US*
    - → *Quality of life*
- *Business potential* → *Public sector*
  - → *Private sector*
- *Ease of operations*

The alternatives: These consisted of potential cities where the office could be opened. After making an extensive list, the decision makers identified the following cities: Paris, Brussels, Amsterdam, Berlin, Warsaw, Milan and London as potential alternatives.

Steps 4, 5 and **6** depend on the type of MCDM method used. The three types of MCDM models mentioned earlier- value measurement theory; outranking methods and aspiration-based methods are all types of preference models. The analytical hierarchy process (AHP) is similar to the value measurement theory and has therefore been included. The sections below will give an outline of these methods and how steps 4, 5 and 6 are performed, using the same location example to show the differences in the approaches.

5.4.1. Value measurement models

The basis of this method is to associate a value V(A) with each alternative A, such that alternative A is preferred to alternative B (A $\succ$ B) on all criteria if and only if V(A) > V(B); V(A) = V(B) implies an indifference between A and B (A~B). In this model, steps 4 and 6 are relatively easy but step 5 is complicated. Therefore, for the sake of clarity, steps 4 and 6 are explained before step 5.

Step 4: In most multi-criteria decision problems, the criteria under consideration are not of equal importance to the decision maker- *i.e.* they do not have the same weight. Therefore it is important to assess the relative importance of the criteria.

The method of 'swing weighting' to elicit weights for the criteria is frequently used. This is based on comparisons of differences: how does the swing from 0 to 100 on one preference scale compare to the 0 to 100 swing on another scale? To make these comparisons, assessors are asked to take into account both the difference between the least and most preferred options, and how much they care about that difference. For example when buying a house, its cost may be considered to be important in the absolute sense. However, when choosing, the choice may have been narrowed to a shortlist of, say, five houses. If they only differ in price by € 2000, the price may no longer be such an important factor. That criterion would then receive a low weight because the difference between the highest and lowest price houses is so small. If the price difference was € 20,000, the criterion may be given a higher weight.

Thus, there is a crucial difference between measured performance (*e.g.* actual cost) and the value of that performance in a specific context (*e.g.* when all alternatives don't differ much from each other). Improvements in performance may be real but not necessarily useful or much valued: an increment of additional performance may not contribute a corresponding increment in added value.

So, the weight of a criterion reflects both the range of difference of the alternatives, and how much that difference matters. It may well happen that a criterion which is usually seen as 'very important' - say safety - will have a similar or lower weight than another usually lower priority criterion - say maintenance costs. This would happen if all the options had much the same level of safety but varied widely in maintenance costs. Any numbers can be used for the weights so long as their ratios consistently represent the ratios of the valuation of the differences in preferences between the top and bottom scores (whether 100 and 0 or other numbers) of the scales that are being weighted.

The 'swing' that is usually considered is one from worst to best value in each criterion. The criterion for which the swing will give the greatest increase in overall value will have the highest weight. This process is continued for all remaining criteria till a ranking is obtained. Weight values are next assigned by asking the decision maker to compare the criteria to the highest ranked one. The weight w_i represents the relative importance of criterion i *i.e.* the gain associated with replacing the worst outcome with the best for this criterion. For any two criteria, i and k, w_i/w_k is the increment on the value scale for criterion k, *i.e.* change in $v_k(A)$, that will compensate for one unit loss on value scale $v_i(A)$, for criterion i.

Step 6: This is the final step where alternatives are ranked. It is also known as the aggregation model. The value V (A) of alternative A can be estimated in the following ways:

$$V(A) = \sum_{i=1}^{m} w_i v_i(a) \tag{5.1}$$

The value of alternative A is therefore an additive aggregation of the partial values for each criterion i.

The alternatives can also be ranked based on a multiplicative aggregation model. If the value of the above ratio, AA/AB, is >1, then it implies alternative A is more desirable than alternative B (Triantaphyllou, 2000). When the ratio is calculated for all the alternatives, the ranking is obtained. This model has the advantage that it is a dimensional analysis as it eliminates any units of measure and can be used in the case of multi-dimensional MCDM.

$$R(A_A/A_B) = \prod_{i=1}^{m} (v(a)_i / v(b)_i)^{w_i} \tag{5.2}$$

A variation of this method is to calculate the performance of alternative A with the product approach.

$$P(A_A) = \prod_{i=1}^{m} v(a)_i^{w_i} \tag{5.3}$$

Step 5: Scoring alternatives: Alternatives are scored with respect to criteria. This implies that the criteria have to be measurable. Criteria have to be defined and can be converted to measurable forms (performance indicator, PI) with the aid of partial value functions and qualitative scales. However if direct rating of alternatives is used, only end points of the scale are defined, as explained below.

1. Partial value function- this relates value to the PI that is measurable. The value function represents the decision maker's preference for different levels of achievement. Such functions can be assessed directly or indirectly after determining whether the function increases or decreases monotonically against the natural scale. A fundamental property of this function is that alternative A is preferred to alternative B on criteria i if and only if $v_i(A) > v_i(B)$; $v_i(A) = v_i(B)$ implies an indifference between A and B.

Example
Criterion i: Level of SO_2 reduction
Alternatives: A, B
Partial preference function z_i
z_i (A): Actual level of reduction in the case of alternative A

z_i (B): Actual level of reduction in the case of alternative B
v_i(A): a non decreasing but not necessarily linear function of z_i (A) i.e. the partial value function.
v_i (z_i): this implies that the partial value function can be related directly to the criterion without specific reference to an alternative.

The assessment of the value of choosing a specific alternative for the relevant criteria is the score of the alternative i.e. deriving the value of v_i (A). The values need to be assessed on an interval scale, (a scale where the difference between points is important). The partial value functions are standardized with the 'best' and 'worst' outcome described for each criterion. This is easily done for criteria with measurable values and is done qualitatively for the others. Therefore two reference points have to be specified and numerical values have to be assigned to them. A local scale or a global scale can be used. In the former case, the best from the alternatives is given a score of 10 or 100 and the one that does least well is equated to zero. All other alternatives receive an intermediate score. On a global scale, the end points are defined by the ideal and worst conceivable performance of a criterion. The set of alternatives are then ranked relative to these.

Example
Access from the United States was evaluated with the aid of a constructed scale. The example below shows the difference between a local and global scale and shows how a partial preference function can be converted to a partial value function. The criterion accessibility from the US was measured using the number of direct flights per week from the alternative cities to Washington D.C. on a preferred airline. The number of flights varied from 2 per week (from Warsaw) to 15 per week from Amsterdam. A local scale was constructed with v_i (2) =0 and v_i (15) = 100 and all the alternatives were scored on this scale. A global scale can also be constructed with the view that there is unlikely to be more than 28 flights per week from any future alternative city on a preferred airline. So v_i (28) = 100 and v_i (0) =0

Once the end points of the scale are fixed, the shape of the partial value function can be derived by two widely used methods; the bisection method and the difference method (von Winterfeldt & Edwards, 1986). In the bisection method, the decision maker is asked to identify the point on the criteria scale that is half, quarter and three quarter of the way in value between the end points.

Example
The criterion availability of staff was assessed with the bisection method. The information that was available suggested that there would be at least 4 applicants for a post and not more than 50. The increase from 4 to 10 was found equivalent in value to the increase from 10 to 50. The quarter point was 8 and the three-quarter point was found to be 20. Two end points (4 and 50) and three midway points (8, 10 and 20) were sufficient to define the function.

2. <u>Qualitative scale</u>- values are assessed with references to word models e.g. Beaufort scale to measure wind strength. The scales should be operational, reliable and justifiable to an independent observer.

3. Direct rating of alternatives. The end points of the scale are specified. A local or global scale can be used. The decision maker specifies a number or uses an analogue scale. This method looks at one criterion at a time and compares all the alternatives pair wise. "Thinking of the quality of life, is city *a* preferred over city *B*?" If *A* is preferred over *B*, then the decision makers are asked to indicate the strength of their preference. Alternatives can also be rated directly by pairwise comparisons. No preference functions are constructed.

Steps 4, 6 and 5 of the value measurement method are now illustrated with the example. From the value tree it is obvious that there are five bottom level criteria via which these alternatives can be evaluated. According to the methodology, the methods for measuring the criteria have to be chosen and the scales defined if required (Table 5.1). The first, second, fourth and fifth criteria are the measured using preference functions.

Table 5.1: Criteria and performance measure/indicator

CRITERIA →	*Staffing issues*			*Business potential*		*Ease of set up of operations*
	Avail. of staff	*Access from US*	*Quality of life*	*Public sector*	*Private sector*	
Method	*N, partial*	*N*	*Qualt. scale*	*CS*	*CS*	*Direct rating*
Performance indicator	*Recruitment agency numbers*	*# flights /week*	*Table 5.2*	*# government offices and hospitals*	*# head offices*	*Through discussion*

N/CS: Natural or constructed scale

The quality of life is evaluated with the help of a qualitative scale (Table 5.2). It was based on the following factors: Climate, standard of living (schools, housing), ease of adaptation (favourable if English is spoken), cultural activities, pollution, safety (crime levels) etc. Each of these factors was rated as favourable, acceptable or unfavourable.

Table 5.2: Qualitative scale for 'Quality of life'

Value	*Description*
10	*all factors are favourable*
5	*all factors are acceptable*
0	*None are favourable and 3 or more are unfavourable*

Step 7: The final step of decision making is where the choice can be made. This is a separate step because no formal analysis technique can incorporate into a model changes in the state of the world, political upheavals, income distribution etc. It is also possible that the final decision may be taken by someone who was not involved in the decision making process. Even at this late stage in the process, new alternatives may be included or the current analysis may be revised (if new information is found).

5.4.2. Analytic Hierarchy Process (AHP)

The AHP method is based on the priority theory of Saaty (1980) which is a decision aid based on pairwise comparisons of criteria and alternatives. This theory first identifies the criteria that are relevant to rank the available options (alternatives). It then calculates their relative weights and scores the alternatives on each criterion and then simultaneously on all criteria.

The AHP method can be seen to be a variant of the value based measurement methods, as it is a preference model. The main factors that differentiate the AHP from value measurement based methods are the use of pair wise comparisons and the use of ratio and not interval scales for all judgements. Instead of constructing a partial value function or a qualitative scale, the decision maker compares the criteria and then the alternatives pairwise resulting in numerical scores.

Priority theory starts with the idea that it is easier to consider the criteria in pairs. First criterion 1 is compared to criterion 2, to decide whether they are equally significant, or whether one of them is somewhat more significant than the other in the given situation. Quantification of this pairwise comparison leads to a number expressing the preference of the decision-maker (Table 5.3). Then criterion 1 is compared to criterion 3, 4, .., m. After this, criterion 2 is compared to all other criteria, etc. The results of all these comparisons are shown in matrix A, a pairwise-comparison matrix. In matrix A, the element on row i and column j (a_{ij}) gives the relative preference of criterion i over criterion j for a decision-maker. If criterion i and j are considered to be equally important, then $a_{ij} = 1$. If i is more important than j then $a_{ij} > 1$; and if i is less important then j, $0 < a_{ij} < 1$. The element a_{ij} can be expressed as w_i/w_j. Matrix A has the following structure:

$$\begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1m} \\ . & . & . & . & . \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{im} \\ . & . & . & . & . \\ a_{m1} & \cdots & a_{mj} & \cdots & a_{mm} \end{bmatrix} = \begin{bmatrix} \frac{w_1}{w_1} & \cdots & \frac{w_1}{w_j} & \cdots & \frac{w_1}{w_m} \\ . & . & . & . & . \\ \frac{w_i}{w_1} & \cdots & \frac{w_i}{w_j} & \cdots & \frac{w_i}{w_m} \\ . & . & . & . & . \\ \frac{w_m}{w_1} & \cdots & \frac{w_m}{w_j} & \cdots & \frac{w_m}{w_m} \end{bmatrix} \qquad i = j = 1, 2, .., m \text{ (\# criteria)}$$

Matrix A has several properties. The number of rows is the same as the number of columns, which is equal to the number of criteria (m). All the elements a_{ii} on the diagonal are 1 as the criterion is compared to itself (and $w_i/w_i = 1$). Furthermore the matrix is reciprocal; if criterion i is a_{ij} times more important than criterion j, criterion j will be $a_{ji} = 1/a_{ij}$ times more important than criterion i. (See Table 5.4 for illustration).

Table 5.3: Quantification of pairwise comparisons

Verbal statement	Quantification
Criteria i and j are equally important	1
Criteria i is weakly more important than j	3
Criteria I is strongly more important than j	5
Criteria i is much more important than j	7
Criteria iis absolutely more important than j	9

Ideally matrix A should be consistent. This means that if criterion i is a_{ij} times more important than criterion j, and criterion j is a_{jk} times more important than criterion k, then criterion i is $a_{ik} = a_{ij} * a_{jk}$ times more important as criterion k. For example: if criterion 1 has two times more priority than criterion 2 (so $a_{12} = 2$), and criterion 2 is three times more important than criterion 3 ($a_{23} = 3$), then criterion 1 should be six times more important than criterion 3 ($a_{13} = a_{12} * a_{23} = 2*3 = 6$). In practice it appears that matrices put together by decision-makers are seldom perfectly consistent. If, in this example, a_{13} is chosen to be 5, the matrix is not consistent. Inconsistency can be measured (in step 4), and if more than the allowed amount, the results from that decision maker should be discarded.

Step 4:
It is possible to calculate the weights of the criteria (w_1, w_2, …, w_p), from the relative priorities shown in matrix A.

$$\sum_{j=1}^{p} a_{ij} = w_i \cdot \sum_{j=1}^{p} \frac{1}{w_j} \tag{5.4}$$

Equation 5.4 shows the sum of the matrix elements in row i.

$$\sum_{i=1}^{p} a_{ij} = \frac{1}{w_j} \cdot \sum_{i=1}^{p} w_i = \frac{1}{w_j} \tag{5.5}$$

Equation 5 shows the sum of the matrix elements in column j. From equation 5.5 it can be concluded that the sum of all the matrix elements is:

$$\sum_{j=1}^{p} \sum_{i=1}^{p} a_{ij} = \sum_{j=1}^{p} \frac{1}{w_j} \tag{5.6}$$

For an ideal ('perfect consistent') matrix, the weights w_i can now be calculated in two different ways. The first way uses equations 5.4 and 5.6:

$$w_i = \frac{\sum_{j=1}^{p} a_{ij}}{\sum_{j=1}^{p} \sum_{i=1}^{p} a_{ij}} \tag{5.7}$$

The second way to calculate the weights w_i is with the help of equation 5.5

$$w_j = \frac{1}{\sum_{i=1}^{p} a_{ij}} \tag{5.8}$$

If matrix A is perfectly consistent, the weights obtained with equation 5.7 will be the same as the weights obtained with equation 5.8. These weights are the real weights w_i. If matrix A is not perfectly consistent, it is possible to get an approximation xi of the real weights w_i. The approximation x_i can be obtained with the equations 5.7 and 5.8. But the approximations obtained with equation 5.7 will differ from the approximations obtained with equation 5.8. The decision-maker now has to choose which approximation x_i he will use.

The more matrix A is inconsistent, the more the approximation x_i will differ according to their calculation method. Therefore it is useful to have an indicator for the inconsistency of a matrix. Equation 5.9 (Saaty, 1980) provides a measure of the decision maker's judgement to check if the elicited responses follow the reciprocal rule and to see if the decision maker's responses are consistent.

$$CR = \frac{\lambda_{\max} - p}{(p-1) * \rho} \tag{5.9}$$

In equation 5.9, λ_{max} is the absolute largest eigen value of the matrix A and p is the number of rows or columns (which is equal to the number of criteria), ρ is the random index found by Saaty (1980) by simulations. CR < 0.10 is acceptable.

Step 5: The next step is to see how the different alternatives score on each criterion. The alternatives are compared for each criterion, and a number is given to each alternative, to express the score of that alternative. It is very important that the same scoring method is used for all the criteria. An example is to rank the alternatives on a scale *e.g.* one to ten, for every criterion. The scores are placed in a score/value-matrix V = (v_{Ai}):

$$\begin{bmatrix} v_{11} & \cdots & v_{1i} & \cdots & v_{1p} \\ . & . & . & . & . \\ v_{k1} & \cdots & v_{ki} & \cdots & v_{kp} \\ . & . & . & . & . \\ v_{m1} & \cdots & v_{mi} & \cdots & v_{mp} \end{bmatrix}$$

A = 1, 2, .., m (# alternatives)
i = 1, 2, .., p (# criteria)

Some criteria are measurable with respect to the alternative, for instance the profits of a company. However hard data like cost should not be directly converted to preferences or priorities. A car with a top speed of 300 mph may not be twice as preferable as a car with a top speed of 150 mph for an ordinary driver. In such cases, the criteria can be assigned intensities or priorities that are then compared pairwise to each other. The scores thus obtained can be used to score the alternatives.

An example for this method of scoring is found in Saaty (2005). Employees in a company have to be evaluated for raises. The criteria are dependability, education, experience and quality. The intensities chosen here are outstanding, above average, average, below average and unsatisfactory. These were compared pairwise to each other and preference scores were obtained.

Outstanding	*0.419*
Above average	*0.263*
Average	*0.160*
Below average	*0.097*
Unsatisfactory	*0.062*

The employees were then evaluated for the criterion of dependability based on these preference scores.

Alternatives can also be scored using a pairwise comparison. For each criterion i, alternatives are compared to each other in pairs and the score matrix is filled in. This evaluation method is more subjective than the above one.

Step 6: The overall ranking of the alternatives is done using the additive model (equation 5.1).

The location problem discussed above can also be solved with AHP. The bottom level criteria- availability of staff, accessibility from the US, quality of life public sector business potential, private sector business potential and the ease of set up of operations are compared pairwise to each other and the vales are entered into a comparison matrix (as described in the methodology above) and the values are processed to arrive at the criteria weights, w_i, using equations 5.4, 5.5 and 5.6.

An example of the pairwise comparison of the alternatives for the criterion quality of life is shown below. "Thinking of the quality of life, is city A preferred over city B?" If A is preferred over B, then the decision makers are asked to indicate the strength of their preference with the aid of Table 3. Once all the pairs of alternatives are compared in this way, the numeric values are entered into a matrix (Table 5.4)

Table 5.4: Example of a pairwise comparison matrix (Belton and Stewart, 2002)

	Paris	*Brussels*	*Amsterdam*	*Berlin*	*Warsaw*	*Milan*	*London*
Paris	*1*	*3*	*4*	*6*	*7*	*1/3*	*3*
Brussels	*1/3*	*1*	*1*	*5*	*7*	*1/5*	*½*
Amsterdam	*¼*	*1*	*1*	*3*	*5*	*1/5*	*½*
Berlin	*1/5*	*1/5*	*1/3*	*1*	*5*	*1/7*	*1/5*
Warsaw	*1/7*	*1/7*	*1/5*	*1/5*	*1*	*1/9*	*1/7*
Milan	*3*	*5*	*5*	*7*	*9*	*1*	*3*
London	*1/3*	*2*	*2*	*5*	*7*	*1/3*	*1*

The matrix shown in table 4 is the pairwise comparison matrix (matrix A). The figures in each row indicate how much better the alternative in that row is better than the alternatives heading each column. Here the alternative locations are compared to each other pairwise *with respect to the criterion quality of life. Matrix entry a_{14} is 5. This indicates that Paris is strongly preferred over Berlin. This matrix is reduced to a comparison vector which is a set of scores that represents the relative performance of the alternatives. This is the eigen vector that corresponds to the maximum eigen value of matrix A. The scores obtained here are normalised and the ranking of the alternatives (with respect to quality of life) is as shown below. Table 5.3 is how the alternatives are ranked with respect to the criterion quality of life (generated from the matrix in table 5.2). Scores are similarly generated for all the alternatives with respect to the criteria and the values are entered into a score matrix V and the value of each alternative V (A)*

Table 5.5: Scores for quality of life

Location	Score, v(a)
Milan	0.37
Paris	0.23
London	0.14
Brussels	0.1
Amsterdam	0.08
Berlin	0.05
Warsaw	0.02

Scores are similarly generated for all the alternatives with respect to the remaining criteria and the values are entered into a score matrix V and the value of each alternative V (A) is calculated with equation 1. The final ranking of the alternatives is then obtained with Equation 5.1.

$$V(A) = \sum_{i=1}^{m} w_i v_i(a)$$

, where w_i is the weight of criterion i and vi (A) is the score of alternative A for criterion i

5.4.3. Outranking models

As with the aspiration models, outranking models are also applied to the partial preference functions. These functions may have performance values on a cardinal scale or be constructed as ordinal or categorical scales. It has been in stated in value models that alternative A is preferred to alternative B in terms of criterion i, if $z_i(A) > z_i(B)$; alternative A is preferred to alternative B if a is as good as or better than B in the case of all criteria. Outranking models differ in that there are two more qualifiers:

1. There is an emphasis on the strength of evidence of ‘A is as good as B’ rather on strength of preference.
2. Indifference is not implied when neither A nor B outrank either- it may be that the two alternatives are incomparable

Therefore four situations may arise: A better than B; B better than A; A and B are the same; A and B are incomparable.

Two rules govern the final ranking of the alternatives.

1. if A is as good as or better than B according to a large weight of criteria, then there is evidence to say that A outranks B- concordance principle
2. if B is very strongly preferred to A on one or more criteria, this is considered to be evidence against the statement A outranks B- discordance principle.

The meaning of weights in outranking is different from that in the earlier models. Weights here do not represent trade offs or scaling factors. The weight measures the influence that a criterion has to build up a case for the assertion that one alternative is better than another. The criterion on which the alternatives differ most greatly will have the largest weight.

Concordance gives a measure of the strength of support for a hypothesis than one alternative is as good as or the same as another. Discordance is similar to a 'veto'. If the difference z_i (B) - z_i (A) is greater than a threshold value, then under no circumstances can A be said to be at least as good as B i.e. A can never outrank B even if it does better than B in terms of other criteria.

ELECTRE 1

The alternatives can be evaluated with respect to the criteria on ordinal scales, *e.g.* on a 5-point scale: Very low (VL), Low (L), Average (Av), High (H) and Very High (VH) - a higher rating indicates a higher preference. The weights allocated to the criteria show their importance- a higher weight implies a greater importance. As said before, weights do not represent trade-offs like in the value function methods but are rather a 'voting' power associated with each criterion. The ELECTRE methods are based on the evaluation of the 'concordance' index and the 'discordance' index. The concordance index, C (A, B) measures the strength of support in the given information for the hypothesis that A is at least as good as B. The discordance index, D (A, B), measures the strength of evidence against this hypothesis.

$$C(A, B) = \frac{\sum_{i \in Q(a,b)} w_j}{\sum_{i=1}^{m} w_j} \qquad (5.10)$$

where Q (A, B) is the set of criteria for which A is equal to or as good as B.

The concordance index is therefore the proportion of criteria weights allocated to those criteria for which A is equal to or preferred to B. This index takes on values between 0 and 1; a value of 1 indicates that A dominates or is as good as B.

The discordance index, D (A, B) can be defined by a veto threshold for each criterion i, t_i, such that A cannot outrank B if the score for B on any criterion exceeds that of A by an amount = > t_i.

$$D(A, B) = \begin{cases} 1 \text{ if } z_i(B) - z_i(A) > t_i \text{ for any } i \\ 0 \text{ otherwise} \end{cases} \qquad (5.11)$$

Finally to build an outranking index, C* and D* have to be specified. They are the concordance and discordance thresholds respectively. Alternative A outranks alternative B if C (A, B) > C* and D (A, B) < D*. These values are reached by experimentation and must be high enough (in the case of C*) and low enough (in the case of D*) to be able to provide useful output. ELECTRE 1 aids in the identification of preferred alternatives and not in the best alternative. A kernel of preferred alternatives is formed (the alternatives not in this set are the dominated ones). The sensitivity of this method depends on the criteria weights and the values of C* and D*.

This methodology is illustrated with the same location problem. The alternatives are evaluated with respect to the criteria on a 5-point ordinal scale: Very low (VL), Low (L), Average (Av), High (H) and Very High (VH) - a higher rating indicates a higher preference. Table 5.4 shows the decision matrix with criteria weights for the problem. Amsterdam ranks low on availability of staff but is very high when accessibility from the US is considered.

Table 5.6: Decision matrix- ELECTRE

	Staffing issues			*Business potential*		*Ease of set up of operations*
	Avail. of staff	*Access from US*	*Quality of life*	*Public sector*	*Private sector*	
Weights	***6***	***4***	***3***	***10***	***8***	***6***
Paris	*Av*	*H*	*H*	*H*	*VH*	*Av*
Brussels	*L*	*Av*	*Av*	*VH*	*Av*	*Av*
Amsterdam	*L*	*VH*	*Av*	*H*	*VH*	*H*
Berlin	*H*	*L*	*L*	*Av*	*H*	*H*
Warsaw	*H*	*L*	*L*	*Av*	*Av*	*L*
Milan	*H*	*L*	*VH*	*Av*	*H*	*H*
London	*Av*	*VH*	*H*	*Av*	*H*	*VH*

As can be seen from the criteria weights in the Table 5.6, Business potential-public sector was considered the most important and the quality of life the least. Using equation 5.10 and the ratings from table 5.3, the concordance index that measures the strength of support in the given information for the hypothesis that alternative A is at least as good as alternative B can be calculated as follows:

Paris is equal to or better than Brussels in all criteria except Business potential-public sector (Table 5.4). Q (Paris, Brussels) is availability of staff, Accessibility from the US, quality of life, Business potential-private sector and ease of set up of operations.

Therefore from equation 5.10,

$$C(\text{Paris, Brussels}) = \frac{\sum(\text{all criteria weight except Business potential, public sector})}{\sum(\text{all criteria weights})} = 27/37 = 0.73$$

Similarly C (Amsterdam, Paris) =0.76, C (Milan, Berlin) =1.00.

As mentioned earlier, D (A, B) is evaluated with a veto threshold, t_i. This value was set at 3 for this problem. This implies alternative A cannot outrank alternative B if B is 3 or more points higher on the 5 point scale on even one criterion; e.g. if B scores VH and a scores L or VL on any criterion. The matrix (Table 5.7) is shown below: an entry of 1 in any cell (A, B) means that alternative A cannot outrank alternative B.

Table 5.7: Discordance matrix

	Paris	*Brussels*	*Amsterdam*	*Berlin*	*Warsaw*	*Milan*	*London*
Paris	-	*0*	*0*	*0*	*0*	*0*	*0*
Brussels	*0*	-	*0*	*0*	*1*	*0*	*0*
Amsterdam	*0*	*0*	-	*0*	*1*	*0*	*0*
Berlin	*0*	*0*	*1*	-	*0*	*1*	*1*
Warsaw	*0*	*0*	*1*	*1*	-	*1*	*1*
Milan	*0*	*0*	*1*	*0*	*0*	-	*1*
London	*0*	*0*	*0*	*0*	*0*	*0*	-

The decision makers specified C^* =0.7 and D^* = 0.1 initially. As D has values of 0 and 1 only all non zero values of D are equal. It was found that Paris and Amsterdam outrank each other. They also outrank all other alternatives. Amsterdam and London, and Paris and Milan form kernels. The value of C^* was increased to 0.8 and a stronger outranking relationship was found. The kernel then consisted of all alternatives other than Berlin and Warsaw.

ELECTRE 2 was developed to provide a ranking of alternatives rather than just a kernel of preferred ones. Two types of outranking relationships are Built- strong and weak. Another change is the introduction of a new constraint: now C (A, B) >= C (B, A), in addition to C (A, B) >C*. The ranking order is determined in two ways. One ranks the alternatives from best to worst and the other from worst to best. It is possible that the two orders don't give the same results. One method for resolving this is by the 'intersection' of the orders.

ELECTRE 3 introduces the concepts of preference and indifference thresholds. This approach constructs a concordance index Ci (A, B) such that:

$$\text{Ci (A, B)} = \begin{cases} 1 \text{ if } z_i(B) > z_i(A) + q_i[z_i(A)] \\ 0 \text{ if } z_i(B) >= z_i(A) + p_i[z_i(A)] \end{cases} \quad (5.12)$$

where: p_i [z_i (A)] is the preference threshold for criterion i and q_i [z_i (A)] is the indifference threshold; and p_i [z_i (A)] > q_i [z_i (A)].

The overall concordance index is:

$$C(A, B) = \frac{\sum_{i=1}^{m} w_i * C_i(a,b)}{\sum_{i=1}^{m} w_i} \quad , \tag{5.13}$$

and the discordance index is:

$$D(A, B) = \begin{cases} 0 & \text{if } z_i(B) <= z_i(A) + p_i[z_i(A)] \\ 1 & \text{if } zi(B) >= z_i(A) + t_i[z_i(A)] \end{cases} \tag{5.14}$$

The overall concordance and discordance indices are combined to give an overall ranking. Alternative A is compared to alternative B with a credibility index S (A, B).

$$S(A, B) = C(A, B) \qquad \text{if } D_j \ldots (A, B) <= C(A, B)\ \forall I \tag{5.15}$$

otherwise:

$$S(A, B) = C(A, B) \quad \prod_{i \in J(a,b)} (1 - D_i(a,b)) \div (1 - C(a,b)) \tag{5.16}$$

where J (A, B) is the set of criteria for which D_i (A, B)>C (A, B).

As is with the earlier ELECTRE methods, ELECTRE 3 gives descending and ascending order of the alternatives. The two orders are combined with a distillation process to give an overall ranking (see Belton and Stewart (2002) for details).

5.4.4. Goal, aspiration or reference models

In such models the partial preference functions are used without further conversions. The goal programming method is a form of the above method. The aspiration levels are the a priori goals and mathematical programming is used to reach as close as possible to these values. It is therefore necessary that the problems have a mathematical programming structure. The location selection example is qualitative in nature and cannot be solved meaningfully with this approach.

5.5. Sensitivity analysis

It is important to confirm if the preliminary conclusions from the model are robust or if they are sensitive to changes in the model. Changes in parameters, weights etc may be made to investigate the effect of a decision maker's perspective or uncertainty on the overall results.

According to Belton and Stewart (2002), sensitivity analysis can be done from a technical perspective, from an individual's perspective or from a group perspective. The former involves looking at changes in the overall ranking of alternatives when input parameters are changed *i.e.* whether a change in criteria weights can affect the overall preference order. Sensitivity analysis from an individual's point of view is to provide a sounding board to test their intuition and satisfaction of the problem and results

The next chapter (Chapter 6) uses some of the methods and models described above to aid in the decision making process of designing food supply chains.

5.6. References

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Chapter 6

Application of MCDM to food supply chain design – A case on novel protein foods.

6. Application of MCDM to food supply chain design - A case on novel protein foods.

6.1. Introduction

This chapter proposes and applies a methodology to design food supply chains (FSCs). Traditionally, supply chain (SC) management refers to managing a supply chain to meet end-customer needs through product availability and responsiveness, on-time delivery etc. (Beamon, 1998; van der Vorst *et al.*, 1999; Wang *et al.*, 2004). The chain starts at the supplier and ends at the retailer or the consumer and costs are minimised over these links of the chain. However, when a FSC is being considered, the chain starts a few links earlier, *i.e.* at the primary production of the raw ingredients and goes all the way through to the consumer (Apaiah *et al.*, 2005). Another characteristic of FSCs is that the attributes of the product (taste, texture, nutritional level) that are important to the consumer, are a result of the SC variables in each link. It is the achievement of these attributes that may influence the success of the product. FSC design has to focus on product attributes by looking at the FSC backwards, from the consumer through to primary production (Apaiah *et al.*, 2005). This chapter therefore looks at SC design from this different perspective: it focuses on how to design the entire chain from start to finish, so that the consumer gets a product that he/she wants, *i.e.* concentrating on product attributes rather than on the delivery of the product, as is the case in traditional SC management.

The qualitative model presented in Apaiah *et al.* (2005) is extended with a quantification of the model. Potential chain designs are proposed, evaluated and the best design is recommended. Finally, a sensitivity analysis is performed on the results. The selection of attributes, identification of variables, generation of alternatives and the final evaluation require decisions to be made. The problem has qualitative and quantitative elements; the decision space is discrete and conflicting criteria have to be considered simultaneously. The criteria are hybrid in nature (Belton and Stewart, 2002), the number of alternatives is large and there are multiple stakeholders. Thus a decision making aid like multiple criteria decision making (MCDM) is ideal for a problem of this genre.

MCDM models handle qualitative data very well. These models do not try to compute an optimal solution. Instead, many alternatives are proposed or generated as may be the case, and the decision maker ranks them with respect to the criteria (attributes). There is no objective statement and therefore no trade offs in the traditional sense as each criterion is ranked according to its importance to the decision maker (Zak *et al.*, 2002). An inherent property about decision making is subjectivity. MCDM does not dispel this but shows the need and makes the process of making such decisions transparent (Belton and Stewart, 2002). The process of MCDM is divided into three phases- identification of the problem, building the model and finally developing action plans.

There are some basic steps that are common to all approaches in MCDM (Belton & Stewart, 2002; Triantaphyllou, 2000). The general model described in chapter 5 (Figure 2, Chapter 5) summarises the process. It is applied to the novel protein food (NPF) supply chain design problem and a structured approach to such cases is developed here. The terminology used in the rest of this chapter has been explained in chapter 5.

6.2. The Novel Protein Food case

6.2.1. The initial steps

The first three steps are descriptive and don't depend on the type of model being used.
Step 1: Generation of ideas.
The case material presented in this study was collected in the framework of PROFETAS. One of the tenets of the project was that the non-meat protein products on the market did not meet the expectations of most consumers and thus could not be considered realistic substitutes to meat; thus the prospects for replacing meat-derived ingredients by non-meat ingredients- Novel Protein Foods (NPF) were more promising (www.profetas.nl).

The decision makers involved in this project were food technologists, environmental scientists and economists. The issues that arose during brainstorming sessions were:

- The current food production and consumption pattern has a strong impact on the environment and natural resources
- Meat production in particular is not appealing from an environmental point of view because of the inefficient conversion of protein in the feed into protein in the slaughtered animal, the manure generated and the amount of water used
- A shift to a completely vegetarian diet is not a sensible suggestion
- Pork meat is popular in the Netherlands.
- A feasibility study to decide whether a partial diet conversion (pork products to NPF) is possible could be done
- The vegetable source that can be used to partially replace pork is dry green peas. Peas are popular in the Netherlands, they are grown locally and expertise is easily available
- The non-meat protein products presently on the market do not meet the expectations of most consumers and thus cannot be considered realistic substitutes to meat. There are problems with the texture and taste of the products and they are expensive when compared to pork
- The product will be successful if consumers want it. Therefore consumer studies are important to discover what product attributes will make a NPF desirable to consumers
- The new product should have a low impact on the environment- to start with, lower than meat
- The entire supply chain, from primary processing to the consumer impacts the product
- The feasibility study should aim at partially replacing processed pork products.

Step 2: Structuring of ideas
The main ideas that came up from Step 1 are summarized below.

- The feasibility study will look at a partial conversion of the diet; 20% of processed pork products by the year 2020 (Apaiah & Hendrix, 2005; www.profetas.nl)
- Currently available NPFs are expensive and do not have a good texture and taste; developing a product with good texture will be a priority
- The new product must be more environmentally friendly than pork meat
- Consumer studies and market research are necessary to make a successful product
- The entire supply chain has to be investigated

Step 3: Model building- determining the relevant criteria and alternatives.

i. The model values: from consumer studies and discussions with stakeholders, it was apparent that the overall goal was to make a 'good' meat substitute. Important product attributes that came out from the discussion were good taste and texture, competitive pricing and environmental friendliness. Therefore the design of a supply chain to deliver such a product became imperative. The chain study would concentrate on product attributes rather than on the delivery of the product. This implied that goals/criteria of good quality, environmental and economic sustainability (Apaiah *et al.*, 2005) had to be taken into account while designing the chain.

According to the requirements in Belton & Stewart (2002) the criteria were found to be relevant, understandable and independent of each other. They were however not directly measurable. The goals were further defined and performance indicators chosen as follow:

- Economic sustainability- cost to manufacture the product (Apaiah & Hendrix, 2005)
- Environmental sustainability - exergy input required (Apaiah *et al.*, 2006)
- Quality- texture, absence of undesirable flavours, nutritional level (van Boekel, 2005)

ii. The alternatives: The generation, evaluation and screening of alternatives are important aspects in MCDM. The generation of alternatives requires a complete understanding of the problem on hand and it's surrounding situation as well as a great deal of creativity and imagination (Walker, 1988). Alternatives represent the different choices available to the decision makers. As said earlier, the aim was to design a supply chain for NPFs. The alternatives therefore become potential chain designs *i.e.* a combination of the links and transport modes.

<u>Generation of alternatives</u>: In cases like a location selection problem, alternatives are explicit and well defined. In this study however, generating the alternatives was an integral part of the methodology.

Two factors have to be taken into account when designing these food supply chains:

- It is necessary to start from the consumer and go back to the very beginning, *i.e.*, in the case of a food product, to the production of the raw ingredients that go into the product.
- The boundaries of the system have to be demarcated *i.e.,* what constitutes the primary chain and what inputs will be considered as is, have to be specified. This is required as raw materials are not the only inputs into the product. Fertilizers, electricity, labour, machinery are few of the 'other' inputs. However, the chains for these products will not be included in the design as this will not be practical and will probably be impossible when considering the manpower and time required.

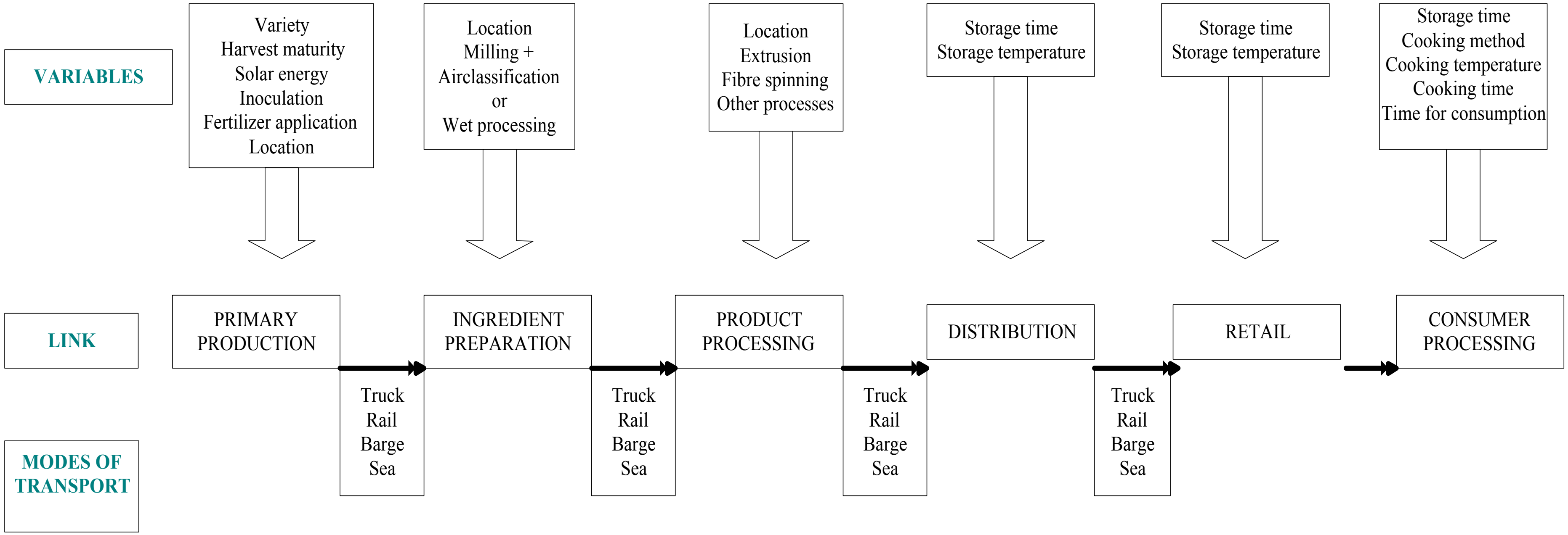

Figure 6.1: Generic supply chain for NPFs (Apaiah *et al.*, 2005)

Figure 6.1 gives an overview of the variables and links in a generic food supply chain for NPFs. These variables were the result of brainstorming sessions. The potential alternatives for the supply chain design are a combination of the choices for the control variables *i.e.* of the transport modes, locations for the production, preparation and processing plants, processing methods, storage time and temperature and aspects of consumer processing. In other words, Figure 1 describes possible chain designs.

<u>Screening the variables for the alternatives</u>: Further sessions were conducted to screen these variables. The results are presented in Table 6.1. Strategies that were used to discard variables were:

1. If there is no effect of a variable on the three criteria, it will be discarded
2. Commonly used farming and industrial practices will be taken into account, *e.g.* peas are almost always harvested at 11% moisture
3. If a variable cannot differentiate between alternatives, it is discarded

Table 6.1: Results of the screening strategies: effect of variables on criteria

	Link	Variable	Effect on Cost	Effect on Quality	Effect on Environmental load
5	Primary production	Location	x		x
		Variety			
		Maturity			
		Fertilizers			
		Inoculation			
		Solar energy			
4	Ingredient preparation	Location	x		x
		Processing method	x	x	x
3	Product processing	Location	x		x
		Processing method	x	x	x
2	Distribution	Storage time	x	x	x
2	Retail	Storage temperature	x	x	x
	Mode of transport	Rail, barge, Truck, sea	x	x	x

x indicates that a criterion is affected by the variable under consideration

Table 6.1 shows that the only variable in link 5 to affect the cost and environmental load is the location. Pea varieties and inoculation do not change the cost of the end product. The maturity of the pea is not a variable in this case as it was decided to use peas that were harvested at 11 % moisture (see screening strategy 2). The solar energy and application of fertilizers depend on the location, so are not included again. Quality, as specified earlier, refers only to the texture, absence of components that cause undesirable flavours and the nutritional composition of the end product. Work done by O'Kane (2004) showed that the gelation of pure pea protein solutions is affected by the ratio of the proteins, legumin and vicilin present in the pea. The texture of the gels obtained and the rate of formation would therefore also be affected. However, the effect of the ratio of proteins on the texture and gelation of real food systems is not known yet. Therefore the influence of varieties and breeding will not be taken into account now.

As stated earlier, the product is for the Dutch market, so location alternatives for distribution and retail were never considered. After the NPF is made, a distribution and retail company handles the product. Distribution and retail variables will affect the criteria; however, all the products that enter the chain at this point will be handled in a similar manner. Therefore, all potential chain designs after this link will be identical, as what affects product A will affect product B to the same extent. Therefore alternatives for chain design will stop after this point (screening strategy 3). This seems to clash with the idea of chain design propounded in this thesis-"the idea of chain design is to look at the entire chain". The reason the last part of the chain is not included when constructing the alternatives is as follows: the quantity of product that is being considered in this study is about 30,000 MT per annum. This is not large and the product will not have a sufficient market share to have a separate distribution network. The product will be transported to the distribution centres of the retail company. It will then be incorporated into the existing network of the retail company. The variables in link 2, as shown in Table 1, will affect the criteria, but all products will be influenced to the same extent and therefore no alternatives will arise.

Final selection:

- The locations for primary production were finalised according to the following rules:
  - NL (The Netherlands) - was chosen as the product is meant for the Dutch market
  - FR (France) - is the largest pea growing nation in the EU
  - UKA (Ukraine) – is a large grower of peas outside the EU, with relatively low labour and utility costs (www.researchandmarkets.com & http://www.cerc.gouv.fr)
  - CAN (Canada) – is the largest pea growing nation in the world.
- The choices for the processing locations are the same as for primary production
- Ingredient preparation. The main step here is the concentration of pea flour. The industry uses two methods, air classification and wet extraction, to make pea concentrates and pea isolates. Both these methods have been considered in this study.
- Product processing: Three methods were evaluated- air classification + extrusion, specialised processing A and specialised processing B (details are in the appendix).

The variables were screened according to the rules mentioned above. Figure 6.2 shows the SC after the screening process. The grey highlighted areas are the links and variables that were used to construct the alternatives.

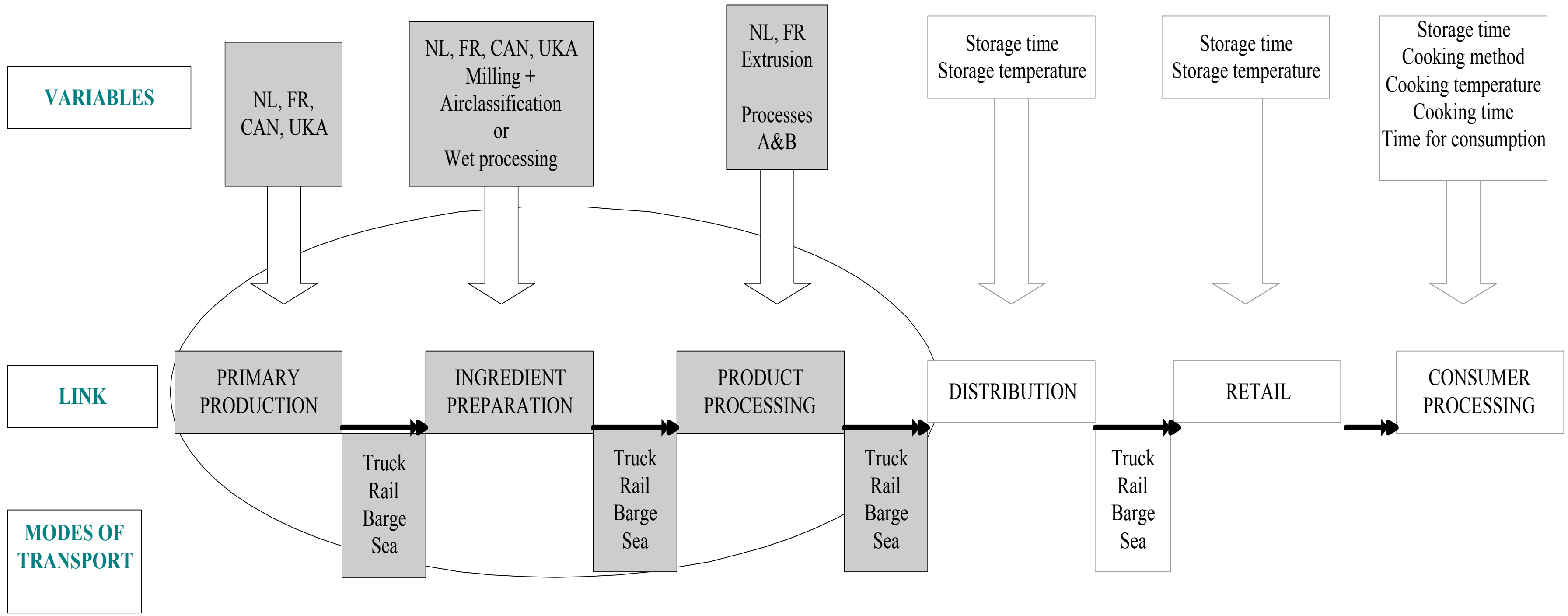

Figure 6.2: Potential alternatives after screening

Table 6.2 shows the details of the 11 alternatives that resulted from the generation and screening procedures described above.

Table 6.2: List of alternatives that resulted after the screening process

	PP location	Transport mode	ING location	Processing Method [Prot Concentration (%)]	Transport mode	NPF preparation Method in NL	Transport mode
1	UKA	Truck	UKA	AC [50-60] D	Truck Rail	Extrusion	Truck
2	NL, FR CA, UKA	Truck Sea Rail	UKA CAN	AC [50-60] D	Truck Rail	Extrusion	Truck
3	NL	Truck	NL	AC [50-60] D	Truck Rail	Extrusion	Truck
4	NL	Truck	NL	WP [25] W, **A**	Truck	**A**	Truck
5	FR	Truck	NL	AC [50-60] D	Truck	Extrusion	Truck
6	FR	Rail	FR	AC [50-60] D	Truck	Extrusion	Truck
7	UKA	Truck	NL	WP [80-90] D, **B**	Truck	**B**	Truck
8	FR NL	Truck Rail	NL	WP [25] W, **A**	Truck	**A**	Truck
9	CAN	Rail	CAN	AC [50-60] D	Sea	Extrusion	Truck
10	CAN	Rail	CAN	WP [80-90] D, **B**	Sea	**B**	Truck
11	FR	Rail	FR	WP [80-90] D, **B**	Truck	**B**	Truck

D= Dry; W= slurry; AC= air classification; WP= wet processing, **A, B =** processes A or B

PP = Primary production; ING = ingredient preparation; NPF = product processing; NL = The Netherlands; FR = France; CAN = Canada; UKA = Ukraine

6.2.2. Application of the models

Steps 4, 5 and 6 in of the general model (Figure 2, Chapter 5) depend on the type of MCDM model. The MAVF and AHP models were applied to this case. The two methods mainly differ in the way criteria are treated and in the use of partial value functions in the former and pairwise comparisons in the latter. Goal programming relies on quantitative data only and was therefore not applicable in this case. ELECTRE requires more interaction with stakeholders and decision makers than was possible in this case. The general model in Chapter 5 was modified to give the case specific model (Figure 6.3).

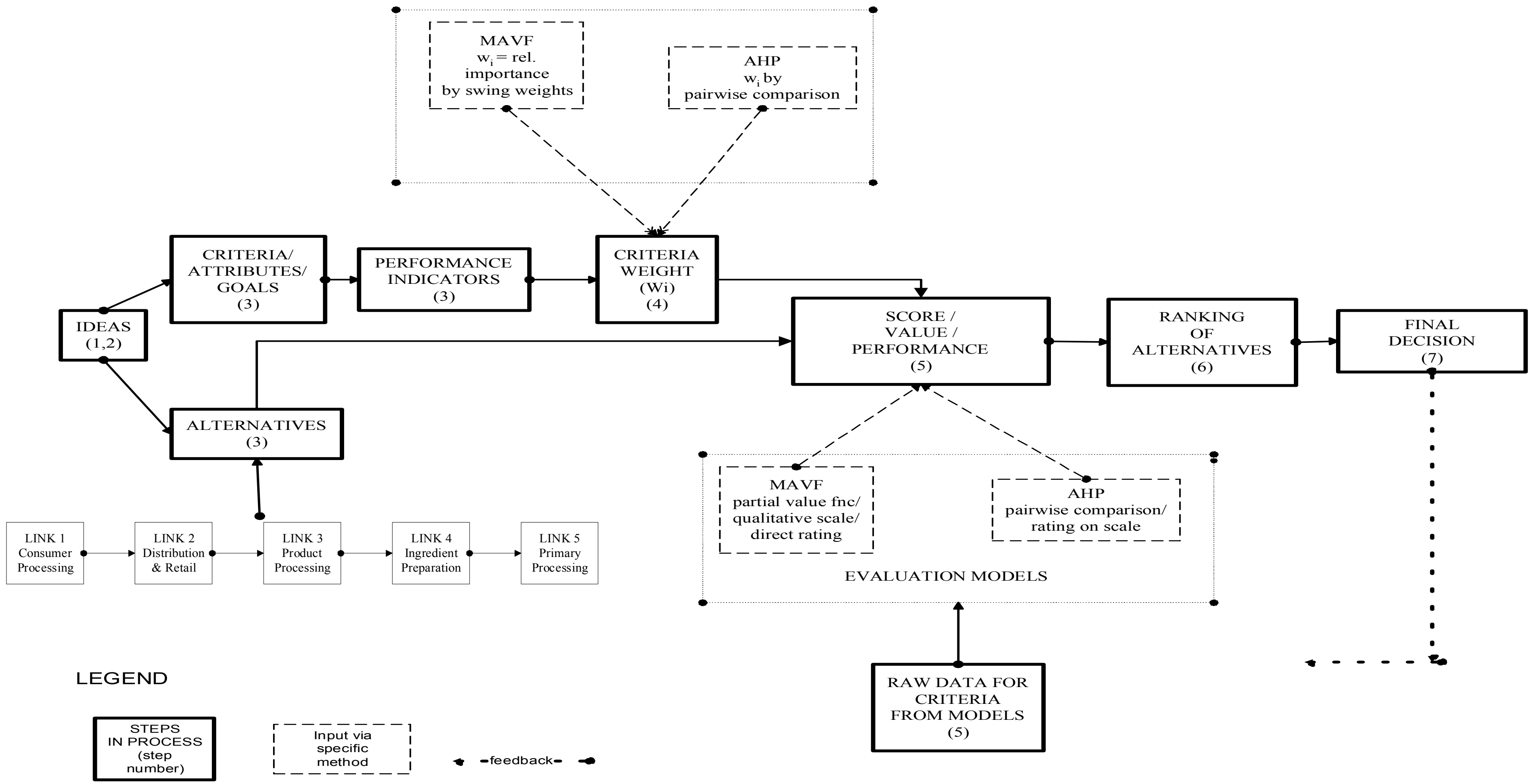

Figure 6.3: The case specific model

6.2.2.1. Application of the MAVF model

Step 4: Determining the relative importance of the criteria.

As in most multi-criteria decision problems, the criteria considered here are not of equal importance to the decision maker- *i.e.* they do not have the same weight. Therefore it is important to assess the relative importance of the criteria. The three top-level criteria of cost, quality and environmental load were weighted according to the swing method (Belton & Stewart, 2000) by a panel consisting of food technologists, social scientists, engineers and environmentalists. The details of the swing method are explained in chapter 5. These criteria were defined as follows:

- Cost- this refers to the cost of manufacture of the NPF. This cost was calculated (Apaiah & Hendrix, 2005; Appendix 6) and ranged from €215 -€610 per MT over the 11 alternatives.
- The environmental load was measured by the exergy input required for each alternative. The exergy input was calculated (Chapter 4 & Appendix 6) and ranged from approximately 14,000 MJ/MT (mega joule per metric ton) to 34,000 MJ/MT over the 11 alternatives.

The raw data of cost and exergy input of each alternative were converted to partial value scales (Chapter 5) where a score of 100 represented the cheapest cost alternative and lowest exergy requiring alternative and a score of zero the other extreme.

- The criterion quality of the end product was defined by consumer research and the brainstorming sessions to be nutritional value, texture and absence of undesirable flavours (sub attributes/criteria). The nutritional value was further sub divided into the following: amino acid availability, anti-nutritional factor (ANF) level and natural fibre content.

1. Texture: a good textured product is one that has a structure resembling that of meat. A score of 100 implies good structure formation and zero implies no fibre formation.
2. Absence of off-flavour: this refers to the absence of components that cause undesirable flavours. A score of 100 implies no beany off flavours after processing; zero implies a perceptible beany flavour.
3. Nutritive value: refers to the amino acid availability (score of 100 is no destruction of amino acids; zero implies most of the amino acids are destroyed), ANF content (lectins and trypsin inhibitors: a score of 100 implies no ANFs present and a score of 0 indicates the presence of a large amount of ANFs) and the presence of natural food fibres in the NPF after processing (score of 100 indicates that there is an appreciable amount of fibre and a score of zero indicates no natural fibre remains in the product).

The panellists were asked to consider how the swing from 0 to 100 on one preference scale compared to the 0 to 100 swing on another scale and filled in tables like Table 6.3.

Table 6.3: Elicitation of weights in the swing method

Criteria	Order	Weight	Normalised weights
Cost			
Quality			
Environmental load			

The results presented below are from four panellists (Table 6.4). The panellists first ordered the criteria and then assigned weights. The data on weights and orders (Table 6.4) were used to calculate the normalised weights and the average. Table 4 shows that panellists 1, 2 and 3 have similar preferences with regard to the order of the criteria, but differ greatly on the relative important of the criteria. Panellist 4 ranked environmental load as the most important criterion but note that the relative difference between the criteria is small in his case. This highlights the fact that the opinions and bias of decision makers can exist and ultimately may influence the final ranking of the alternatives.

Table 6.4: Top criteria weights for the NPF via the swing method

Panellist		Cost	Quality	Environmental load
1 (Food engineer)	Order	2	1	3
	Weight	80	100	20
	Normalised weight	0.4	0.5	0.1
2 (Food engineer)	Order	2	1	3
	Weight	50	100	25
	Normalised weight	0.29	0.57	0.14
3 (Consumer scientist)	Order	2	1	3
	Weight	50	100	5
	Normalised weight	0.32	0.65	0.03
4 (Environmental scientist)	Order	2	3	1
	Weight	90	70	100
	Normalised weight	0.35	0.27	0.38
Average weights		**0.34**	**0.5**	**0.16**

The swing method was also used to elicit weights for the quality sub criteria. Table 6.5 gives the normalised weights that were calculated from the responses elicited from the experts (similar to Table 6.4). Three of the four experts ranked texture as the most significant sub criterion. The fourth expert ranked texture and absence of off flavours at the same level.

Table 6.5: Quality sub criteria weights for the NPF elicited via the swing method

Experts	Texture	Absence of off flavours	Absence of ANF	Amino acid avail.	Natural fibres
A (Consumer scientist)	0.42	0.25	0.08	0.13	0.12
B (Food scientist)	0.31	0.31	0.28	0.03	0.06
C (Food scientist)	0.43	0.34	0.13	0.06	0.04
D (Food chemist)	0.36	0.33	0.15	0.13	0.04
Average	0.38	0.31	0.16	0.09	0.07

Step 5: Determining the impact of the alternatives on the criteria (scoring)

As shown earlier, 11 alternatives were generated. Each of these influence the criteria and the quality sub criteria to different extents *i.e.*, each alternative will have a different score on each of the criteria.

i. <u>Scoring the alternatives for quality</u>

The quality of the end product from each alternative is the result of the processing method that is used to make it (Table 6.1). As three processing methods can be used, NPFs of three different qualities were defined. A qualitative scale was used. Each sub-attribute of the end product was scored as: Good (10 points), Acceptable (5 points), and Bad (zero points), with respect to the alternatives by experts (the same as those used in Table 6.5) from food processing, food engineering and food chemistry. Table 6.6 classifies the alternatives on the basis of the processing methods. The results of the scoring are given in Table 7.

Table 6.6: Processing methods and alternatives

Processing method*	Number of alternative
AC+ Extrusion	1,2,3,5,6,9
From process A	4,8
From process B	7,10,11

*details on processing methods available in appendix xx

Table 6.7 gives the scores of the alternatives for quality of the end product. The weighted score was calculated by multiplying the numerical score elicited from the panellists with the criteria weights (Table 6.5). The weighted score thus takes into account the relative importance of the quality sub attributes.

Table 6.7: Weighted scores of alternatives for quality with the MAVF method

Attributes\Processes → ↓	AC+ Extrusion	From process A	From process B	Weights
Texture	0	10	5	0.38
Absence of off-flavours	0	5	10	0.31
Absence of ANFs	10	5	10	0.16
Amino acid availability	0	10	5	0.09
Natural fibre	10	0	0	0.07
Weighted scores (numerical score*weight)	**23**	**71**	**70**	

ii. <u>Scoring the alternatives for cost</u>

To ensure economies of scale 30744 MT per annum was used as the demand for the product in the Netherlands. The cost of manufacture (ex-factory) of the NPFs was calculated for each alternative (Apaiah & Hendrix, 2005; Appendix 6). The cost per ton of the product was calculated from the above data and is given in Table 6.8. This is the actual cost data. The value of the cost is non-linearly related to the hard data as can be seen from the partial value function (Apaiah, 2006) derived. The bisection method (Belton and Stewart, 2002) was used to scale this cost data onto a partial value scale with the aid of a partial value function. This function decreases monotonically and is non-linear. Two scales were used to present two different viewpoints- how the different scales (global and local) would affect the final ranking of the alternatives.

In the first case, a global scale (the two end points represent the worst and best possibilities ever) was used. The NPF is to ultimately replace pork meat; therefore the worst cost option for the NPF is a cost of manufacture more than that of pork mincemeat. '0' represented this worst cost option, €1200 per MT. The '100' on the scale represented the 'best' price that was achieved in this exercise. The partial value function in Figure 6.4, case 1 was derived with the bisection method. A score of 50 on the scale represents a cost of €950, 75 represents €650 and 25 represents €1100. The partial value function $y = -9^{-5}x^2 + 0.0373x + 95.24$ was obtained from this data and was used to calculate the scores for the other alternatives.

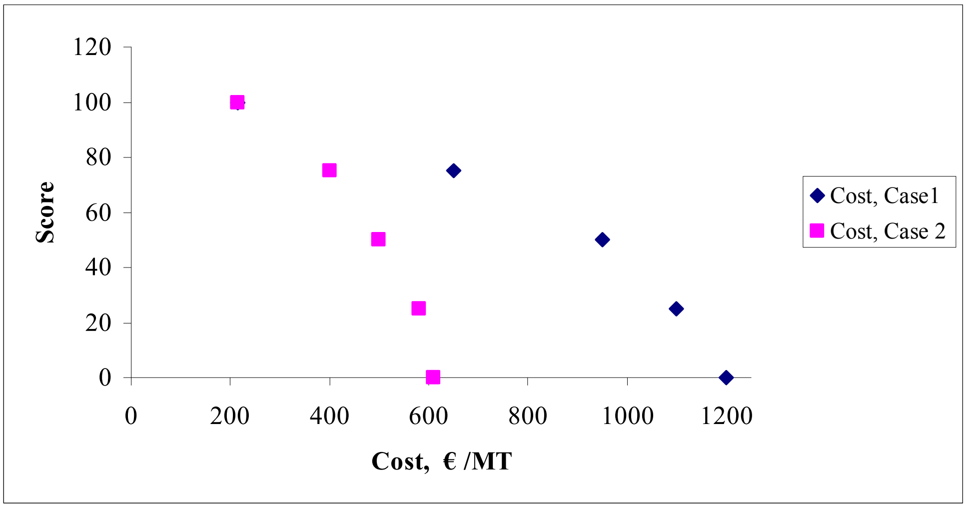

Figure 6.4: Partial value function for both cost cases

In the second case, a local scale was used (the two end points represent the worst and best alternatives in this case). The '0' represented the worst cost option- *i.e.* the cost of manufacture of the most expensive alternative, €609 per MT. The '100' on the scale represented the 'best' price that is achievable *i.e.* the cheapest alternative. The partial value function in Figure 6.4, case 2 was also derived with the bisection method. A score of 50 on the scale represents a cost of €500, 75 represents €400 and 25 represents €580. The partial value function $y = -0.0006x^2 + 0.2297x + 76.26$ was obtained from this data and was used to calculate the scores for the other alternatives. Table 6.8 gives the scores for both cases.

Table 6.8: Score for cost and environmental load with the MAVF method

Alternatives	Cost, € /MT	Cost score, Case 1	Cost score, Case 2	Exergy input, MJ/MT	Exergy score
1	215.90	99	99	27415	35
2	266.11	99	9	22007	63
3	282.89	99	95	15109	99
4	570.00	87	17	14761	100
5	315.80	98	91	18468	81
6	304.42	98	92	16213	93
7	609.42	85	0	33891	0
8	584.70	86	10	15551	96
9	315.47	98	91	21679	64
10	487.89	92	49	23605	54
11	484.01	92	50	16892	89

iii. Scoring of alternatives with respect to environmental load (in terms of exergy input)

The environmental load of the alternatives is measured as the exergy input required for each alternative. The exergy input that is required to make 30744 MT of NPF was calculated for each alternative (Appendix **). The requirement per ton is shown in Table 6.8. This data was converted to a partial value scale with the aid of a partial value function. This function decreases monotonically and is linear. '0' represents the worst option- the most exergy intensive alternative. The '100' on the scale represents the 'best' alternative that was achieved. The linear partial value function $y = -0.0052x + 177.17$ was obtained using these end points. It was used to convert the required exergy data to partial value scores (Table 6.8).

Step 6: Processing the values to arrive at a ranking for the alternatives

The three criteria that were evaluated are independent of each other and therefore the additive model can be used to calculate the value V (A) of alternative A.

$$\mathrm{V(A)} = \sum_{i=1}^{m} w_i v_i(A) \tag{6.1}$$

where w_i is the weight of criterion i and $v_i(A)$ is the partial value of alternative A for that criterion. The criteria weights used were the averages that were obtained (Table 6.4). As described earlier, cost was scored using two different scales. The aim was to see how the different scales (global and local) would affect the final ranking of the alternatives. The two cases are presented below. Table 6.9 shows the scores, criteria weights and the value, V (A) of each alternative.

Table 6.9: Value of the alternatives via the MAVF model

		Alternatives										
Criteria	w_i	One	Two	Three	Four	Five	Six	Seven	Eight	Nine	Ten	Eleven
Quality	*0.50*	23	23	23	71	23	23	70	71	23	70	70
Environmental load	*0.16*	35	63	99	100	81	93	0	96	64	54	89
Cost: Case 1	*0.34*	99	99	99	87	98	98	85	86	98	92	92
V(A) 1		**51**	**55**	**61**	**81**	**58**	**60**	**63**	**80**	**55**	**75**	**81**
Cost: Case 2	*0.34*	99	96	95	17	91	92	0	10	91	49	50
V(A) 2		**51**	**54**	**60**	**57**	**56**	**58**	**35**	**54**	**53**	**60**	**66**

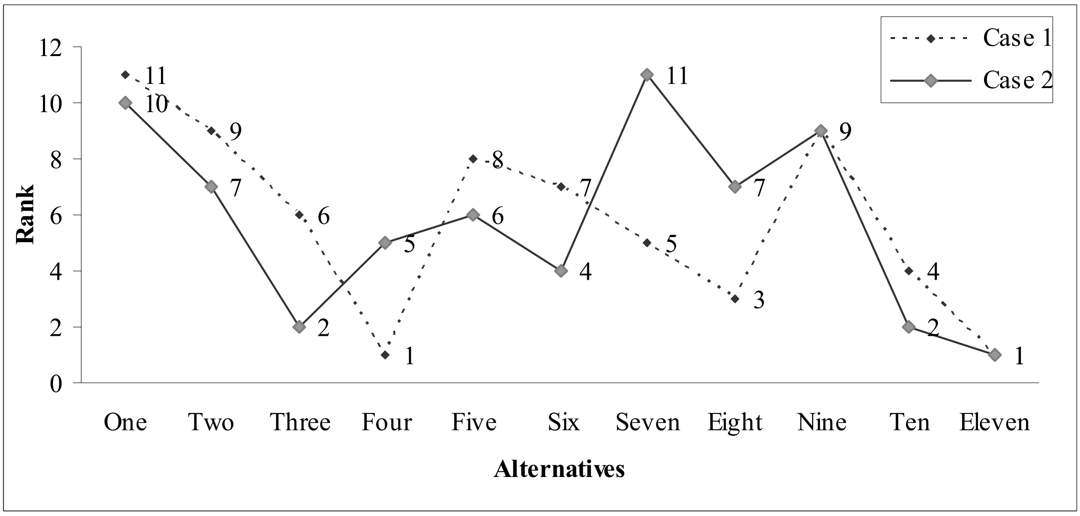

Figure 6.5: Comparison of the two cases in the MAVF model

Figure 6.5 compares the alternatives on the basis of their ranks, with the alternative with the highest value getting the rank of ‘1’. The preference order in the two cases is not the same because of the different scales that were used. Alternative 4 is expensive (€570/MT) when compared to the other alternatives but is cheap when compared to the cost of pork mincemeat (€1200/MT). Therefore, with the global scale, this alternative scores 87 for cost giving it an overall value of 81, whereas on the local scale, it scores only 17 for cost, resulting in an overall value of 57. Alternative 4 therefore goes from rank 1 in the first case to rank 5 in the second case. Alternative 8 similarly falls from the third to the seventh place. This large difference in ranking emphasises the importance that should be given to the selection of the scale and to fixing the end points. The facilitator or the analyst must impress this on the decision makers so that the results generated represent their viewpoints and opinions adequately. Alternative 11 however is ranked in the first place in both cases.

6.2.2.2. Application of the AHP model

Step 4: Determining the relative importance of the criteria

The three top-level criteria of cost, quality and environmental load were weighted according to the pair-wise comparison method by the same panel used for the swing method. The normalised weights of the pair-wise comparison are shown below (Table 6.10, details in appendix 6).

Table 6.10: Normalised top criteria weights for the NPF via the AHP method

Panellist	Cost	Quality	Environmental load
1 (Food engineer)	0.28	0.64	0.07
2 (Food engineer)	0.19	0.74	0.08
3 (Consumer scientist)	0.29	0.65	0.06
4 (Environmental scientist)	0.30	0.07	0.63
Average weights	0.27	0.52	0.21

This method of elicitation was also used to weight the quality sub criteria. The five bottom level criteria were compared to each other pairwise. The panel was the same as that used to elicit these weights with the swing method. The comparisons of panellists 4 and 5 were inconsistent and were not included in the calculation of the average weights (Table 6.11, details in appendix). Inconsistency can occur even when experts in the field give there preferences as people are not always able to convert opinions into numbers easily. Figure 6.6 shows the hierarchy of the criteria and the weights.

Table 6.11: Normalised quality sub criteria weights via the AHP method

Panellist	Texture	Absence of off flavours	Absence of ANF	Amino acid availability	Natural fibres
1	0.58	0.20	0.04	0.09	0.09
2	0.40	0.40	0.13	0.04	0.04
3	0.56	0.19	0.05	0.05	0.15
Average	0.51	0.26	0.07	0.06	0.09

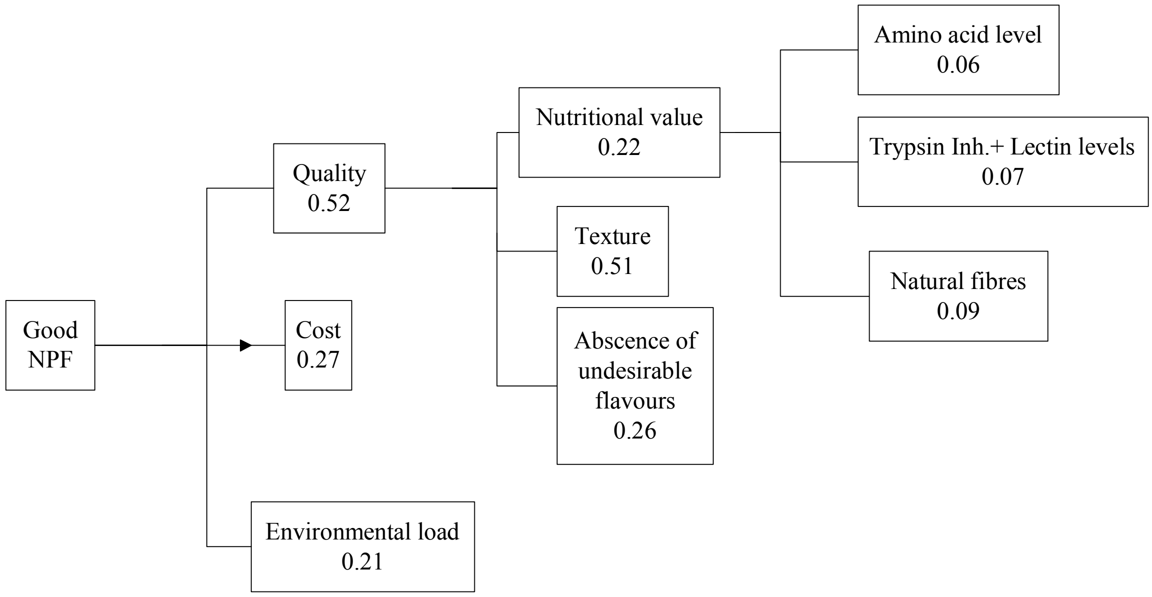

Figure 6.6: The AHP hierarchy

Step 5: Determining the impact of the alternatives on the criteria (scoring)

i. Scoring of alternatives with respect to quality

The overall score for the quality of the alternatives via the AHP method is the weights of the quality attributes multiplied by the score (obtained by pair-wise comparison) of each alternative on the corresponding attribute. The quality of NPF from each alternative is the result of the processing method that was used to make it. As three processing methods were used, NPFs of three different qualities were defined (Table 6.1).

Table 6.12: Normalised weighted scores for quality sub attributes via the AHP method

Attributes\Processes ↓ →	AC+ Extrusion	From process A	From process B	Weights
Texture	0.07	0.66	0.27	0.51
Absence off-flavour	0.10	0.46	0.45	0.26
Absence of ANFs	0.47	0.09	0.45	0.07
Amino acid availability	0.13	0.55	0.32	0.06
Fibre	0.74	0.13	0.13	0.09
Weighted score	**0.17**	**0.51**	**0.32**	

Table 6.12 gives the normalised score for the quality of the NPF as a result of the processing methods. Alternatives 1, 2, 3, 5, 6 and 9 have a score of 17, alternatives 4 and 8 have a score of 51 and alternatives 7, 10 and 11 have a score of 32.

ii. Scoring of alternatives with respect to cost

The cost of manufacture was divided to ranges *i.e.* 200-300, 300-400, ….>600. 200-300 implies the manufacturing cost from € 200 to € 300. The preferences (weights) for the ranges were calculated by comparing them pair-wise as shown in Table 6.13.

Table 6.13: Preferences for cost ranges

	200-300	300-400	400-500	500-600	>600	Weights
200-300	1	3	5	7	9	0.5
300-400	1/3	1	3	5	7	0.26
400-500	1/5	1/3	1	3	5	0.13
500-600	1/7	1/5	1/3	1	3	0.07
>600	1/9	1/7	1/5	1/3	1	0.03

The alternatives were then scored according to these weights or preferences. Table 6.14 presents the results.

Table 6.14: AHP cost and environmental load scores

Alternatives	Cost, € /MT	Cost range	**Cost score**	**Environmental load score**
1	215.90	200-300	**0.5**	**0.35**
2	266.11	200-300	**0.5**	**0.63**
3	282.89	200-300	**0.5**	**0.99**
4	570.00	500-600	**0.07**	**1.0**
5	315.80	300-400	**0.26**	**0.81**
6	304.42	300-400	**0.5**	**0.93**
7	609.42	>600	**0.03**	**0**
8	584.70	500-600	**0.07**	**0.96**
9	315.47	300-400	**0.5**	**0.64**
10	487.89	400-500	**0.13**	**0.54**
11	484.01	400-500	**0.13**	**0.89**

iii. Scoring of alternatives with respect to environmental load (in terms of exergy)

The environmental load of the alternatives was measured as the exergy input required for each alternative. The exergy input that is required to make 30744 MT of NPF was calculated for each alternative. The requirement per ton is shown in Table 6.8. AHP normally uses a pairwise comparison to directly compare alternatives or divides them into ranges and then elicits preferences. The environmental load, measured as the exergy input is however scored on a linear scale in this case.

Step 6: Processing the values to arrive at a ranking for the alternatives

The three criteria that were evaluated are independent of each other and therefore the additive model (Equation 6.1) can be used to calculate the value V (A) of alternative A. The criteria weights were obtained from Table 6.10. Table 6.15 shows the scores, criteria weights and the value, V (A) of each alternative.

Table 6.15: Value of the alternatives via the AHP method

		Alternatives										
Criteria	w_i	One	Two	Three	Four	Five	Six	Seven	Eight	Nine	Ten	Eleven
Quality	*0.52*	0.17	0.17	0.17	0.51	0.17	0.17	0.32	0.51	0.17	0.32	0.32
Environmental load	*0.21*	0.35	0.63	0.99	1.00	0.81	0.93	0.00	0.96	0.64	0.54	0.89
Cost	*0.27*	0.5	0.5	0.5	0.07	0.26	0.5	0.03	0.07	0.5	0.13	0.13
V(A)		30	36	43	50	33	42	17	49	36	31	39
Rank		10	7	3	1	8	4	11	2	6	9	5

Alternatives 4 and 8 are ranked the highest. This is because the two alternatives give an end product with a very good quality and the fact that quality has a high weight. The weight and score of quality is high enough to compensate for the low score for cost (0.07). Alternative 1 has a high score for cost and a medium score for environmental load but the poor quality pulls it down in the ranking. The importance of criteria weights can easily be seen here.

6.2.3. Comparison of the MAVF and AHP methods

The final ranking of the alternatives with the two methods are not the same (Figure 6.7). Even within the MAVF method, the ranking of the alternatives in case 1 and case 2 are not the same. These dissimilarities are due to different scaling and scoring methods that resulted in different criteria weights and scores. This can be seen clearly in the scores for quality. The MAVF method used a qualitative scale; processes A and B had almost similar scores of 71 and 70. The pairwise comparison method of the AHP however differentiated greatly between the quality of the end product from process A and B (scores of 51 and 32 respectively).

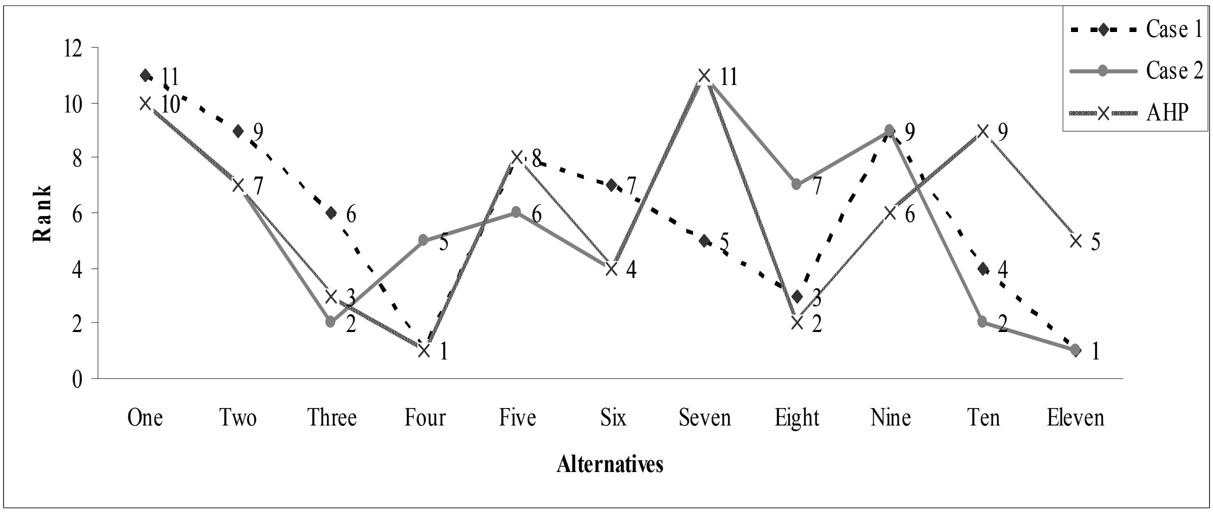

Figure 6.7: The overall ranking of alternatives

6.3. Sensitivity analysis

The data from MAVF, Case 2 was analysed to examine the sensitivity of the overall preference order to the criteria weights and the preferences of the panellists

6.3.1. Sensitivity to criteria weights

The criteria weights were varied from 0 to 1 to observe the changes. This analysis was carried out on Microsoft excel and web hipre (http://www.hipre.hut.fi/). The results that were obtained are similar.

Effect of varying the weight of quality:

Alternative 11 is the best when the weight of quality is between 0.40 and 0.94 (Figure 6.8a). This implies that alternative 11 is not very sensitive to the weight of quality. Alternative 4 gives a product with a very good quality and a low environmental load, but is expensive. Therefore only when the weight for quality is very high (> 0.99), this alternative becomes the most preferred. The value of the alternatives which score low in quality (*e.g.* alternatives 1, 2, 3, 5, 6, 9) falls rapidly as the weight for quality increases. Similarly, the value of those alternatives which have high quality scores increase as the weight of quality increases.

Effect of varying the weight of cost

It can be seen from Figure 6.8b that alternative 11 is the most preferred when the weight of cost varied from 0.17 to 0.45. The order of preference of the overall value of alternatives is thus more sensitive to the weight of cost. It follows that alternative 1 which is the cheapest but has a very high environmental load and poor quality becomes the most preferred when the weight of cost is 1.

Effect of varying the weight of environmental load

Alternative 11 is the most preferred alternative when the weight of environmental load is below 0.5 (Figure 6.8c). At higher weights the more environmentally friendly alternatives are preferred *i.e.* alternatives 4, 3 and 8.

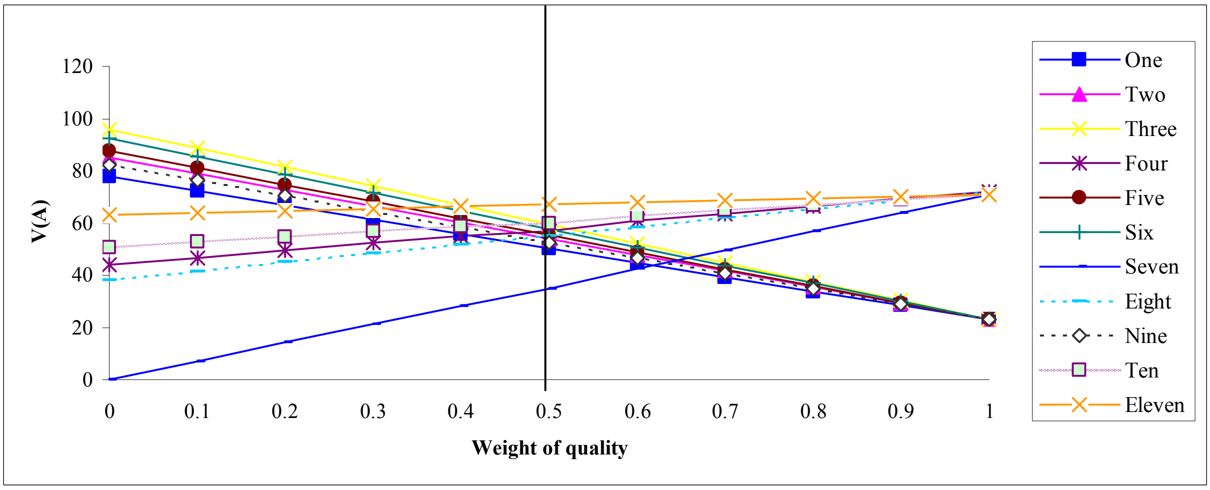

Figure 6.8a: Effect of varying the weight of quality on V (A)

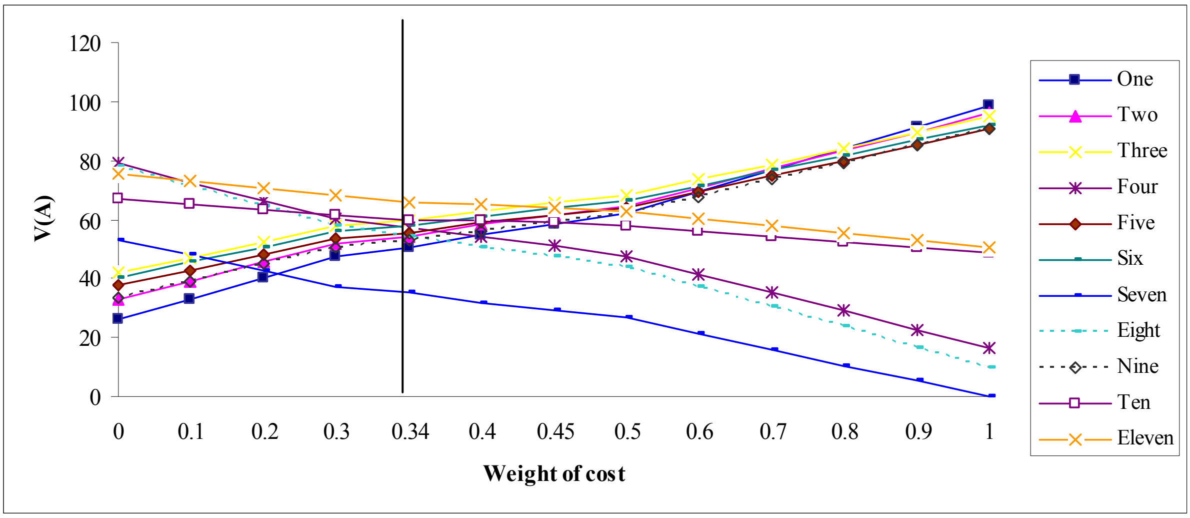

Figure 6.8b: Effect of varying the weight of cost on V (A)

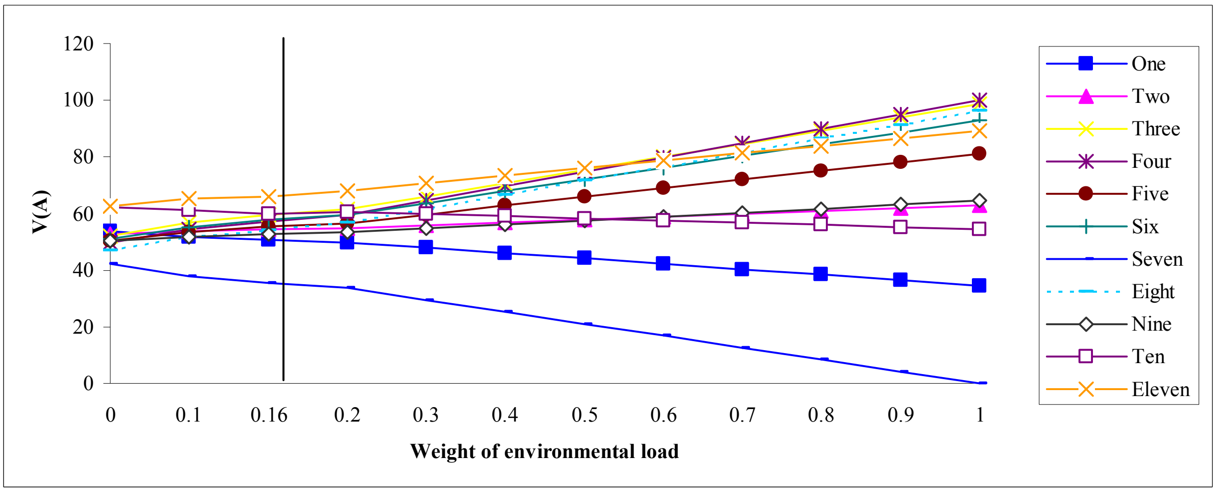

Figure 6.8c: Effect of varying the weight of environmental load on V (A)

6.3.2. Sensitivity to panellist preferences:

The ranking of the alternatives in cases 1 and 2 was done with the average criteria weight (Table 6.5). However the weights or preferences of the individual panellists vary (Table 6.5). If the individual weights are used instead of the average, the preference order changes. Figure 6.10 shows the alternatives from best to worst using the average values and then compares the preference orders from each panellist to this.

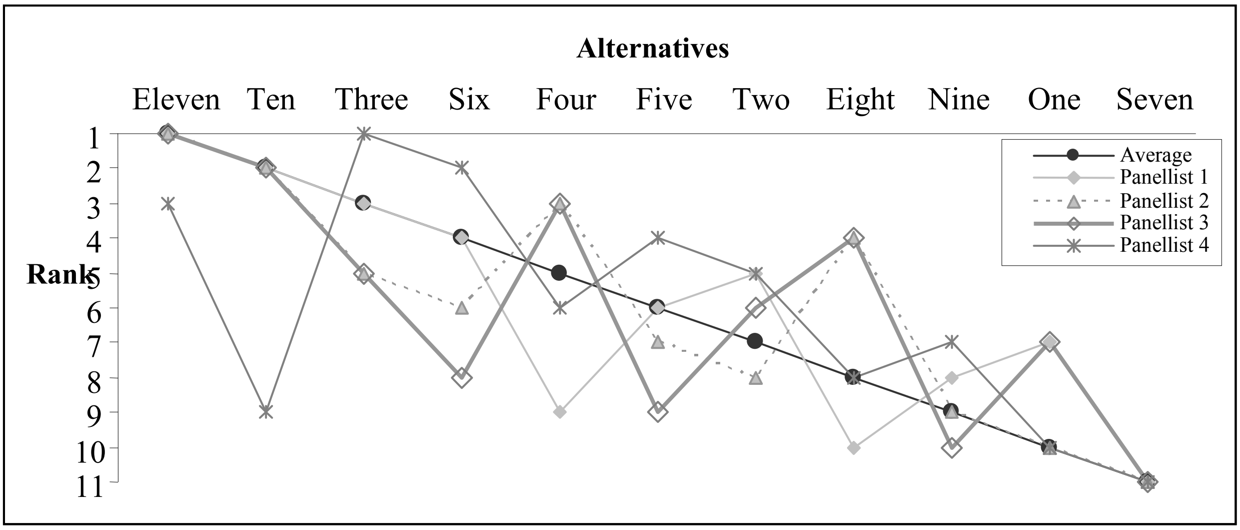

Figure 6.9: Sensitivity of ranking to panellist preferences

The results that are obtained from this graph agree with those of the sensitivity analysis done earlier. Panellist 4 weighted quality at 0.27. According to the sensitivity analysis of the preference order to the weight of quality, any weight more than 0.4 will result in alternative 11 being the best, below this value alternative 3 gets rank 1. This is confirmed from Figure 6.9.

6.4. Discussion

The aim in this paper was to use MCDM models to aid in designing food supply chains. The generation of ideas helped to make goals concrete. In this case, the overall goal was to make an NPF that consumers will want to buy. The structuring of ideas gave a concrete list of attributes for the product by which the goal could be reached. It was evident that to be able to give the consumer a product that he/she wants, the whole chain of the product, from primary production of the ingredients that went into the product, to the distribution and retailing of the product, had to be studied in detail (Apaiah *et al.*, 2005). A methodology to design a food supply chain that would deliver the specialised product became imperative. The SC consists of five links (Apaiah *et al.*, 2005; Apaiah & Hendrix, 2005). As shown in Figure 6.2, there exist variables in each of these links that influence the attributes of the end product. Potential SCs (alternatives) to achieve the desired end product were a combination of these variables. An infinite number of possibilities existed at this stage. Screening strategies were developed to narrow the possibilities. One of the important ones stated that if the variable or link did not differentiate between the alternatives, then it should be discarded. The last two links in the chain, distribution and retail, were the same for all possible alternatives as the product was for the Dutch market only. Thus these links were not used to construct the alternatives.

The general model for MCDM helped to coordinate the whole design process. The stepwise procedure made the method transparent for the decision makers and the analysts and aided in the evaluation of the screened alternatives. Two out of the four models, MAVF and AHP, mentioned in Figure 5.2 (Chapter 5), were chosen and a case specific model was formed (Figure 6.3). The most important factor in the choice of these models was the ease with which they could handle a mix of quantitative and qualitative information, quantify the qualitative information it and generate an overall value for each alternative.

The preference order generated with the two models is very different. The main reason for this difference is the *manner* in which criteria weights were elicited and alternatives scored and the use of scales in MAVF versus the pairwise comparison in the AHP model. It is interesting to note though, that the preference order of the top criteria with both methods is the same and the weights are also similar (Tables 6.4 & 6.10).

MCDM gives recommendations to the decision makers. It is then up to them to look at the preference orders and make their final choice. In case 1 of the MAVF method, alternatives 4 and 11 have the same overall value.

However each alternative scores differently on the three criteria. The quality of alternative 4 is better than alternative 11, but alternative 4 is more expensive and exergy intensive compared to alternative 11. The picture is clear and therefore the decision makers can make their choice on which supply chain (alternative 4 or 11) they would like to implement or they can chose to study the two alternatives in greater detail.

Table 6.16: The top ranking alternatives*

Alternative	PP location	Transport mode	ING location	Processing Method [Prot Concentration (%)]	Transport mode	NPF preparation method	Transport mode
4	NL	Truck	NL	WP [25] W, A	Truck	A	Truck
11	FR	Rail	FRA	WP [80-90] D, B	Truck	B	Truck
8	FR NL	Truck Rail	NL	WP [25] W, A	Truck	A	Truck

*refer to Table 6.2 for the abbreviations used in this table

In case 2 of the MAVF method, the use of the local scale differentiated the alternatives to a greater extent and therefore the overall value of each alternative changed. As alternative 4 was more expensive compared to alternative 11, it was scored lower and alternative 11 was ranked the highest. The AHP model ranked alternative 4 as the highest followed by alternative 8.

The methodology was successful in focussing the decision makers' attention to the issues on hand. The ideas generated were made concrete and the path to the final choices is clear. The stepwise process made the decision making process transparent and easy to review and audit.

6.5. Appendix 6

Sample calculations to show data and methods used to calculate the exergy load and cost for an alternative**.**

Table A6.1: Alternative11

	PP location	Transport mode	ING location	Processing Method [Prot Concentration (%)]	Transport mode	NPF (NL) preparation method	Transport mode
11	FR	Rail	FR	WP [80-90] D, B	Truck	New process from B	Truck

D= Dry; W= slurry; AC= air classification; WP= wet processing, A, B = processes A or B
PP = Primary production; ING = ingredient preparation; NPF = product processing; NL = The Netherlands; FR = France; CAN = Canada; UKA = Ukraine

Four countries were chosen as potential candidates for study (Ref: Chapter 6). The table below shows the growing areas and the processing sites for the ingredients and the final product as the case may be.

Table A6.2: Countries for primary production and processing

Country	Growing area	Processing site
Netherlands	Brabant	Europoort
France	Provence/Cote d'Azur	Marseille
Canada	Saskatchewan	Churchill, Hudson Bay
Ukraine	Entire country	Kiev

Table A6.3: Distances in km between the four areas considered

	To			
From/By	NL	FR	UKA	CAN
NL/sea		(100)+3900		(100)+7300
NL/barge	100	1142	2100	
NL/rail	100	1142	2100	
NL/truck	100	1142	2100	
FR/sea	3900			8800
FR/barge	1362	185	2475	
FR/rail	1362	185	2475	
FR/truck	1362	185	2475	
UKA/sea				
UKA/barge	2325	2856	288	
UKA/rail	2325	2856	288	
UKA/truck	2325	2856	288	
CAN/sea	(950)+7400	(950)+8800		
CAN/barge				950
CAN/rail				950
CAN/truck				950

Total cost per MT of NPF = Dry pea cost * quantity + transportation cost from PP location to ING location * quantity + ING preparation cost (labour + energy+ equipment cost) * quantity + transportation cost from ING location to NPF location * quantity + NPF preparation cost (labour + energy+ equipment cost) * quantity

Total exergy required per MT of NPF = Exergy for [PP + transportation from PP location to ING location + ING preparation + transportation from ING location to NPF location + NPF preparation]

Table A6.4: Fuel efficiency* of the four modes of transport considered.

	Transport mode	Miles per gallon for 1 ton
	Sea	607
	Barge	514
	Rail	202
	Truck	59.2

*http://mts.tamug.tamu.edu/Modal_Shift/modal.html#top
*http://www.geo.msu.edu/glra/workshop/01wresworkshp/AMtalks.htm

Alternative 11 considers process B to make the NPF. The details on composition and the process are given below in the tables and schemes.

Table A6.5: Composition of the NPF via processes A & B*

Composition	Kg
PP isolate	254
Polysaccharides	83
Water	555
Fat	108
	1000

*Boekel, Vereijken & Goot, 2005

Table A6.6: Composition of pea protein isolate

PP isolate composition	%	In 254 Kg
Protein	87.7	222.76
Starch	0	0.00
Water	3.3	8.38
Fibre	0.2	0.51
Ash	5.8	14.73
Fat	3.0	7.62

* Sosulski *et al.*, 1988

The wet isolation process yields 18.2% of pea protein isolate (87.7% protein) (Sosulski *et al.*, 1988). The Figure below presents a scheme to make the isolate from dry peas. The quantities considered in Figure A6.2 are those required to make 30744 MT of the product (Apaiah & Hendrix, 2005).

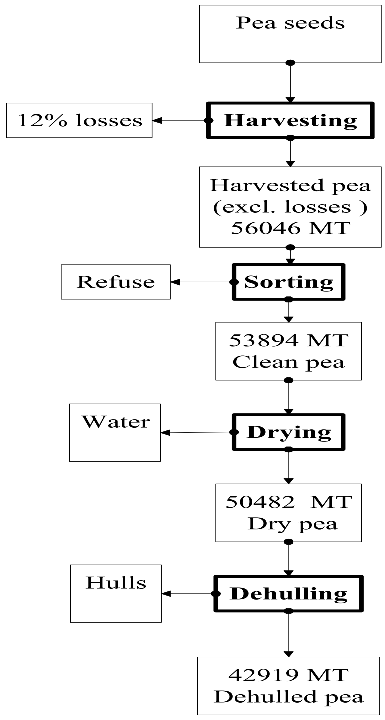

Figure A6.2a: Scheme to make the NPF via processes A and B (Vereijken and Goot 2005)

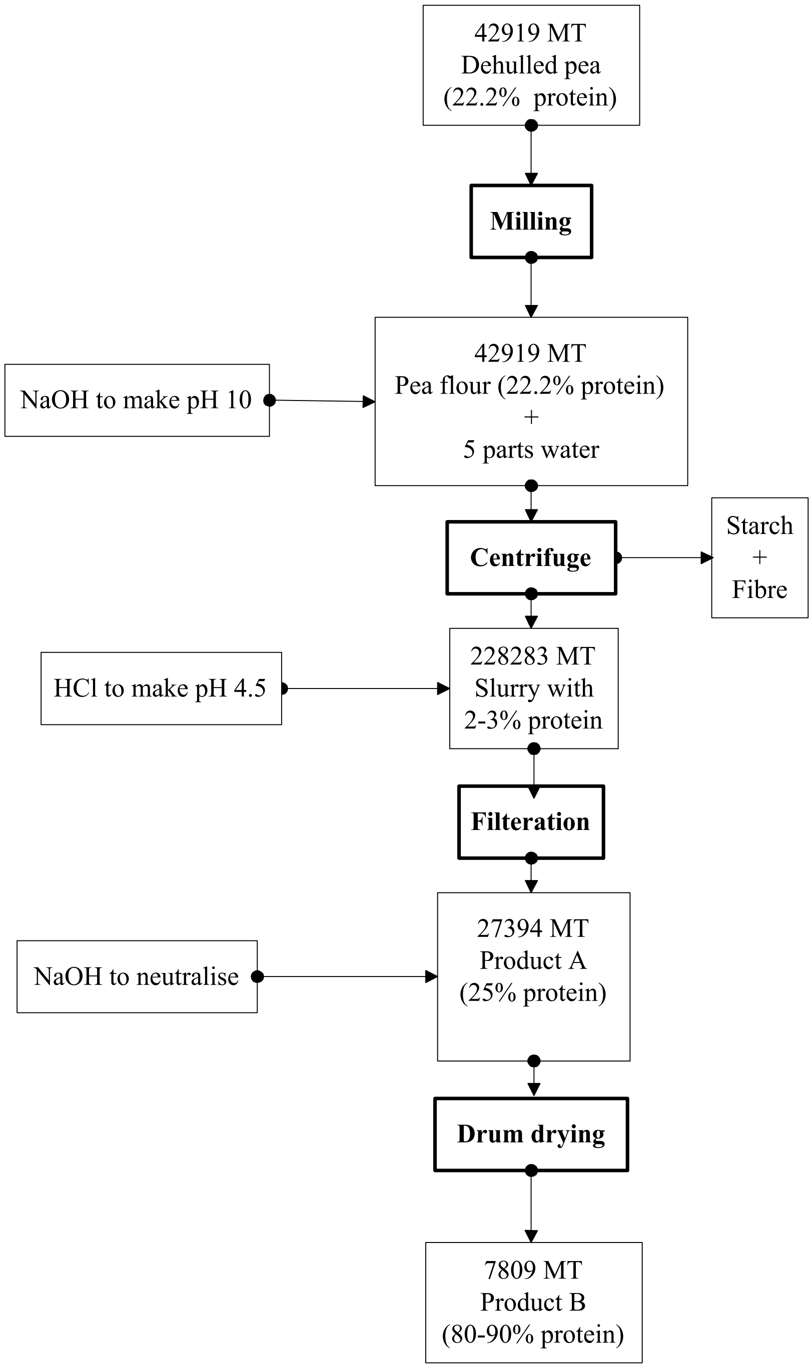

Figure A6.2a (contd.): Scheme to make the NPF via processes A and B (Vereijken and Goot 2005)

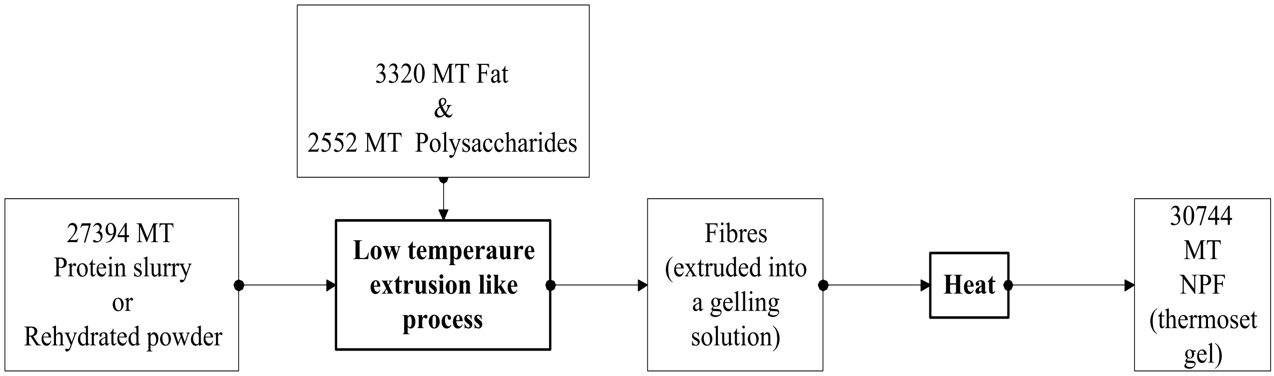

Figure A6.2b: Scheme to make the NPF via processes A and B (Vereijken and Goot 2005).

Energy (electricity) requirements for the various process involved in the manufacture of the NPF are shown in the table below.

Table A6.7: Electricity requirements[#] for processes in NPF manufacture

Process	Energy, MJ/MT
Drying	2250
Dehulling	108
Milling	158
Mixing/ Centrifuging	7.2
Drum drying	2257
Cutting	158.00
Shaping [*]	57.14
Packaging, electricity[*]	685.68
Extrusion like process[+]	230.19
Heating[”]	242.31

[#]Goot, 2005, Perry, 1997
[*]van der Steen, 2002
[+]calculated using specific heat capacity of the mixture

Table A6.8: Transport cost in € per ton (using fuel costs 2003-2004)

	sea	rail	barge	truck
CANADA.CAN [*]		16.62		
CANADA.FRA	55.02			
CANADA.UKA	55.02			
CANADA.NLD	55.02			
FRANCE.CAN	55.02			
FRANCE.FRA		10.88		
FRANCE.UKA	50.9	167.9	21	20
FRANCE.NLD		75.4	13.5	16
UKRAINE.CAN	55.02			
UKRAINE.FRA	50.9		21	20
UKRAINE.UKA				

UKRAINE.NLD	50.9		21	20
NETHERLANDS.CAN	55.02			
NETHERLANDS.FRA		50.96	13.5	16
NETHERLANDS.UKA	50.9	91.4	21	20
NETHERLANDS.NLD		3.92	5	10

[*] CANADA, FRANCE, UKRAINE, NETHERLANDS are the primary production locations;
CAN, FRA, UKA, NLD are the ingredient preparation locations
www.railcan.ca

Table A6.9: Cost data

		NL	Canada	UKA	FRA
Cost of dry peas	€/MT	147	160	129	154
Energy	€ /MJ	0.0361	0.0069	0.0006	0.0083
Labour	€ /year/person	40462.4	24024	7884.8	42926.4
	€/year for 30 people	1,213,872	720,720	236,544	1,287,792
Equipment cost[*]	€	239,258	239,258	239,258	239,258

[*] equipment cost = 10% (total cost * fanning factor of 2)

Table A6.10: Primary production Figures

		NL	Canada	UKA	FRA
Yield for dry peas	Kg/ha	4500	1672	1102	4406
Dry peas for 1 MT NPF	Kg (process B)	2041	2041	2041	2041
Land for 1MT NPF	ha	0.454	1.221	1.852	0.463
Exergy required for PP[*]	MJ/MT	3819.76	10280.46	15597.94	3901.25

Exergy = fuel for sowing, harvesting and other related activities and exergy of fertilizers and pesticides

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Chapter 7

General Discussion

7. General Discussion

7.1. Discussion

The hypothesis of this thesis

The work presented in this thesis validates the hypothesis that a structured methodology is necessary to be thoroughly objective about the choices, planning and decisions involved in designing food supply chains. The importance of considering all the attributes of a product together and their role in shaping the ultimate design of the chain was demonstrated. The necessity of looking at the entire supply chain as a unit was also shown.

In the case of a food supply chain, design implies the following: where to produce and process raw materials and manufacture the product, *i.e.* location decisions; what varieties of raw material and what technologies to use to manufacture the product; how much to make, how to price the product; what attributes the product should have *i.e.* nutritional value, microbial safety, taste etc. In other words, designing is all about planning, *i.e.* looking at the problem and deciding what is required. The methodology presented shows how to achieve it.

What was required?

The research program PROFETAS (www.profetas.nl), of which this is one of the PhD projects, aimed to investigate whether a shift from animal to vegetable protein based foods is feasible. An efficient system that looks at the requirements of the consumer and society, incorporates this into the design and delivers it to the users was needed.

The elements of chain design

The attributes desired in the product set the goals for supply chain (SC) design. As this project was a part of the PROFETAS program, the overall objective of the supply chain was to develop a 'good' novel protein food (NPF). Consumer research and surveys, discussions with stakeholders and other concerned persons in the program about the attributes of the product- what it should look like, how it should taste, its texture, health and nutritional issues, selling prices etc. were discussed and concrete suggestions were made. The goals were formalised as: good quality, affordable price and low environmental load. They were studied independently of each other (Chapters 2, 3 & 4) to investigate the issues involved with each and methods were developed to measure the achievement of level of a goal at the end of a supply chain.

The PROFETAS project chose to use pea proteins as a base for the NPFs from a number of vegetable protein sources (Linnemann & Dijkstra, 2002; Dijkstra *et al.*, 2003). Practical reasons were responsible for this choice. Local expertise was available, the pea was cultivated in the Netherlands, and it was thought that all the literature on soy proteins and soy based replacers could be extrapolated to understanding the pea proteins. However, this was found impossible as there are many differences between the pea and soy, one of the main ones being the presence of oil in soy and starch in the pea. A great deal of extra time was thus invested in studying the pea and its proteins before progress could be made in working on the actual NPF. There is work being done to investigate the characteristics of pea concentrates and isolates (Wang 1999; Parrheim Foods) and two PhD theses were published on pea proteins (Heng, 2005; O'Kane, 2004). NPFs based on pea proteins, however, do not currently exist. This was one of the biggest challenges in the project. To circumvent this problem, a product was created on paper that was made of pea proteins with added carbohydrates, fat, minerals, water etc. to have a similar proximate composition of pork mince meat. The product would also be structurally the same as pork mince and processing techniques were proposed to create it. Imitating pork mince was a starting point to develop the methodology. Once more is known about what type of product consumers want and what is technically possible, a SC for it can be created with this methodology.

The goals and how they were measured

Quality

Quality is a complex entity as it can mean different things to different consumers. It can be scientifically defined in many ways: nutritional value, texture, taste, digestibility, colour, flavour, protein content, microbial safety etc. Many of these factors can be quantified and measured through the chain. In chapter 2, protein content and water holding capacity (a measure of texture of the product) of the NPF were used as performance indicators. This model presented a way to measure quantifiable quality attributes. Target values were specified and were traced back and measured at each link. However, with attributes like end product texture, measuring at intermediate links does not have meaning as the product is in its final form only from the middle of the chain. Thus evaluating the texture of intermediate products (even if possible) in the chain may not provide relevant information on the end product texture. If methods can be developed to relate an end attribute to measurable properties of the ingredients *i.e.* the preconditions for a final proper texture be assessed first and then be evaluated along the chain, this model can be applied. However, this has not been done so far, so aspects of quality that are qualitative in nature- texture, consumer liking- and cannot be related to a performance indicator, PI, and measured. A method was required where all relevant aspects of quality could be simultaneously considered in the end product and qualitative attributes be quantified to some extent.

In Chapter 2, only two aspects of NPF quality were looked at- the protein content and the water holding capacity. However quality is a composite attribute with many more parts to it and an attempt was made to look at these and take into consideration the relationship (relative importance) between these parts in chapter 5. The aspects of quality of the end product that were considered were: texture, an absence of off-flavour producing components and the nutritional value. Microbial safety was not included as it was assumed that any supply chain being considered as an alternative would use good manufacturing practices and HACCP. Microbial safety becomes very important in chains of meat and dairy products, but as the NPF chain uses the dry pea, microbial safety is less of an issue. Experts were asked to look into detail at the links and variables that affected quality. This revealed that, in this case, the quality of the NPF was affected by only the processing techniques (links 1 and 2 are not included in the chain as is explained later).

Costs

For a product to be successful in the market, it has to be economically viable. Today, commonly available meat replacers cost three to four times the price of meat. The question in chapter 3 therefore was: Is it possible to manufacture a pea-protein based NPF at a cost less than that of pork mince? This question was investigated by looking specifically at the cost of manufacture of the product; only the first three links with the associated transport were included in the model; it did not consider the costs of distribution and retail. This seems to clash with the idea of chain design propounded in this thesis-"the idea of chain design is to look at the entire chain". This is because the product is designed to be manufactured only in the Netherlands and was for the Dutch market only. After the NPF is made, a distribution and retail company handles the product. Distribution and retail variables will affect the criteria; however, all of the product that enters the chain at this point will be handled in a similar manner. Therefore, all potential chain designs after this link will be identical, as what affects the product via chain A will affect the product via chain B to the same extent. So, a choice was made to use the existing distribution and retails channels for the NPF. These links have a given impact on the goals of the product and this thesis did not look further at them. The results of the model showed that it is possible to manufacture the NPF at a cost less than pork meat. However, the costs considered were limited to the primary ingredient, the pea and all the processing and transportation associated with it. One of the main reasons for this is that, as mentioned earlier, the product and processing methods are hypothetical and exact quantities and specification of the other ingredients are not known. When a prototype can be made, adjustments can easily be made to the model to include changes and additions.

Environmental load

The environmental sustainability of products and processes is a growing concern. Pollution and depleting resources are making environmental friendliness a necessary and not a choice attribute. A low environmental load thus became an important goal for the supply chain of the NPF. The performance indicator that was chosen to study environmental load was the exergy input for the supply chain to make a specific quantity of the product. Exergy is the available energy or available work or quality of energy. It measures the ability of a source to produce useful work. It is especially useful when comparing alternative chain designs because a chain with a lower input is always better- a design which can deliver the product with a lower use of resources is obviously preferred. As exergy is expressed in one unit, the Joule, the inputs and outputs of each chain are easily comparable. The analysis requires an in-depth input–output investigation of the links of a chain. This involves some investment of time but once this is done, results are visible and conclusions can easily be drawn, as was shown in chapter 4. Exergy analysis also showed that products which are simple, minimally processed, derived from local ingredients and sold in domestic markets have a low exergy requirement. Processed value added products are more exergy intensive.

Many insights into chain design were obtained. One of the research questions- What constitutes the entire supply chain of a food product? - was answered here. The end product was found to be influenced by variables right from the primary production of the ingredients to consumer processing of the product. Therefore, the basic or generic SC for a food product constitutes the following links: primary production, ingredient preparation/processing, product processing, distribution and retailing and consumer processing. The links are connected to each other via modes of transport. Is a SC product specific? Yes, the product and its attributes convert the generic SC to the specific one. The choices available for the links- where to grow, how to process, what ingredients are required- become concrete once the product is known. Do the goals of a SC affect the links that are considered? The goals further concretize the links and modes of transport that can be considered. For example, if the goal of a supply chain is quality at any cost and the product is imported fresh exotic foods, air freight can be used as the preferred mode of transport. The effect of the goals on the SC design was seen in the case of the cost of the NPF.

The final attributes of a food product are a result of what happens to it in all the links of the SC. This is especially true in the case of a food product. As shown in Chapters 2 and 6, the quality of the product can be influenced by the processing methods, and, with innovative technologies can be used to get a perfect product. But the effect of the other links cannot be ignored. If a product of excellent quality is made and delivered to the consumer, bad storage and cooking conditions can completely ruin the taste, texture and safety of the product. In Chapter 4, the exergy input for the NPF is calculated making some assumptions of a consumer's buying and storage patterns (namely, that the NPF is bought, along with other products, by driving to the grocery store). However, if the NPF is transported to the consumer by air, the exergy input will go up tremendously. In the cost calculations in Chapter 3, the NPFs were assumed to join a general distribution network; so all possible chains became the same from this link. However, if a separate distribution network is developed, or if the product processing location (assumed to be the Netherlands) is changed, the cost of transportation will be different and the SC can no longer be assumed to be the same. If the consumer chooses to buy directly from the manufacturer, costs will again change, depending on his mode of transportation etc. This means that the SC is made up of not only the links that influence the product attributes but all the links in the chain. To summarise, all the links and variables in the SC affect the end product, but only certain variables and links can differentiate between alternative chain designs.

The variables

It was seen from Chapters 2 and 6 that the number of variables could potentially be infinite. In the case of primary production, location, breeding methods, varieties, growing and harvesting conditions etc. are some of the variables. An attempt was made in Chapter 2 to look into the relationship between the performance indicators and each of these variables. This proved to be time consuming and difficult and in many instances not relevant to the goal and product. In chapter 6, this problem was countered with the use of screening strategies to discard irrelevant variables. One successful strategy was to retain in each link only those variables that affect the design goals/product attributes being considered.

The methodology

In Chapters 2, 3 and 4, the three goals were examined in detail. They were however dealt with independently of each other. While this gave a clear and comprehensive picture of the goal under discussion, it became necessary to have a method which could take into account multiple goals. The three goals that were chosen were conflicting in nature- it is not possible to make an inexpensive product with the best quality and the lowest environmental load. The new methodology had to be able to integrate these three goals to be able to deliver the desired product. Desirability however, means different things to different consumers and stakeholders. This means that all goals are not equally important.

The selection of attributes, identification of variables, generation of alternatives and the final evaluation require decisions to be made. The problem has qualitative and quantitative elements; the decision space is discrete and conflicting multiple criteria had to be considered simultaneously. This made Multiple Criteria Decision Making (MCDM) models an ideal choice for the chain design problem. The general model summarises the process that can be used in any case. However, in this specific case some adaptations were made. In many MCDM problems the alternatives are easy to generate and explicit- for instance in location decisions. In this case, alternatives were potential chain designs and were not immediately obvious. The chain starts after the NPF is made and goes back through to primary production- three links, transportation between each link and four possible modes of transport. The number of variables is large, the choices for each variable are infinitely many and therefore the number of potential chain designs becomes infinite. The screening strategies described earlier and in Chapter 6 were very useful in systematically and logically eliminating some variables and choosing others.

The three initial steps in the MCDM process, namely the generation of ideas, the structuring process and model building, require input from stakeholders, experts in the fields and an experienced analyst. They are common to all MCDM models. The next three steps, determining the relative importance of criteria, scoring and ranking, depend on the type of model as was shown in chapter 6. Two models were studied in this thesis- the MAVF- Multi Attribute Value Function and AHP- Analytic Hierarchy Process. These models were chosen as they are able to handle quantitative data well and are able to logically quantify qualitative data.

The role played by the analyst is very important. The analyst needs to understand the models and issues to represent the choices and preferences of the decision makers. The analyst has to know what techniques are applicable for each case. He/she has to understand the problem at hand very well to be able to ask the correct questions, elicit information from the decision makers and present the results of the model. It is also important that the analyst is not one of the stakeholders or interested parties so as not to introduce bias into the problem.

It is necessary to remember that the attributes of a product need not be equally important. Step 4 in the general and case specific models is the determination of the relative importance of the criteria. This is a critical step which is subject to much misinterpretation as practitioners often neglect to take into account that the weight of a criterion reflects not only its relative importance but also the range of the criterion over the alternatives. The cost of a product is usually an important factor. In the NPF case, the cost per metric ton (MT) of the product ranges from €215 to €610, a difference of about three times between the cheapest and the most expensive option. The range was sufficient to justify the high weight given to cost in the MAVF model. In the AHP method however cost was not ranked as highly. Quality was the most important criterion in both models and the difference between the worst and best was also large (23-71 in the MAVF model; 0.17-0.51 in the AHP model).

The two models use different techniques to elicit weights for the criteria. The swing method in the MAVF model looks at all the criteria simultaneously to choose the most important one, while the AHP model uses the pairwise comparison method to determine the relative importance. In this case, the order of importance was the same in both models with the actual values differing slightly. The panellists, however, appeared to have found the swing method easier to use than the pairwise comparison. The panellists involved in this research were from different scientific disciplines, representing different stakeholders. Panellists 1, 2 and 3 had the same preference order, but panellist 4 was different. This difference was enough to change the ranking of the alternatives if the preference order from panellist 4 was used.

The cost of manufacture and the exergy input required for one MT of end product was calculated with the models in chapters 3 and 4 respectively. The data obtained was hard and quantitative. In the MAVF method, this data has to be scaled onto a local or global scale depending on the preferences or priorities of the decision makers. It seems logical at this stage to derive preferences from the hard data. However, preferences are not usually linearly related to the hard data. As was seen from the cost data and the preferences expressed by the decision makers, decreases in cost (€580 to €500 to €400) were not linearly related to a corresponding increase in score (value, from 25 to 50 to 75). However, the decision makers agreed that the exergy data translated linearly onto the partial value scale- anything less was better. A local scale was used here; a global scale was not suitable as the universal best and worst exergy requirement can range from zero to infinity.

In the MAVF method, a word scale (good, bad, acceptable) was used to describe each sub-attribute of quality of the end product at the end of each of the eleven SCs. In the AHP method, the three processing techniques were compared pairwise to quantify quality. It was realized that the relative importance of these sub-attributes were not the same, so weights were elicited (swing technique for MAVF and pairwise comparison for AHP) and these weights were included in the final calculation for the overall quality of the NPF. The results showed that the AHP method was able to differentiate better between the three methods than the MAVF. It is possible that this was due to the fact that the AHP uses a 5 points scale and the MAVF used a 3 point qualitative scale.

The models gave a number to the three attributes, using a 0-100 scale in the MAVF method and a 0-1 scale with the AHP method. The hybrid attributes (criteria) were now comparable to each other. The criteria weighting methods elicited the relative importance of the criteria. The overall value of each alternative was calculated. The two MAVF cases gave slightly different results because of the different scales. The results from the AHP model were also slightly different. Each method has some advantages over the other. The swing weights in the MAVF appeared easier to use than the pairwise comparison but the 5 point scale in he AHP seemed to differentiate better than the MAVF 3 point scale. It could be argued that if the MAVF method had used a larger scale, this problem would not have occurred. The experts in the panel had trouble with the pairwise comparisons. There were many inconsistent responses (inconsistency was judged by Saaty's method) when the quality sub-attributes had to be compared. This did not occur when comparing the criterion weights. It is possible that judgments about broad attributes like quality, cost, and environmental load are easier to make. The data had to be discarded. The direct judgments with the word scale in the MAVF method was in contrast much easier to use.

What constitutes an optimal or best chain design?

As mentioned in the preceding paragraph, MCDM gave each alternative a number, an overall value that reflects the opinions and choices of the decision makers. In the NPF case, the decision makers were shown that alternative 11 (primary production and ingredient processing via method B in France) was the best with the MAVF model and alternative 4 (all production and processing in the Netherlands via process A) was the best with the AHP model, with the information and preference that they gave. They have to look at the ranking of the alternatives with one model and make a final objective decision to choose a specific SC. The value of each alternative, the score of each criterion for that alternative is clearly seen along with the weight of the criteria. The pros and cons of each choice are visible and the ramification of each choice is known. The methodology thus shows the choices, the 'correct' answer has to be made from these. In the MAVF model, case 1 gives alternatives 4 and 11 the same value. So, in this instance, the decision makers have to decide whether they want the entire SC in the Netherlands (alternative 4) or partially in NL and France. In a general case, say, some alternative Z is the best. If the choice is not acceptable at this stage to anyone, the decision making process can easily be reviewed as it is clear and transparent. Also, if the choice is not suitable because of geo political reason, exchange rates, other import-export issues etc., it is not difficult to go back through the steps in the model to look for another alternative. It is important to remember here that the preference order achieved is because of the choices of a particular set of decision makers. The best alternative may not remain the 'best' with another set of people.

The value V (A) and hence the ranking is able to discriminate sufficiently between 'good' and 'bad' alternatives. The sensitivity analysis performed on the outcomes (Chapter 6) also shows that the results are robust with respect to the criteria weights. The sensitivity to panellists' preference as shown in the same chapter presents an important aspect in such analyses where opinions are elicited. Different stakeholders (as represented by the panel) have different views. The weights elicited from them were averaged and used for the analysis. However, the ranking is very different when individual preferences are retained as shown in the Figure. So, it is essential that the analyst talks to the stakeholders involved in the decisions to come to a consensus on the criteria weights rather than just average them.

The challenges

Many challenges were encountered in the methodology development; the biggest was the lack of information, time and resources. When the proposal for the chain design project was first made, it was assumed that a methodology that would use optimisation methods would be developed. Quantitative data would be made available from the other PROFETAS projects, literature and experiments, and this data would be put into the model to give the 'best' chain design. However, after the project started it was seen that this would not be possible. The lack of information and the mix of quantitative and qualitative information were big hurdles to the original proposal. Precise optimisation techniques that gave one answer thus could not be used. So many educated guesses and assumptions had to be made with the help of experts and literature in the various fields. The lack of information was not such a problem with developing the methodology, but with its validation. Concrete information to prove that a new methodology will work is important. Once the method has been accepted by the scientific community and other users, the lack or paucity of information in subsequent use will not be a big drawback, as many decisions are made on the basis of limited information. The three processing techniques that were used had to be developed on paper as a part of this thesis, again, because there was not enough information on producing pea based NPFs. If the product could have been made with these three techniques, its attributes could have been studied to a greater extent. The behaviour of pea proteins has been studied in native state but not in complex food systems. The effect of variety and genetic breeding and final product characteristics is suspected but not certified. To compensate for the lack of information and data, expert opinion was used where necessary. As the aim of the thesis was the development of the methodology, the absolute accuracy of the numbers was not crucial; the case on NPFs was a means to demonstrate the methodology. As more information is made available, it can be easily input into the model and the required changes made.

The choice of the performance indicators and the methods to measure them was an important issue. An attempt was made to look into the nature of each attribute and goal when choosing the performance indicator. The fact was that each alternative was a chain of links and not a single entity and the measurement techniques that were developed in chapters 2, 3, 4 and 6 were designed to handle this. They are therefore an integral part of the methodology. The choice of the performance indicators for each goal was satisfactory in this case. However, if a better (as defined by the decision makers) or different indicator is found, it can be substituted easily into the model.

The methodology presented in this thesis will be successful if all the actors in the links agree to work together for the overall benefit of the chain. In the real world this does not always happen as people work to maximise their own rewards. However, a multinational company which is involved in all the links of the chain can use this methodology successfully when exploring the possibilities for a new product and designing its SC as there is sufficient manpower or resources to make prototypes. In the case of multiple actors and many interested parties, issues like conflict of interest or power struggles about who makes the final decisions will occur. This still needs to be resolved.

To conclude, decision making is subjective; however the methodology presented in this thesis gives structure and rationality to the process of making the choices involved in designing supply chains. It is a clear and transparent approach but care needs to be taken to implement it correctly. The methodology presented in this thesis is easy to use and no special software other than a spreadsheet is required. New data and changes in existing data are easily incorporated into the spreadsheets. It brings many disciplines like product development, economics, consumer research and basic science together to aid in the design of a SC for a multi attribute product.

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Summary

This thesis proposes and implements a structured methodology to aid chain design and the evaluation and decision making processes that accompany it. It focuses on how to design the entire chain from start to finish, so that the consumer gets a product that he/she wants, *i.e.* concentrating on product attributes rather than on the delivery of the product. The novel protein food (NPF) case from the PROFETAS (www.profetas.nl) program was used to develop the methodology.

Chapter 1 is the introduction to the thesis- Designing food supply chains- a structured methodology: A case on Novel Protein Foods. In the case of a supply chain, some of the design elements are: where to produce and process raw materials and manufacture the product, *i.e.* location decisions; what varieties of raw material and what technologies to use to manufacture the product; how much to make, how to price the product etc. In the case of a food supply chain (FSC), emphasis on which attributes the product should have *i.e.* nutritional value, microbial safety, taste is also important.

Chapter 2 is titled 'Qualitative methodology for efficient food chain design'. This chapter presents the qualitative part of an approach to develop a methodology for multiple-goal food chain design. The goal of good quality was studied in detail. Two attributes of quality were investigated: the water holding capacity, *i.e.* a measure of the texture of the NPF, and the protein content. Target values were specified for the two attributes and these were traced back though the chain to primary production. The following insights were obtained: The basic or generic supply chain for a food product constitutes the following links: primary production, ingredient preparation/processing, product processing, distribution and retailing and consumer processing. This entire chain from primary production up to and including consumer processing influences the final product; but the relative contribution of the links varies according to the goal for which the chain is being designed and optimised. Chains have to be designed for a specific end product as the chain pathway changes and the relative contribution of the links changes with the product. Chain design also changes with the goal. The choice of performance indicators is important as these directly relate to the goal and trace changes to it in the chain. The methodology presents a systematic way to identify problem areas in supply chains.

Chapter 3 is titled 'Design of a supply chain network for pea-based novel protein foods'. In this chapter, an Operations Research technique that can be used for supply chain design is presented and is used to create a supply network with a goal to manufacture a pea-based NPF as cheaply as possible. The non-meat protein products presently available do not meet the expectations of most consumers and cannot be considered as realistic alternatives to meat. They are niche products and are expensive when compared to pork. The model developed was used to answer the question: *Is it possible to manufacture a pea-protein based NPF at a cost less than that of pork mince?* This question was investigated by looking specifically at the cost of manufacture of the product; only the costs in the first three links with the associated transport were included in the model; it did not consider the costs of distribution and retail. The model was used to develop scenarios. In the first scenario, there were no constraints on the amount of pea that can be sourced in each primary production area. This

therefore resulted in a single flow/chain with the model choosing the cheapest route through all the links in the supply network. In the second scenario, simple upper limit capacity constraints were used. The model specified the amount of pea that can be sourced from each location. This is done to ensure a supply from all sources so as not to be dependent on any one location. The flow changed from a single chain to a network. The cost estimations were limited to that for the main ingredient, the pea and the concentrate made from the former. The procurement costs for the other ingredients like oil, functional ingredients, flavours were not considered. However it is known from preliminary calculations, that the inclusion of these costs would still limit the production cost per ton of the product to below € 1000. Further value is added with the inclusion of the costs of the second part of the supply chain – packaging, distribution and retail.

Chapter 4 presents exergy analysis as one of the ways to study the environmental impact of supply chains. The method identifies the links where exergy destruction takes place and shows where improvements are possible to minimize this destruction. The supply chains of three products were investigated: pork mincemeat, novel protein food (NPF) made from dry peas and pea soup. Exergy content and requirements of the various streams, products and processes were calculated for the three chains. As exergy is expressed in one unit, the Joule, the inputs and outputs of each chain are easily comparable. The contributions of the links to the total exergy loss are different in each chain. In the NPF chain, greatest input is required in the processing link whereas for the pork chain, primary processing and transportation require the highest inputs. Surprisingly, the NPF chain is only slightly more efficient (in terms of exergy) than the pork meat chain; this is mainly due to the exergy loss in the non-protein fraction that was considered as waste. Such analyses are also useful in the design and redesign of supply chains.

The selection of attributes, identification of variables, generation of alternatives and the final evaluation require decisions to be made. The problem has qualitative and quantitative elements; the decision space is discrete and conflicting multiple criteria had to be considered simultaneously. This made Multiple Criteria Decision Making (MCDM) models an ideal choice for the chain design problem. The theory behind MCDM is presented in Chapter 5. Various ways of classifying multiple criteria problems are explained. Three main models: MAVF (Multiple Attribute Value Function), AHP (Analytical Hierarchy Process) and ELECTRE are described in detail with the aid of an example.

Chapter 6 implements a structured methodology based on MCDM to aid in the evaluation and decision making processes of chain design. The goals used to evaluate the alternatives are the quality of the product, the cost and the environmental load. Variables in each link of the chain are screened to generate potential supply chains (alternatives) and these are evaluated with two MCDM models and ranked. The preference order generated with the two models was very different. The main reason for this difference is the *manner* in which criteria weights were elicited and alternatives scored and the use of scales in MAVF versus the pairwise comparison in the AHP model. The most important factor in the choice of these models was the ease with which they could handle a mix of quantitative and qualitative information, quantify the qualitative information it and generate an overall value for each alternative. The methodology was successful in focussing the decision makers' attention to the issues on hand. The ideas generated were made concrete and the path to the final choices is clear. The stepwise process made the decision making process transparent and easy to review and audit.

Chapter 7 is the general discussion. The main findings of this thesis are analysed and the challenges and future direction of this research are discussed. It is concluded that the methodology presented in this thesis gives structure and rationality to the process of making the choices involved in designing supply chains. It is a clear and transparent approach but care needs to be taken to implement it correctly. The methodology is easy to use and no special software other than a spreadsheet is required. New data and changes in existing data are easily incorporated into the spreadsheets. It brings many disciplines like product development, economics, consumer research and basic science together to aid in the design of a supply chain for a multi attribute product.

Samenvatting

Dit proefschrift presenteert en implementeert een gestructureerde methodologie ter ondersteuning van het ontwerpen van ketens en de evaluatie- en besluitvormingsprocedures die daarmee gepaard gaan. Het proefschrift richt zich op het ontwerpen van de gehele keten van begin tot eind, zó dat de consument het product krijgt dat hij/zij wil hebben, d.w.z. gericht op producteigenschappen en minder op de levering van het product. De zogenaamde Novel Protein Food (NPF) case van het PROFETAS (www.profetas.nl) programma is gebruikt om de methodologie te ontwikkelen.

Hoofdstuk 1 vormt de introductie op het proefschrift – Ontwerpen van productieketens voor levensmiddelen – een gestructureerde methodologie: Een casus over Novel Protein Foods. Ontwerpelementen van een productieketen zijn: de plaats waar de grondstoffen geproduceerd en verwerkt zullen worden, d.w.z. besluitvorming over de locatie; de keuze van de variëteiten en de technologieën die gebruikt zullen worden om het product te maken; de hoeveelheden, de prijsstelling etc. Voor ketens van levensmiddelen ligt bovendien nadruk op de eigenschappen die het product zal moeten hebben, d.w.z. voedingswaarde, microbiële veiligheid, smaak etc.

Hoofdstuk 2 is getiteld "Kwalitatieve methodologie voor het efficiënt ontwerpen van productieketens voor levensmiddelen". Dit hoofdstuk presenteert een kwalitatieve aanpak om te komen tot een multi criteria methode voor het ontwerpen van levensmiddelenketens. Het criterium om te komen tot een goede kwaliteit werd daartoe uitgewerkt. Twee kwaliteitskarakteristieken werden bekeken: het watervasthoudend vermogen, een maat gerelateerd aan de textuur van een NPF, en het eiwitgehalte. Eindwaarden werden vastgesteld voor de twee kwaliteitskenmerken en deze werden teruggevolgd door de keten tot de primaire productie. De volgende inzichten werden verkregen: de generieke keten van een levensmiddel bestaat uit de volgende schakels: de primaire productie, de bereiding van ingrediënten en van het product, distributie en verkoop, en bereiding door de consument thuis. Deze volledige keten bepaalt uiteindelijk de hoedanigheid van het eindproduct. Echter, de relatieve bijdrage van de verschillende schakels is afhankelijk van het doel waarvoor de keten wordt ontworpen. Ketens worden ontworpen voor een specifiek eindproduct, waarbij mogelijke routes en de relatieve bijdrage van de schakels worden bepaald door de karakteristieken van het eindproduct. Het ontwerp wordt voornamelijk bepaald door de gekozen doelstelling. De keuze van de kwaliteitskarakteristieken die worden gebruikt als indicatoren in de keten, is van belang aangezien deze het doel zo dicht mogelijk moeten benaderen en veranderingen in de keten ten opzichte van dit doel aangeven. De gepresenteerde methodologie geeft een gestructureerde en systematische manier om probleemgebieden in de keten te identificeren.

Hoofdstuk 3 heet "Het ontwerpen van een productienetwerk voor NPFs gemaakt van erwten". In dit hoofdstuk wordt een Operations Research techniek gepresenteerd die kan worden gebruikt voor het ontwerpen van een productieketen. Deze techniek wordt toegepast om een productieketen te vinden waarmee een NPF op basis van erwten kan worden geproduceerd tegen zo laag mogelijke kosten. De huidige vleesvervangers voldoen niet aan de verwachtingen van de consument in die zin dat ze als serieuze alternatieven voor vlees worden beschouwd. Het zijn niche producten, die duur zijn vergeleken met varkensvlees. Het

ontworpen model heeft de doelstelling om een antwoord te vinden op de vraag: *Is het mogelijk om een NPF op basis van erwten te produceren tegen lagere kosten dan gehakt van varkensvlees?* Daarbij werd specifiek gekeken naar de productiekosten. De kosten in de eerste drie schakels van de keten, te weten de productie en het transport, werden bekeken; distributie en verkoop werden niet meegenomen omdat ze als identiek aan die voor varkensvlees werden beschouwd. Verschillende scenario's werden gegenereerd. In het eerste scenario werd aangenomen dat er geen beperking was met betrekking tot de hoeveelheid beschikbare erwten van verschillende herkomst. Dit resulteerde in een enkele keten door het vinden van de goedkoopste route in het netwerk. In een tweede scenario werden eenvoudige bovengrenzen gezet op de productiecapaciteiten van de verschillende bronnen. Het model gaf een maximale hoeveelheid voor ieder gebied waarvan de erwten zouden kunnen worden betrokken. Op deze manier is de productie niet afhankelijk van een enkele bron. De resulterende stroom bestaat dan niet meer uit een enkel pad maar geeft een netwerk weer. De kosten kwamen vooral voort uit het verkrijgen en verwerken van de erwten. Overige kosten voor ingrediënten zoals oliën en smaakstoffen, werden niet beschouwd. Voorlopige berekeningen toonden echter aan dat de totale productiekosten per ton minder dan € 1000 bedragen, óók wanneer deze kosten wel worden meegenomen. Een verdere waardevermeerdering vindt plaats in de laatste schakels van de keten, namelijk door verpakking, distributie en verkoop.

Hoofdstuk 4 geeft een exergie analyse als één van de manieren om het milieu effect in een keten te bestuderen. De methode vindt schakels waar verlies van exergie plaatsvindt en laat zien waar verbeteringen mogelijk zijn om dat verlies te minimaliseren. De ketens van drie producten werden bestudeerd: gehakt van varkensvlees, NPF uit gedroogde erwten en erwtensoep. De inhoud en behoefte aan exergie van de verschillende paden, de producten en de processen die plaatsvinden, werden berekend voor de drie ketens. Exergie is uitgedrukt in één eenheid, de Joule. Daardoor kunnen inputs en outputs van de verschillende ketens gemakkelijk worden vergeleken. De bijdrage van de schakels in het verlies aan exergie varieert over de ketens. De NPF keten vereist de meeste input in het verwerken van de erwten, terwijl de varkensketen het meeste nodig heeft in de primaire productie en het transport. De NPF keten is slechts enigszins efficiënter (in termen van exergie) dan de varkensvleesketen, hetgeen voornamelijk te wijten is aan het verlies dat optreedt omdat de niet-eiwit fractie (voornamelijk zetmeel) niet verder is gebruikt. Een dergelijke analyse blijkt nuttig voor het ontwerpen en verbeteren van ketens.

De selectie van kwaliteitsattributen, het benoemen van relevante variabelen, het genereren van alternatieven en de uiteindelijke keuze vereisen vele beslissingen. Het probleem omhelst zowel kwalitatieve als kwantitatieve elementen. De beslisruimte is discreet en conflicterende meervoudige criteria moeten tegen elkaar worden afgewogen. Dit alles vereist een methode waarmee deze problemen te lijf kunnen worden gegaan, en de zogenaamde MCDM (Multiple Criteria Decision Making) methode lijkt daar bij uitstek voor geschikt. De theorie ten aanzien van Multi Criteria besluitvorming wordt uitgelegd in hoofdstuk 5. Verschillende classificaties van MCDM problemen worden gegeven. Drie belangrijke modellen worden in detail beschreven: MAVF (Multiple Attribute Value Function), AHP (Analytical Hierarchy Process) en ELECTRE, en uitgewerkt met behulp van een voorbeeld.

Hoofdstuk 6 gebruikt een gestructureerde methode gebaseerd op MCDM als hulpmiddel voor het ontwerp en de evaluatie van, en besluitvorming rond de inrichting van een keten. De criteria voor de evaluatie van alternatieven zijn de kwaliteit van het product, de kosten en de impact op het milieu. In elke schakel werden de variabelen van invloed op de criteria geïdentificeerd en gebruikt voor het genereren van mogelijke ketens (alternatieven). De alternatieven werden geëvalueerd en gerangschikt met behulp van twee MCDM methoden, MAVF en AHP. De rangorden, zoals gegenereerd door de twee methoden, verschillen. De belangrijkste oorzaken hiervoor zijn de manier waarop de gewichten voor de verschillende criteria worden verkregen, de waardebepaling van de alternatieven en het gebruik van absolute schalen in de MAVF methode versus de paarsgewijze vergelijking door de AHP methode. Een aspect bij de keuze voor de methoden is het gemak waarmee ze kunnen omgaan met een mix van kwalitatieve en kwantitatieve informatie. De kwalitatieve informatie kan worden gekwantificeerd en een totale score voor elk alternatief kan worden bepaald. De methodologie blijkt effectief in het richten van de aandacht van de betrokkenen bij het besluitvormingsproces op de verschillende aspecten die van belang zijn. De gegenereerde ideeën worden concreet gemaakt en het pad naar de uiteindelijke beslissingen wordt duidelijk. Het stapsgewijze proces maakt de besluitvorming transparant en gemakkelijk te volgen.

Hoofdstuk 7 bevat een algemene beschouwing. De belangrijkste bevindingen van het proefschrift worden geanalyseerd en toekomstige richtingen voor verder onderzoek worden gepresenteerd. Geconcludeerd is dat de gepresenteerde methodologie structuur geeft aan het besluitvormingsproces en het mogelijk maakt om rationele beslissingen te nemen t.a.v. de inrichting van een keten. Echter, hoewel het een heldere en transparante methode is, vereist het wel de nodige aandacht om het te implementeren. Met inachtneming daarvan is de methodologie gemakkelijk in het gebruik en er is alleen maar eenvoudige software zoals een spreadsheet vereist. Indien nieuwe gegevens of veranderingen in bestaande gegevens beschikbaar komen zijn die heel eenvoudig te implementeren. De methodologie ondersteunt een multidisciplinaire aanpak om een voedselketen in te richten en dat is bijzonder gewenst omdat levensmiddelen gewoonlijk meerdere relevante productattributen kennen. Het betreft disciplines als productontwerpen, economie, consumentenonderzoek, en levensmiddelen-technologische basiskennis.

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About the author

Radhika Apaiah was born in Bangalore, India – a city now known for its large and successful IT industry. After her schooling in various places in India, she completed her graduation in Chemistry from the Women's Christian College in Chennai, India. After a post graduate program in Food Technology in University Department of Chemical Technology, Mumbai, she headed to the US to the Ohio State University on a full scholarship to finish her Masters degree in Food Science and Technology. After working with Nestle in the US as a product scientist for a short while, she moved to the Netherlands in 2000 to join her husband and started a doctoral program at Wageningen University in November 2001. The project was a part of a large nationwide endeavour called PROFETAS and Radhika was responsible for developing a methodology to design food supply chains. Her daughter Samyukta Varanasi was born in the fall of 2003.

Publications

Apaiah, K.R. (2004). “Linear programming for supply chain design- A case on novel protein foods” 14th Annual World Food and Agribusiness Forum, Symposium and Case Conference, 2004, Montreux, Switzerland.

Apaiah, K. R. & Hendrix, E.M.T. (2005). “Design of a supply chain network for pea-based novel protein foods.” Journal of Food Engineering, 70: 383–391.

Apaiah, K. R., Hendrix, E.M.T., Meerdink, G. & Linnemann, A.R. (2005). “Qualitative methodology for efficient food chain design.” Trends in Food Science and Technology, 16:204–214.

Apaiah, K.R., Linnemann, A.R. & Kooi, H.J. van der. (2006). “A tool to study the sustainability of food supply chains." Food Research International. 39: 1-11.

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Educational Activities

Discipline specific activities

- Course Simulation and optimisation tools for food processes, E.U. Socrates Intensive program, Nantes, 2003
- Supply chain management, Erasmus University, 2001
- Decision Sciences I, ORL, Wageningen University 2002
- Decision Sciences II, ORL, Wageningen University 2003
- Operations Research and Logistics, LNMB, 2002
- Operations Research, ORL, Wageningen University 2003
- Annual Meeting, International Food & Agribusiness Management Association, Netherlands 2002
- Annual Meeting, International Food & Agribusiness Management Association 2004, Switzerland
- Conference on Optimisation in Supply Chain, Maastricht, 2002

General Courses

- Career Perspectives 2005

Optional activities

- Preparation PhD research proposal