Integration of Operational Research and Environmental Management

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Integration of Operational Research and Environmental Management

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Abstract

The subject of this thesis is the integration of Operational Research and Environmental Management. Both sciences play an important role in the research of environmental issues. Part I describes a framework for the interactions between Operational Research and Environmental Management. The framework describes three levels of incorporating environmental issues in economic decision making: waste management, recovery management and preventive management, as well as three types of policy approaches towards environmental problems: local orientation, regional orientation and global orientation. This classification helps to find possibilities of including environmental issues in existing Operational Research models and methods and to find possibilities to use Operational Research models and methods in solving environmental problems. Part II contains three examples of dealing with environmental issues in Operational Research models: waste disposal in a location model, manure utilization in a farm management model and an environmental extension of a blending model. Part III contains two examples of using Operational Research models and methods in environmental management: a linear programming model for the mineral excess problem in the Netherlands and a network flow model for paper recycling in Europe. The final chapter confronts the general ideas from the framework with the knowledge obtained from Part II and III.

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STELLINGEN

(I)

Operationele Research is een geschikt instrument voor milieubeleid (Environmental Management). Voorwaarde hierbij is wel dat het aspect van de interdisciplinariteit, kenmerkend voor de beginjaren van Operationele Research, weer hoge prioriteit krijgt.
(Dit proefschrift)

(II)

De 'keten' benadering van milieuproblemen – van de wieg tot het graf – valt samen met de opkomst van de 'integrale ketenbenadering' binnen de Operationele Research. Deze samenloop van omstandigheden biedt een niet te missen mogelijkheid voor samenwerking tussen beide vakgebieden.
(Dit proefschrift)

(III)

Het fractioneel programmeringsprobleem $\max_{x \in [l,u]} f(x) := \frac{d^T x}{q^T x}$, met de vectoren d en q strikt positief, kan optimaal opgelost worden via het zgn. threshold-algoritme.
(Dit proefschrift)

(IV)

De combinatie van een multicriteria methode, een levenscyclus analyse en een optimaliseringsmethode lijkt een zeer geschikt instrument voor het ontwikkelen van produkten die zowel goedkoop moeten zijn als aan een 'groen profiel' moeten voldoen.
(Dit proefschrift)

(V)

Het bedrijfsleven kan Operationele Research modellen gebruiken om de gevolgen van slecht doordachte en weinig effectieve wetgeving kenbaar te maken.
(Dit proefschrift)

(VI)

In onze huidige consumptie-cultuur is er geen sprake van rentmeesterschap, aangezien wij niet alleen van de rente leven, maar ook van het kapitaal.

(VII)

De airmiles-aktie werkt overconsumptie van vliegreizen in de hand. Uit milieu-overwegingen zou deze aktie dus niet gebruikt moeten worden door bedrijven die pretenderen milieu-vriendelijk te zijn.

(VIII)

Als milieubeleid gericht is op maatregelen die het gedrag van mensen niet wezenlijk veranderen, zal de consument met een gerust geweten de auto blijven gebruiken na de groene en grijze afvalbak op de voor hen bestemde plek te hebben neergezet.

(IX)

Sperziebonen uit Thailand worden in Nederland nog steeds verkocht ondanks het feit dat uiteindelijk 170 keer zoveel energie is verbruikt dan bijvoorbeeld bij een Belgische boon. Het wordt tijd om energie-kosten volledig in de kostprijs van produkten te laten meetellen.

(Bron: Kramer, K.J., W. Biesiot, R. Kok, H.C. Wilting, en A.J.M. Schoot Uiterkamp (1994), *Energie geld(t), Mogelijke energiebesparingen op huishoudelijke uitgaven*, IVEM Onderzoeksrapport 71, Rijksuniversiteit Groningen.)

(X)

Nederlandse garnalen worden naar Marocco vervoerd om gepeld te worden, waarna ze in Nederland verkocht worden. Deze situatie geeft aan dat het transport van goederen een essentieel onderdeel van een eco-keurmerk moet worden.

(XI)

De wiskundige operatie 'delen' heeft in het spraakgebruik geen eenduidig gevolg, immers: gedeelde vreugd is dubbele vreugd, maar gedeelde smart is halve smart.

(XII)

Het hebben van vaste rustpunten in het ritme van de tijd is een universele menselijke behoefte om zich houvast te geven. Daarom dient de zondagsrust gehandhaafd te blijven.

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Contents

Part I

Operational Research and Environmental Management: a challenge

Chapter 1

Introduction

1.1 Subject of the thesis

The subject of this thesis is the *integration of Operational Research (OR) and Environmental Management (EM).* Both the fields of OR and EM are still young. The general interest in, as well as the research effort spent on, environmental problems has grown enormously since the first indications that economies cannot grow forever without strong negative effects on natural resources and the environment (Meadows [104]). The field of OR, in itself hardly 50 years old, became interested in environmental issues as an application area in the mid-seventies. This introductory chapter gives a brief background on the fields of OR and EM. It also stresses the need for a framework approaching environmental issues from both an economic (efficient) and an environmental (sustainable) point of view.

We consider *Operational Research* to be a scientific approach to decision making, which seeks to determine how best to design and operate a system, usually under conditions requiring the allocation of scarce resources (Winston [165]). Operational Research has shown to be very useful in industrial decision making problems such as:

- control of production processes (tuning of machines, scheduling of operations, selection of raw materials);

- inventory control (optimal reorder levels, sizing of warehouses);

- control of flows of goods (throughput time reduction, location of distribution points, routing).

Operational Research has produced practical tools for analysing these decision making problems. Tools include mathematical programming techniques (linear programming, integer programming, non-linear programming), network analysis, queuing theory, stochastic programming, and simulation among many others. For the reader with limited knowledge on Operational Research, good introductory textbooks are available (e.g. Winston [165], and Schrage [138]).

Environmental Management (or Environmental Resource Economics) concerns the management of scarce environmental resources like raw materials, fossil fuels, but also clean water and air. Environmental Management is based on conflict analysis, characterized by technical, socio-economic, environmental and political value judgements. It concerns the development of instruments to reduce or prevent environmental problems. These instruments can point directly at processes in the environment (e.g. global warming, stratospheric ozone depletion), or at social causes of environmental problems (e.g. overpopulation, traffic intensity). Effect-directed instruments support the forecasting and evaluation of the environmental effects of human activities. Source-directed instruments support changes in economic behaviour due to environmental problems. The relation between the economic process chain (production-consumption-waste) and the environmental effect chain (emissions-pollution-depletion) is essential in Environmental Management studies.

Operational Research and Environmental Management can play a complementary role in the research of environmental issues. The international nature and the complexity of many environmental problems make it almost impossible to base decisions on intuition and simple methods. Operational Research has a long and outstanding tradition in the allocation of scarce economic resources (e.g. money, materials, etc.). This knowledge is very useful in the management of scarce environmental resources. Environmental issues have come to play an important role in decision making processes of industries. Decisions on production planning, logistics, allocation and inventory control are changing due to legal requirements or consumer pressures to reduce waste and emissions. The knowledge of Environmental Management is essential while including environmental issues in Operational Research models (e.g. conflict analysis in multiple criteria situations, life cycle analysis if environmental impacts have to be compared with 'hard' metrics such as costs). These developments give the opportunity to build a framework on the interaction of environmental issues and economic activities using both Operational Research tools and Environmental Management instruments. We see the integration of OR and EM as a two-sided relationship. OR models and methods should be adapted to accommodate environmental issues, and become more sustainable like economic-ecological models in EM. Economic-ecological models, traditionally descriptive, should be adapted to accommodate decision support, in order to *(i)* determine an efficient design of the economic system under environmental constraints, and *(ii)* solve environmental problems under economic constraints.

1.2 Purpose of the thesis

This thesis aims to investigate the possibilities of incorporating environmental issues in 'traditional' OR applications, *and* the possibilities of using OR models and techniques in

Environmental Management models. Examples will demonstrate the additional value for both OR and EM.

We structure the research on the relations between OR and EM by finding answers to two research questions:

1. How can Operational Research models and methods be adapted to include environmental issues?

2. To which degree can Operational Research models and methods be used to solve environmental problems?

The research questions imply that we pay more attention to the general approach of Operational Research and Environmental Management than to the development of new solution techniques in a concrete decision making situation. Nevertheless, typical (sometimes simplified) problem settings will be analysed in order to generalize conclusions to a broader category of problems. We expect that the results for the specific problem settings will enrich both OR and EM.

Part I of the thesis contains a broad literature review on Operational Research and Environmental Management dealing with both research questions. It is not the purpose to give an exhaustive review of examples on the interactions between Operational Research and Environmental Management. Instead, the discussion is structured around some carefully selected examples of fruitful interactions between OR and EM. General incentives and constraints regarding these interactions are stated. In order to structure the interactions between OR and EM we introduce a framework showing how environmental issues and economic activities interact in a two-sided way. The first part of the review deals with changes in economic processes (the supply chain). The second part of the review deals with environmental problems (the environmental chain).

We explore this framework in Parts II and III of the thesis, by studying examples for each element in the framework. Each subject has a scientific value on its own, but can also serve as an illustrative example for a wider range of applications. Each chapter focusses on one problem, and describes the necessary steps to deal with the problem, i.e.: problem description, model formulation, literature review, solution procedures and computational results based on real life test data.

The examples in this thesis do not cover the complete range of Operational Research tools as briefly mentioned in Section 1.1. All problems are dealt with as mathematical programming models, either linear programs, mixed integer programs or non-linear programs. Simulation models, queuing networks or stochastic programming are not studied in these chapters. However, they are included in the general review of Part I. The same limitation holds for the range of Environmental Management instruments and environmental problems. The examples in this thesis do not cover all relevant environmental problems or use all well-known Environmental Management instruments. Environmental life cycle analysis (together with material balancing) is one of the instruments that receives broad attention.

1.3 Outline of the thesis

Part I: Operational Research and Environmental Management: a challenge

Part I consists of this introductory chapter and a literature review on the interactions between Operational Research and Environmental Management (Chapter 2). Chapter 2 presents a framework to show how environmental issues and economic decision making interact in two ways. This is an important chapter to understand the underlying structure of the thesis. It shows that the growing attention for environmental issues within the field of Operational Research is in concordance with the shift from corrective policies towards prevention of environmental problems, and the expanding scope of environmental policy. These trends cause a natural opportunity for the integration of OR and EM. However, issues like complexity, measurability and the social character of environmental problems may obstruct this integration.

Part II: Environmental issues in Operational Research applications: some illustrative examples

Part II consists of three chapters on the integration of environmental issues in supply chain modelling. In the first example (Chapter 3), only distribution and disposal are influenced by environmental issues. The second example (Chapter 4) considers all changes in the supply chain that concern recovery management. The third example (Chapter 5) considers the supply chain from the cradle to the grave.

Chapter 3 studies the problem of *coordinating product and by-product flows* in a distribution network. In this problem, a single product is produced at multiple plants in order to fulfil customer demands. In the production process a by-product is generated that must be transported to and processed at a waste disposal unit. This example illustrates end-of-pipe waste management modelling and has close relations with traditional OR models. The approach in this thesis is new as it combines both product management and waste management. This chapter is rather technical, and requires some background in the mathematics of Operational Research.

Chapter 4 extends simple *farm management modelling* with a manure and fertilizer aspect. Manure used to be treated as a waste product that has to be disposed of. However, it can also be applied for fertilizing purposes, replacing expensive inorganic fertilizers, under certain quality conditions. The choice between disposing or applying manure changes the model from a linear program to a non-linear program. This example illustrates the issue of product recovery modelling. Recovery modelling is still an unexplored field that will appear to be very useful for companies dealing with recycling issues. Recovery models are in general much harder to solve than models without recovery options, due to feedback loops (causing non-linearities), and uncertainty in time, quality and quantity of the supply of used products (causing stochastic processes). This chapter is also rather technical, and requires some background in the mathematics of Operational Research.

Chapter 5 studies a methodology to improve the *environmental impacts of fat blends* for margarines. This chapter illustrates a from the cradle to the grave modelling approach that is necessary for changes at the source of the supply chain. We combine here a methodology for environmental life cycle analysis with multiple criteria decision making and linear programming. Application of linear programming to life cycle analysis is a novel approach to analysing and managing the environmental performance of a complete product system.

Part III: Operational Research tools for environmental problems: some illustrative examples

Part III contains two elaborate examples on the use of OR tools for environmental policy making. The first example describes the manure excess problem in the Netherlands (Chapter 6) that causes local and national water, air and soil pollution. The second example considers the waste paper problem in Europe (Chapter 7). In both examples, the economic consequences of environmental policy making play an important role. Both the livestock sector and the paper industry contribute heavily to Gross National Products and employment in the regions considered.

Chapter 6 analyses *emission abatement strategies in intensive livestock*. This chapter starts with a historical review of the manure problem, environmental policies and specific abatement measures. We stress the need for an integrated chain approach to understand the effects of all measures on emissions, transportation, investments in processing capacities and income. The integrated chain approach is used to develop a large-scale linear programming model for designing a mixture of policy instruments which is as effective and efficient as possible.

Chapter 7 explores the *environmental impact of the European paper and pulp sector*. We analyse scenarios with different paper recycling strategies in Europe using an approach that combines materials accounting methods and optimization techniques. Combining environmental life cycle analysis and network optimization techniques, we can define feasible life cycle configurations for the sector and search for those with the lowest environmental impacts.

Finally, Chapter 8 summarizes the conclusions of the studies described in Part II and Part III. We confront the general ideas from Part I (i.e. the framework) with the contributions of Part II and III (i.e. the 'capita selecta') to find satisfying answers to the research questions.

Large parts of this thesis draw upon technical reports and publications that appeared earlier. Chapter 2 is published as [22]. Chapter 3 is based on [26, 27], Chapter 4 on [24], and Chapter 5 on [25]. Chapter 6 contains the literature review [23] and unpublished material on the development and implementation of an optimization model together with computational results. Chapter 7 is based on Weaver et al. [163], and [28].

Chapter 2

Interactions between OR and Environmental Management

2.1 Introduction

In the last few decades environmental problems have received increasing attention. Protection of the environment has become an issue at all levels of society: worldwide (UNCED '92), regional (European Union), national, sectoral and the individual consumer.

Within the field of Operational Research (OR), attention for environmental issues is now growing rapidly. In 1991, a special issue of Transportation Science was devoted to the transportation of hazardous materials. Van Beek et al. [19] demonstrated how Operational Research can play an important role in visualizing and solving environmental problems. The June 1992 issue of OR/MS Today featured the title "Reflections on OR and the Environment". One of the authors, F.W. Talcott of the U.S. Environmental Protection Agency (EPA), stated:

"*... the opportunities for OR and MS are numerous. Environmental problems are substantial; the costs of dealing with them are imposing. Because our resources - natural and financial - are limited, it is critical that we think smart and plan smart in dealing with environmental issues. Good analysis can pay off.*" (Talcott [149])

As early as 1976, a special issue of Computers & Operations Research was devoted to macro economic environmental models. The first examples of the application of OR optimization models to environmental problems appeared in the mid-seventies in journals on environmental issues such as *Environment and Planning* (e.g. Böttcher and Rembold [29]) and *Water Resources Research* (Das and Haimes [45]). Later, applications of OR to Environmental Management (EM) appeared also in OR/MS journals such as *Operations Research* (Batta and Chiu [15]), *European Journal of Operational Research* (Ellis [51]) and *Management Science* (Bouzaher et al. [30]). Nowadays, literature on a wide variety of environmental problems, using all kinds of OR techniques, can be found in both environmental journals and OR journals.

It is not the purpose of this chapter to give an exhaustive review of examples on the interactions between Operational Research and Environmental Management for the simple reason that the area is too large for that. For some specific issues, it is possible to briefly describe previous work. When we arrive at these issues, we refer to reviews and bibliographies. However, most of the work in this area is still very much in development and some applications have only just started. Therefore, this chapter is structured around some carefully selected examples of fruitful interactions between OR and EM.

We distinguish two ways of looking at the interactions between OR and EM:

1. *Impact of environmental issues on the supply chain:* Environmental issues play a role in the routine activities of business firms. Decisions on production planning, logistics, location-allocation and inventory control will change due to legal requirements or consumer pressures to reduce waste and emissions. Therefore, there is a need to adapt OR tools such as production planning algorithms, location models and routing heuristics in order to deal adequately with a new situation requiring 'green supply chain modelling'.

2. *Impact of economic activities on the environmental chain:* The amount of waste and the level of emissions caused by the supply chain result in a number of serious environmental effects, such as global warming and acid rain. Frequently, these environmental problems are international and complex. The interaction between OR and EM can result in a clear formulation of these problems and in new insights in the impacts of alternative policy measures.

This chapter is structured as follows. In Section 2.2, some incentives and constraints regarding the interactions between Operational Research and Environmental Management are stated. We explain why, in our opinion, the knowledge of OR will be useful in environmental problem solving, and why incorporating knowledge from environmental management will enrich the working area of Operational Research. Furthermore, a framework is presented to show how environmental issues and business interact in the two ways described above. In Section 2.3, we discuss in more detail the environmental issues in a supply chain. In Section 2.4, some examples are given of OR work that deals with reducing waste and emissions in the supply chain. In Section 2.5, we turn to the environmental chain and discuss the effects of business on the environment and the way environmental policy makers try to deal with these effects. In Section 2.6, some OR work in this area is presented. Finally, Section 2.7 provides some conclusions.

2.2 OR and Environmental Management

In this section, we indicate why closer interaction between OR and EM may become very fruitful and even necessary.

2.2.1 Internalization

Thinking about the environment has evolved from *end-of-pipe control* (reduce waste and emission flows) towards *waste prevention at the source* by redesigning products and processes. This change in attitude poses many questions which OR can help answering. As Kleiner [86] mentioned: "A recycling operation must deal with the same transport difficulties and storage problems that challenge any distribution system; a landfill is, in effect, like a warehouse whose inventory never shrinks; garbage barges and toxic trains are the environmental equivalents of production-distribution networks".

In line with the shift in attitude from end-of-pipe controls to prevention at the source, laws are changing from strict rules and specific emission controls towards a policy of leaving operational managers more flexibility to decide how to keep pollution within given emission limits (Corbett and Van Wassenhove [41]). This market-based policy ('bubble policy') treats entire firms as being enclosed in a bubble and allocates to each bubble a specific total pollution limit. This allows firms to decide for themselves where and how to cut back pollution and results in more degrees of freedom for the decision makers to optimize their behaviour.

2.2.2 Scope

The international nature and the complexity of many environmental problems in relation to supply chains make it almost impossible to make decisions based on intuition. A quantitative model-based representation of the problem will often be extremely useful.

Although model building can provide insights in the characteristics of a complex problem, it can be very hard to 'solve' such models. Sterman [145] mentioned that "whenever the problem to be solved is one of choosing the best from among a well-defined set of alternatives, optimization should be considered. If the meaning of best is also well-defined and if the system to be optimized is relatively static and free of feedback, optimization may well be the best technique to use". The latter conditions are rarely satisfied for the economic and ecological systems that are dealt with in Environmental Management. Fortunately, more and more optimization techniques (e.g. multicriteria analysis and dynamic programming) try to overcome these problems. Moreover, discrete and continuous simulation can identify how feedback, nonlinearity and delays interact.

The complexity of environmental problems is also characterized by the typical difficulty to find a unique quantitative measure for 'being green'. Environmental damage cannot easily be compared with parameters such as costs or time that are 'hard' metrics. However, environmental evaluation techniques should make it possible to compare products based on their environmental profile. Furthermore, environmental regulations are often stated in quantitative terms (e.g. emission standards to air and water).

Some environmental management issues deal with behaviour. These issues do not easily lend themselves to OR modelling. In addition, environmental decisions are often made by politicians not familiar with, and indeed sometimes suspicious of, mathematical modelling. The review by de Melo and Câmara [106] shows how policy makers can be successfully involved in the development of models for the optimization of regional wastewater treatment systems. Moreover, Operational Research models can be used as a rational tool in otherwise irrational and emotional debates on environmental issues.

2.2.3 Framework

The shift from effect-oriented control towards prevention and the increasing acknowledgement of the complexity and international character of environmental problems are open invitations for the increasing interactions between OR and EM.

The interactions between OR and EM can be rather straightforward in the sense that an end-of-pipe approach (e.g. an emission standard) can be incorporated in a classical OR production-distribution model as an additional constraint. In this way, effect-oriented approaches involve adjustments to classical OR models. Preventive approaches acknowledging the complexity and international character of environmental problems require more fundamental thinking, the development of new models and the use of different techniques. They provide a great challenge to OR.

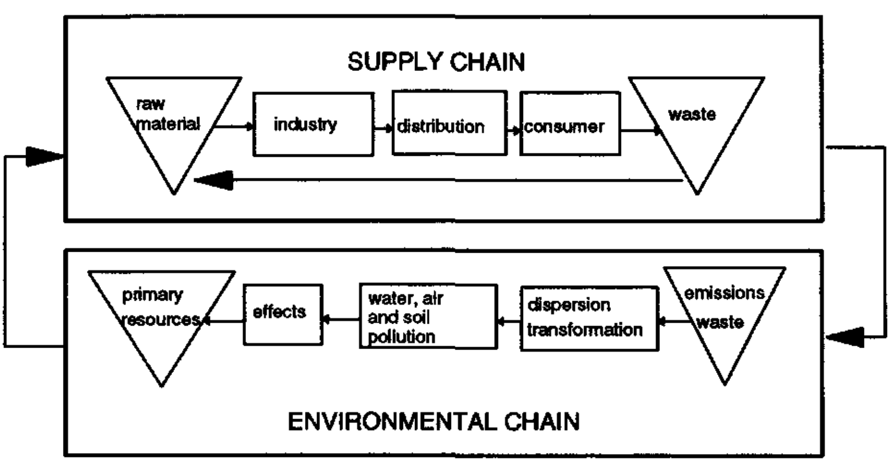

Figure 2.1: Framework for the interactions between OR and EM

We illustrate the shift in policy within the context of both the supply chain and the environmental chain (Figure 2.1) and point out opportunities for OR.

The *supply chain* contains the extraction of raw materials (e.g. agriculture, refinery), manufacturing, distribution and use of goods. Waste, generated in each component of the supply chain, is collected at the end of the chain. In general, changes within the supply chain are necessary to reduce the amount of waste and emissions, and the use of non-renewable resources. In Sections 2.3 and 2.4, we explore the incorporation of environmental issues when analysing supply chains. We structure the discussion around a hypothetical shift from an effect-oriented approach towards waste prevention at the source, and the corresponding development of OR as a tool in green supply chain modelling.

The supply chain causes emissions in the *environmental chain*. The emissions and waste are transported and transformed and result in water, air and soil pollution with damaging effects to the environment. In addition, the supply chain's need for resources extracts non-renewable and scarce resources from and places a burden on the environmental chain. In Sections 2.5 and 2.6, we focus on the development of OR as a tool for analysing and solving environmental problems on a large scale. The discussion deals with a hypothetical shift from local end-of-pipe policies towards an integral approach in order to prevent environmental problems.

2.3 Green supply chain management

During each step in the supply chain, emissions take place that can be a threat to people, plants, animals and ecosystems. New decisions are necessary to decrease emissions and waste flows. Legal requirements and changing consumer preferences increasingly make suppliers and manufacturers responsible for their products, even beyond their sale and delivery. To comply with these new regulations, producers have to apply cradle-to-grave product management covering the entire supply chain. Figure 2.2 presents potential environmental actions in a supply chain in more detail.

The first actions, quite easy to apply, have been effect-oriented (end-of-pipe) such as waste treatment. Somewhat more integrated are waste- and emission-oriented adaptations in technology such as reuse of materials and packaging and recovery of products. The most integrated approach is source-oriented and deals with adaptation of raw materials, product redesign and process changes.

Barry et al. [14] introduced a five-stage outline for analysing environmental issues throughout the product life cycle. This outline is used here to discuss the potential environmental actions in Figure 2.2 in more detail. First, the use of fewer raw materials is discussed. This is followed by a discussion of the manufacturing stage covering process and product changes, distribution issues (transport, redesign of locations and reverse logistics), the use of products, and finally, the treatment of waste.

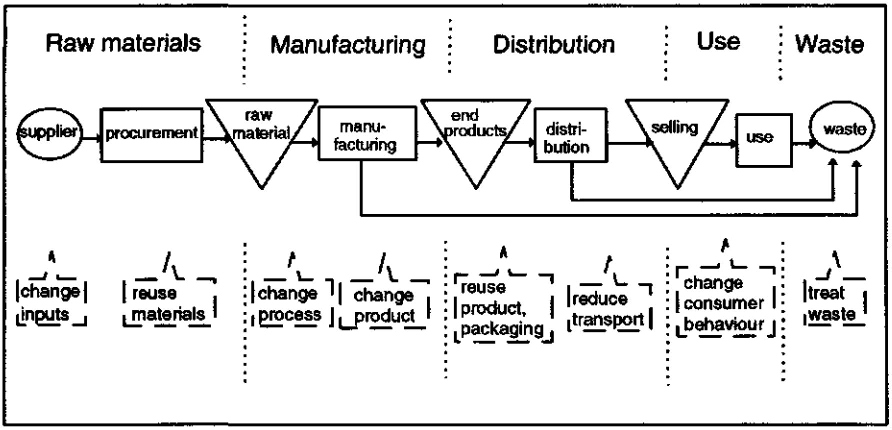

Figure 2.2: Green supply chain

Raw materials Considering raw materials, green objectives may be to minimize the use of materials whose acquisition is environmentally damaging and to maximize the use of recycled materials and renewable resources. In addition, preference can be given to suppliers who operate in an environmentally responsible manner. General Motors, for example, has embarked on an ambitious program in material acquisition. Its WE CARE (Waste Elimination and Cost Awareness Reward Everyone) program involves cooperation with suppliers and includes specific measures to reduce inbound packaging materials, encourage their reuse and increase their recycling ability (Barry et al. [14]).

Manufacturing In manufacturing, both process and product design can be improved. In process design, the goals are to reduce waste, minimize pollution, use resources efficiently and find substitutes for hazardous materials. In product design, the purpose is to design not only for cost-effective assembly but also for disassembly and recyclability. Europe's automobile manufacturers and their suppliers are considering ways to increase the use of recycled parts. BMW and Volkswagen, for example, have set up pilot plants to examine reusability of current models and to develop design requirements for new models (Kleiner [86]).

Distribution Reverse distribution planning is necessary for collecting packaging and used products. In Germany, consumers have the legal right to return product packaging to retailers for recycling and reuse (Töpfer Law, '91). As a reaction, retailers developed the Duales System Deutschland (DSD). This dual system collects used packaging and sorts it by type of material. These materials are then transported to industries that have a license to make the materials valuable (Cairncross [34]).

Use Efficient use means minimizing energy or other resources, increasing the product's durability and lifespan, and minimizing the pollution the product emits during use. Consumers should also be provided with instructions for using the product efficiently, with a minimal impact on the environment. The Dutch electricity firms' 'efficient light bulb' action includes humoristic ads and television shows to change consumer behaviour (VROM [160]).

Disposal Infrastructural measures are necessary to collect and sort waste. In addition, hazardous materials should be collected safely. According to the Office of Technology Assessment (USA), American industry generates approximately 250-275 million metric tonnes of industrial chemical wastes annually. Most of the waste is dumped in landfills and could be quite hazardous (Anandalingam and Westfall [9]).

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The production-distribution-consumption process is a classical source of well-known Operational Research applications such as production planning and scheduling, network optimization, inventory control, etc. These applications can be scrutinized to see how environmental issues can be effectively integrated and how this integration influences model structure and solution methods.

2.4 Integration of environmental issues in supply chain modelling

In order to classify the literature on green supply chain modelling, we structure the discussion around the shift from effect-oriented environmental policy towards integrated waste prevention as mentioned in Section 2.2. As a first phase in the integration of environmental issues in supply chain modelling, the end-of-pipe approach to *waste management* is discussed in Section 2.4.1. In this phase, only distribution and disposal will be subject to changes. In an intermediate phase we consider all environmental issues concerning *recovery management* of used products (Section 2.4.2). Here, manufacturing is also subject to changes due to the supply of used products. Finally, we discuss the source-oriented approach of *preventive management* which encompasses the complete supply chain (Section 2.4.3).

2.4.1 Waste management

Optimization approaches with respect to waste treatment focus on two problems: *(i)* locating sites for the storage of (hazardous) waste and *(ii)* transporting waste to the chosen destination in the safest possible way. These problems have appeared in the OR literature for quite a long time. As early as 1977, Böttcher and Rembold [29] studied the optimal location of facilities in a regional system of solid-waste and waste-water disposals.

We classify the literature on waste treatment into three groups: *(i)* papers dealing with routing and scheduling, *(ii)* papers dealing with location and *(iii)* papers dealing with both location and routing. The state-of-the-art article by List et al. [97] surveys papers spanning risk analysis, routing and scheduling, and facility location. For the purpose of this review, it is sufficient to highlight some issues.

Routing of hazardous waste

For hazardous waste, the routing problem is of the 'many to few' type, because there are a limited number of treatment and disposal sites. Batta and Chiu [15] suggested two single objective formulations for hazardous waste routing. In both formulations, the criterion includes the size of the population potentially impacted by an accidental release of hazardous waste. The authors also mention the difference in risk between network nodes and network links by assigning penalties to nodes and considering different accident probabilities for different links in the network. Unfortunately, single objective models fail to capture the trade-off between transportation risk and transportation costs. Therefore, multi-objective models have been developed using e.g. bi-criterion methods or goal programming. These algorithms focus on finding a set of non-dominated routes explicitly representing the available trade-offs between criteria (List and Turnquist [98]).

Locations for waste disposal

Most location problems attempt to minimize some distance function. However, in the case of waste disposal the (un)desirability of a specific site often has a higher priority than costs (Not-In-My-Back-Yard syndrome). Consequently, such facilities tend to be located near the outskirts of cities with maximum distance to people. Erkut and Neuman [52] give a review of single criterion undesirable facility location. Again, multiple criteria are almost inevitable: potential sites are selected using criteria such as safety, size, distances, investment costs and operating costs. A recommended and often used method to select sites is multiple criteria analysis. Vuk et al. [162] apply the PROMETHEE method to select the location for the disposal of communal waste in Slovenia. Anandalingam and Westfall [9] use multi-attribute utility theory to select waste disposal alternatives.

Location and routing of waste

The disposal of hazardous waste at sites remote from its production requires shipment of waste across a transportation network. The location and routing problem becomes one of choosing where to open disposal sites, how to assign sources to disposal sites and how to route the waste flows from each source to its assigned destination.

If the only objective is to minimize cost, the problem can be modelled as a simple plant location model. Revelle et al. [129] combine a shortest path algorithm with a zero-one location program and the multi-objective weighing method to solve the two-criteria problem of minimizing transportation costs and perceived risk.

In summary, these end-of-pipe approaches to waste management are mostly concerned with managing risk (accidents during transport, exposure at sites) and with the strategic aspect of selecting appropriate locations. For OR modelling this often leads to multiple objective, analytic models, typically closely related to traditional routing and location models which have been studied for a long time. In all these models environmental concerns only affect distribution and waste disposal. The next paragraph introduces the recovery of used products which involves a much more integrated approach to green logistics as the return flows affect production planning and scheduling decisions.

2.4.2 Recovery management

Traditionally, manufacturers did not feel responsible for their products after consumer use. The bulk of used products were dumped or incinerated with considerable damage to the environment. Today, consumers and authorities expect manufacturers to reduce the waste generated by their products.

Product recovery management is defined as "the management of all used and discarded products, components, and materials for which a manufacturing company is legally, contractually, or otherwise responsible" (Thierry et al. [151]). Product recovery management offers several options to handle products after consumer use: repair/reuse, refurbishing, remanufacturing, cannibalization and recycling. Each of the options involves collection, reprocessing and redistribution of the used products. The main difference is in the degree of reprocessing. Figure 2.3 demonstrates the degree of required disassembly. The choice of the 'best' product recovery option in a practical case depends on environmental regulations, technological capabilities, costs, etc.

Uncertainties in product recovery problems occur with respect to time, quality and quantity of returned products (Flapper [58]). The supply of used products may be highly irregular as it is influenced by e.g. alternative uses, loss of products (e.g. car accidents) and the general economic situation. Forecasting the quantity and quality of used products will therefore be hard. The varying quality of the returned product requires screening and sorting, which complicates the modelling and analysis of product recovery problems. However, these issues may have a tremendous effect on production planning and inventory control and represent a challenging research agenda.

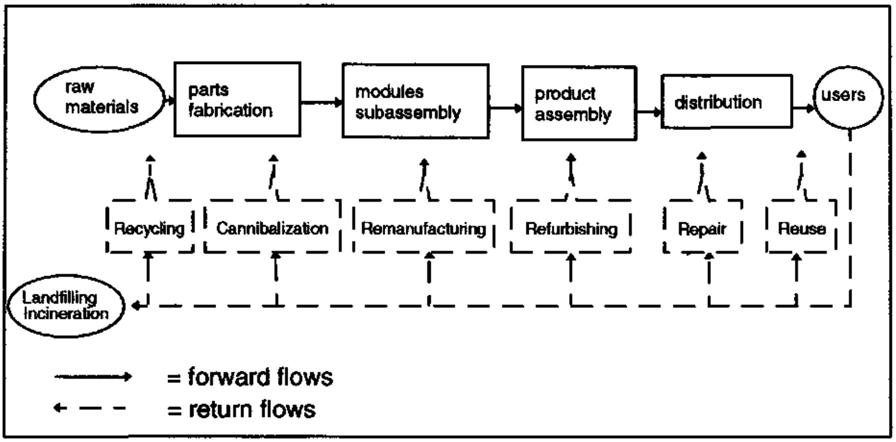


Figure 2.3: Product recovery management (Thierry et al. [151])

As an illustration of such research, we discuss some examples of classical models for production planning and inventory control, adjusted for remanufacturing (Salomon et al. [136]). For example, consider a *periodic review* model with return flows of used products which can either be disposed of or remanufactured to an 'as new' condition. At the beginning of each planning period t, decisions are taken with respect to *(i)* the number of products disposed of in period t, *(ii)* the reorder quantity in period t, and *(iii)* the number of products remanufactured in period t. The objective is to minimize total expected costs over the entire planning horizon. Kelle and Silver [82] formulate the problem as a chance-constrained integer program. They suggest an approximation procedure which contains a transformation to the well-known Wagner-Whitin model and they solve this transformation using a dynamic programming algorithm. *Continuous review* models have also been used for remanufacturing problems. Muckstadt and Isaac [111] present a control strategy with respect to order points and order quantities where returned products will be remanufactured. An approximation procedure, based on Markov-chain models, determines values for the order points and order quantities. Heyman [70] analyses a model where incoming returnables are disposed of whenever the inventory position reaches a predefined disposal level. Recently, models have been formulated in which remanufacturing and disposal decisions are considered simultaneously (Van der Laan et al. [93]).

2.4.3 Preventive management

Examples in this section deal with environmental impacts associated with a product over its entire life cycle. They differ from the above examples which focus solely on waste disposal and product recovery.

For some years now, people have been developing techniques for assessing environmental impacts of products and processes 'from the cradle to the grave'. Such techniques require a lot of environmental data. One of the most promising techniques is *Life Cycle Analysis* (LCA) defined as "a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment" (SETAC [139], p. 3). The knowledge obtained from LCA studies is a valuable input to green manufacturing models.

Haasis [67] studied production planning and control of less emitting production systems. The methodologies used are based on dynamic programming, priority based heuristics and neural networks (machine learning).

Pirila [126] studied emission oriented production planning in the Finnish pulp and paper industry. The production planning model is a large multiple period linear program. Integration of environmental impacts within this model leads to alternative strategies, including process choices, recovery of waste products, etc.

Virtanen and Nilsson [158] studied the environmental impacts of paper recycling for different paper recycling scenarios (zero recycling, selective recycling, and maximum recycling). They used a life cycle model to establish inventory data of the inputs and outputs of the paper making process. A worksheet model, based on the paper-fiber balance of Western Europe then computes the waste streams, available reuse potentials and waste paper exchange between countries.

At this point, two issues remain to be resolved. First, LCA studies are still pretty complex and expensive. Second, the LCA data involve all sorts of environmental effects which should somehow be combined into a single environmental index in order to be useful in an OR decision model. The practical link between LCA and OR models provides a challenging research issue: how to design LCA studies that quickly yield relevant environmental impacts and how to combine these impacts meaningfully into inputs for OR models.

2.5 Environmental policy

In the previous sections, the focus was on environmental actions within the supply chain with the objective to control the amount of waste and the use of non-renewable inputs. In the next two sections, the focus will be on the damaging effects that inputs and outputs of the supply chain can have on the environment.

Once pollutants have left the supply chain, they are emitted to air, water or soil. In each of these environmental compartments chemical transformations take place, e.g. the formation of sulfuric acid from SO_2 in air, causing acid rain. Next, the pollutants are transported through media like air, surface water and groundwater. Most air pollutants are then deposited on soil or water and cause detrimental effects to the environment (e.g. nitrates formed in the air from NO_x cause eutrophication of surface water). Finally, the deposited pollutants lead to reduction and damage of the primary resources. From this description, it will be clear that the environmental problem can also be described as a chain (see Figure 2.1).

In recent years, environmental policy has shown some major shifts. First, it changed its focus from compartments (air, water, soil) to issues (acid rain, climate change). For example, in the Netherlands the following key problems are now the focus of environmental policy (see VROM [160]):

- Change of climate (global)
- Depletion of ozone layer (global)
- Smog (continental)
- Acidification (continental)
- Eutrophication (regional)
- Dispersion of toxic substances (regional)
- Drying out of soils (regional)
- Disposal of solid waste (local)
- Disturbance of the environment by noise or odour (local)

Secondly, traditional end-of-pipe abatement policies are gradually being replaced by an integrated approach. Table 2.1 shows the evolution in Dutch environmental policy according to Cramer [44] (p. 87).

Table 2.1: Development of Dutch environmental policy (Cramer [44])

Period	Characteristics
Seventies:	Approach to 'clear away' (end-of-pipe). Emphasis is on local problems, especially site decontamination of soil pollution;
Eighties:	Policy evolves towards prevention. Effort is on pollution control of regional problems (mainly water pollution);
Nineties:	The ideas of sustainable management and integral chain management develop. Policy becomes global oriented. The intention is to use an integrated approach that can cope with the transboundary issues of air pollution.

In Figure 2.4, the environmental chain shows the pressure of economic activities on the environment and society's response in terms of measures. These measures include traditional end-of-pipe techniques (e.g. flue gas desulfurization), new low waste technologies (e.g. low NO_x burners), decrease of production (e.g. energy conservation), mitigation (e.g. liming of acidified lakes) and adaptation (e.g. acid rain resistant tree species). A major challenge for environmental policy both at the local and the national level is to make an optimal selection of measures from a large set of options. It is here that OR can play a useful role (see Section 2.6). In order to enhance understanding of the (links in the) environmental chain, the different components of the chain are briefly discussed below.

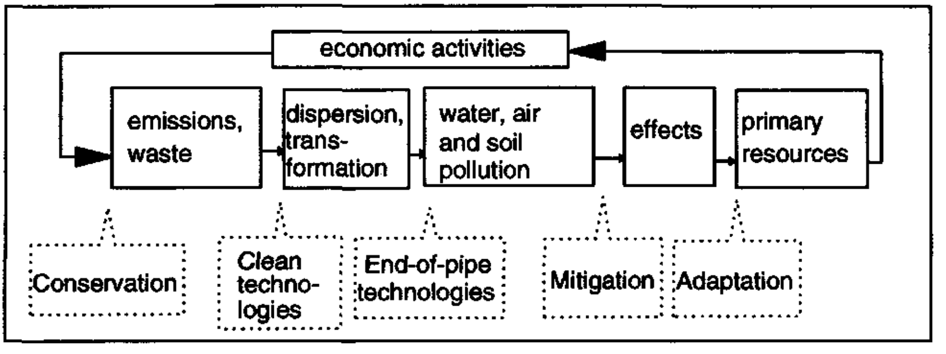


Figure 2.4: Environmental chain

Waste and emissions Broadly speaking, the three main sources of waste are agricultural waste, industrial waste and domestic waste (Kharbanda and Stallworthy [83]). For agricultural waste, the major environmental problems are eutrophication, acidification and use of pesticides. Industrial waste poses by far the biggest problem because of its nature and the vast variety of materials that have to be handled. Much industrial waste consists of hazardous chemicals, often highly toxic, that can damage the health of human beings and the quality of ecosystems. Domestic waste contains not only reusable materials such as glass, paper and food, but also an ever-increasing amount of hazardous waste such as mercury from batteries and PCBs in old TV sets. Consumers often claim to take into account the environment while shopping. However, domestic waste generation seems to be unaffected until now.

Dispersion The environmental effects of emissions and waste disposal depend largely on the distribution and movement of damaging components. The chemical behaviour of air pollutants varies considerably, while meteorological conditions determine the dispersion. In order to detect contamination and air pollution, remote geophysical techniques are increasingly being used to monitor the environment.

Water, air and soil pollution The location of disposal sites and incinerators has a large influence on the possible effects of waste disposal. The problem of locating these sites requires difficult pollution-cost trade-offs. Emissions to air and water are in most cases treated via end-of-pipe techniques. For some air pollutants international agreements on reduction of emissions have been reached in Europe (SO_2, NO_x, VOC) and North America.

Effects Environmental effects of emissions and waste disposal have been found in many species and ecosystems (e.g. fish damage due to acid rain, reduced crop growth due to enhanced ozone levels). Further, at very high levels of concentration some pollutants cause human health effects. Although reduction of the pollutant sources is most effective, in some cases actions are taken to mitigate the effects (e.g. liming of acidified lakes in Scandinavia). In recent years the effects of emissions on the environment have been studied in a new way. Rather than focusing on effects of a single pollutant on a single species, indicators of effects have been used. In 1986 the concept of *critical loads* for acidification has been introduced as the highest deposition of a compound that will not lead to long-term harmful effects on ecosystems (Nilsson [115]). In studies on climate change a similar concept was proposed by Swart [147]. This change in focus is in line with the trend towards issue-driven integrated environmental policy which was signalled before in Table 2.1.

Resources Some, certainly not all, pollutants affect the resources needed for production and consumption. Examples are the reduction of forest growth and fish populations. In cases where it would take a very long time to recover the quality of the environment adaptive measures have been taken. An example is plantation of acid rain resistant tree species in the so-called Black Triangle in Europe (Germany, Poland and the Czech Republic). Another example of adaptation can be found in several studies on climate change (e.g. changes in agricultural practice, see Parry et al. [122]).

Applications of OR can be found in the various parts of the environmental chain, some dating back to the 1980s. With the change in environmental policy from single pollutant/single effect policies to integrated policies on issues (climate, acid rain and the like) the demand for OR is growing. This is caused by both the larger number of options available to reduce environmental effects, and the increased complexity of systems and models. In the next section, a selection of OR work for the environmental chain is presented.

2.6 Integration of Operational Research in Environmental Management

In this section, some examples of the use of Operational Research for solving environmental problems or for environmental policy making are presented. Greenberg [64] surveys the use of mathematical programming models for environmental quality control to identify interesting research avenues in this area. The scope includes air, water, and land quality.

The scale of environmental problems has shifted over the last few decades from the local and regional level to a continental (acid rain) and global (climate change) level. An integral approach to environmental problems has become necessary in order to arrive at good preventive abatement measures.

As in Section 2.4, we classify the examples according to the shift from local end-of-pipe policies towards integrated policies in order to prevent environmental problems. Three categories are described: *local* orientation that deals with technical end-of-pipe solutions for e.g. soil pollution, emission control on a *regional* level and the rather recent *global* approach dealing with climate problems (integrated assessment).

2.6.1 Local orientation

Part of the environmental policy of a central government of a country concerns the decontamination of polluted soils. The source of this pollution is usually a *local* point e.g. a landfill site, a gas station or an industrial district. For each case of soil pollution, several clearance variants are known. Usually, the monitoring of decontamination projects will be decentralized. Operational Research can play a role in allocating a central budget to the local authorities so as to obtain the 'best' overall environmental effect, as described in Corbett et al. [40]. This case can be generalized to any problem to evaluate various budget allocation policies to combat some kind of environmental problem (see also Hordijk [72]). Corbett et al. [40] emphasize that the issue is not so much that the environmental effect measure be precise but rather that all regions agree on a reasonably accurate and easy-to-determine environmental measurement system for budget allocation purposes. The objective is to maximize the beneficial environmental effects of the selected projects, subject to *(i)* budget constraints for each region and the overall budget, *(ii)* storage limitations on the waste generated in each region, and *(iii)* labour supply conditions in each region. The resulting mixed integer programming model is too large to solve optimally. Therefore, the authors propose a two-step heuristic procedure:

1. Local authorities specify the maximum environmental effect they expect to achieve for different levels of budget allocated to them.
2. The central authority determines which budget allocation leads to the highest total environmental effect.

Technically, the information from the first step consists of a matrix containing the attainable environmental effects for each area and each budget allocation. This matrix can be transformed into an acyclic graph. The objective of the second step is then to find a path through the graph maximizing total cumulative environmental effect. This can be done using a dynamic programming recursion formula. The corresponding budget allocation can then be derived by backtracking via the optimal path.

This budget allocation approach can also be used for reduction of noise disturbances. Traditionally, the central government typically controlled the measures for noise disturbance. Recently, policy makers have advised decentralisation in order to give regions their own budgets and responsibility to reduce the disturbances (Vellekoop [156]). These budget allocation problems illustrate the usefulness of decomposition, a common approach in OR.

2.6.2 Regional orientation

We discuss three categories of mathematical models that deal with regional problems: *(i)* lake eutrophication models, *(ii)* non-point sediment pollution control models, and *(iii)* detection models.

Eutrophication

Eutrophication, the increased presence of nutrients, and its consequences has been one of the most serious lake water quality problems over the last decades. One of the major features of eutrophication is that although the consequences become manifest within the lake, the causes (increased use of nutrients) and most of the possible control measures have their origin in the region.

Models developed with the aim of analysing eutrophication can be classified into two groups: *(i)* dynamic simulation models to describe the phenomena (e.g. Orlob [118]), and *(ii)* optimization models with the objective to determine the 'optimal' combination of alternative control measures (e.g. Loucks et al. [100]).

Somlyódy and Wets [142] develop a framework for optimal design strategies for controlling water quality of eutrophic lakes. They combine descriptive simulation models and management optimization models. The first step of their method is to decompose the complex system into smaller, tractable units leading to a hierarchy of simulation models. This step is followed by aggregation, to preserve and integrate only those issues that are essential for the higher level of hierarchy. Only aggregate models are incorporated in an optimization model at the highest level of the hierarchy. This approach can be very useful in coping with complexity.

Nonpoint source pollution

Sediment deposition affects water quality. A major source of sediment deposition is soil erosion from cropland. This is called a nonpoint source of pollution because it is difficult to track discharges back to a specific source. Public officials must determine whether to implement uniform policies, or policies that implement abatement measures selectively. Bouzaher et al. [30] outline a model that can assist controlling agencies by revealing costs and pollution loads due to alternative selective and nonselective policies and can help local and regional environmental quality officers identify how and where selective actions can be taken in the most cost-effective manner. The controlling agency's problem can be viewed as a 0-1 knapsack problem with additional generalized upperboundary constraints. It has been solved using dynamic programming.

Detection

OR has been used to optimize monitoring networks in order to maximize the probability of detection in the face of uncertainty. Meyer and Brill [107] coupled a simulation model of contaminant transport and a facility location model to generate optimal locations for monitoring wells. Modak and Lohani [108] studied the problem of an optimal number and configuration of ambient air quality monitors given an acceptable level of uncertainty. Their approach is based on location models using spatial correlation analysis.

2.6.3 Global orientation

The primary reason for the shift from local and regional problems towards continental and global problems is the recognition of the fact that emissions in one country may affect environmental quality in other countries. In this paragraph we discuss a group of models dealing with acidification and a model dealing with the greenhouse effect.

Acidification

Acid rain is not a new phenomenon. According to Stam et al. [144], over 300 years ago an English nobleman already suggested the theory that sulphur originating from smoke by burning coal turns silver black and destroys iron and stone. Since the first World Conference on Environment and Human Development (Stockholm, 1972), efforts have intensified in order to avoid the negative impacts of sulphur oxide and nitrogen oxide pollution, especially at the local and regional level.

As early as 1980, Lesuis et al. [96] extended a classical economic Input-Output model for the Netherlands with energy and environmental sectors. The thus enlarged model has been put into an LP framework and used to explore various scenarios for the reduction of emissions of SO_2 and their effects on the Dutch national economy. But it is only in recent years that various mathematical models have been developed to cover the acidification process from the sources of emission to the impacts on the environment. These models emphasize the transboundary aspects of air pollution and embody optimization, simulation and often a combination of both. A review is given by Ellis [51].

One of the integrated assessment models is the RAINS (Regional Acidification INformation and Simulation) model (Alcamo et al. [6], Hordijk [72]). It is based on a set of submodels describing pollution generation and control, atmospheric transport and deposition, and environmental impacts (i.e. the processes in the environmental chain of Figure 2.4). RAINS (or its submodels) can be used as input to procedures for optimizing the reduction of emissions. These procedures can be based on linear programming with single or multiple objectives (Ellis [51]), nonlinear multiple criteria modelling (Stam et al. [144]) or stochastic programming (Batterman and Amann [16]). An example of the use of RAINS in its LP mode is presented by Amann et al. [8]. In this study the authors use linear optimization to arrive at a cost optimal solution for a European wide reduction of the emission of SO_2. Starting from maps of current deposition and critical loads for acid rain in Europe, a least cost solution is found to reduce the gap between deposition and critical loads. In recent international discussions on acid rain the results of optimization runs with the RAINS model have served as basis for the negotiations. The final Protocol on the reduction of SO_2 signed by 27 nations in June 1994 is largely based on one of these runs.

Climate Change

A rising amount of CO_2 in the earth's atmosphere can lead to an increasing absorption of heat radiation energy and consequently to an increase in temperature and a shift in wind and rainfall patterns. This is commonly referred to as the enhanced *greenhouse* effect. Not only carbon dioxide, but also N_2O, CH_4, H_2S and aerosols contribute to the global warming effect. The temperature increase could cause melting of the ice caps and consequently a rise in sea levels, which would be catastrophic for countries like the Netherlands. Eventually, ecosystems will be threatened.

One of the models built to gain insight into the greenhouse problem is IMAGE, an acronym for Integrated Model for the Assessment of the Greenhouse Effect (Alcamo [7]). The greenhouse problem is modelled by means of dynamic simulation based on non-stationary Markov chains.

IMAGE can be used as input for optimization routines for developing and improving climate change response strategies (Janssen et al. [79]). In order to cope with the limitations of pure optimization and the slowness of a large simulation model, a meta version of IMAGE was combined with a local search optimization of response strategies for CO_2 reduction.

2.7 Conclusions

The growing attention for environmental issues within the field of Operational Research is in concordance with some trends in society:

- the shift from corrective policies towards prevention (internalization);
- the expanding scope of environmental policy both in content and in area (scope).

These trends cause a natural opportunity for the interaction between OR and EM. However, issues like complexity, measurability and the social character of environmental problems may impose roadblocks to this interaction.

Our examples from literature exploring the interactions between Operational Research and Environmental Management are classified using a framework consisting of two approaches:

- the supply chain approach: integration of environmental issues in supply chain modelling
- the environmental chain approach: integration of Operational Research tools in Environmental Management.

Supply Chain

Within the supply chain, environmental actions can be taken in each link from raw materials to waste disposal. To classify examples of the incorporation of environmental issues, the shift from end-of-pipe correction to source-oriented prevention is used.

Examples of end-of-pipe waste management modelling have appeared in the OR literature for quite a long time. These models are mostly characterized by the strategic aspect of choosing locations for disposal units. The models have a close relation with traditional models. A new aspect in these models is the description of risk.

Recovery management can have a large impact on the supply chain. It affects production planning, inventory control and distribution. Integration with traditional planning and control models (e.g. MRP) is less obvious due to the uncertainties in time, quality and quantity of the supply of used products.

Preventive management requires an integrated approach towards environmental issues. There are at present very few attempts at using a 'from the cradle to the grave' modelling approach. Methods to assess environmental impact of products and processes appear to be essential to these models. The combination of life cycle analysis studies with OR models and techniques is a wide-open area of research.

Environmental Chain

Within the environmental chain, the production and consumption element is the cause of pollution. Other elements in the chain are the atmospheric processes and the environmental impact on soil, water, air and ecosystems. Within each of these elements, OR modelling has turned out to be useful.

The scale of environmental policy to control pollution has shifted from the local and regional level to a continental and global level. This shift has two consequences which both have influenced the use of OR. The first consequence is a more integrated approach to environmental policy and management, in which a manifold of abatement strategies is available. To make an optimal selection between these strategies, OR tools are increasingly used. A second consequence is that models describing these larger systems are much more complex. This can be seen as another cause for the increased demand for tools from OR.

Until recently, local problems like polluted sites and noise disturbance were typically handled at a central level. Nowadays, policy tends towards decentralization and allocation of budgets to local authorities. This development can be supported using the well-tested decomposition approach of Operational Research.

Models for regional problems like eutrophication have to overcome the typical complexity of these problems. An approach combining simulation and optimization has proved to be quite successful, especially when it is possible to decompose the complex system into smaller tractable units.

For global problems, we conclude that an integrated assessment model is the only way to cover the complex system of causes, emissions, transportation, effects and control policies. Optimization appears as a submodule of a larger modelling system. The added value of OR consists of the evaluation (efficiency) and improvement (effectiveness) of emission and waste reduction scenarios.

General conclusions

In general, we conclude that the first phase in the shift from corrective policy towards preventive policy generates a rather straightforward use of all kinds of Operational Research applications both in the supply chain approach and in the environmental chain approach.

The intermediate phase in this shift probably describes the actual state-of-the-art of exploring the interaction between OR and EM. More complicated and adapted models (and methods) are necessary to cope with recovery management in the supply chain approach and with regional problems in the environmental chain approach.

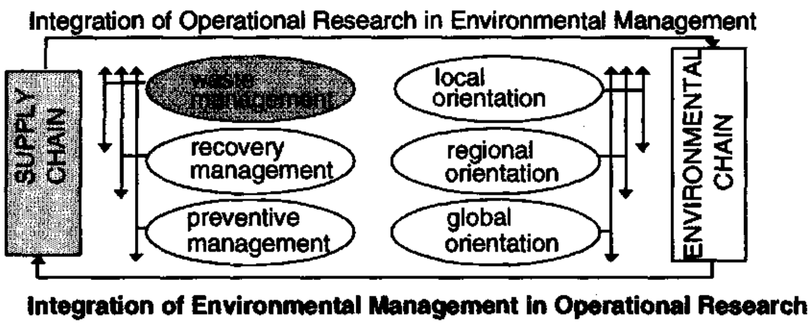
The final stage in the shift will probably be reached in the near future. OR has to integrate with related sciences to be able to use tools like life cycle analysis, economic input-output modelling and systems analysis. The integration of OR with these tools can already start on a simple level, such as applying linear programming modelling with life cycle analysis (Azapagic and Clift [11]) and building simple optimization models based on system analysis knowledge. In this thesis, we illustrate the possible integration of OR with Environmental Management tools in e.g. Chapter 5 (using linear programming in a life cycle analysis study), Chapter 6 (building an integral linear programming model based on results from systems analysis studies), and Chapter 7 (linking life cycle analysis with a network flow model).

Part II

Environmental issues in Operational Research applications: some illustrative examples

Chapter 3

Product and by-product flows



This chapter gives an illustrative example of integrating environmental issues in supply chain modelling through waste management.

Optimization approaches with respect to waste management focus on two problems: locating sites for the storage of waste (or by-products in general) and transporting the waste to the chosen destination in the best possible way. One of the characteristics of this type of problems is the close relation to traditional OR models on routing and location.

We consider the problem of how to design an efficient (minimum cost) distribution structure which simultaneously takes into account the location of plants and disposal sites, the coordination of the flow of materials between plants and customers and the flow of by-products between plants and disposal sites. The approach in this chapter is new as it combines product management with waste management. This simultaneous approach results in a non-trivial extension of the classical location model with a wide range of practical applications.

3.1 Introduction

3.1.1 Problem description

The classical location problem deals with the design of an 'optimal' distribution structure, based on a trade-off between fixed and variable costs. In the mathematical models used to analyse location problems, fixed costs are usually associated with opening plants and distribution centers, while variable costs arise from transportation of goods between plants, warehouses, and customers. Well-known extensions of the classical location model also take into account constraints on available resources like production lines, distribution centers, and transportation capability. Overviews of the broad literature on location theory are found in Francis et al. [60], or Brandeau and Chiu [32], among many others.

Here we consider a variant of the classical location problem, in which *(i)* potential locations for plants, *(ii)* potential locations for disposal units, and *(iii)* predetermined locations of customers are given. At the plants one single product is produced that has to be shipped to the customers in order to fulfil demands. Also a by-product (e.g. waste) is produced during the production process at the plants. This by-product has to be transported to waste disposal units (WDUs). Figure 3.1 gives a graphical representation of the location problem for products and by-products.

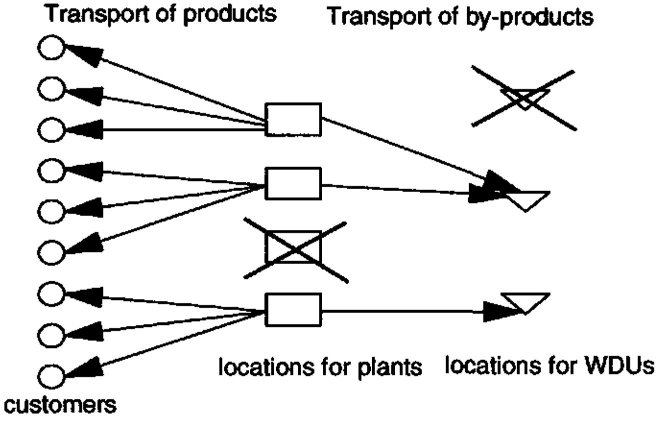


Figure 3.1: Product and by-product flows

The problem described here allows to study the economic consequences resulting from decisions on the location of plants and the transportation of products from plants to customers, as well as decisions on the location of waste disposal units and the transportation of by-products from plants to these units. This problem is not only interesting from an academic point of view. It appears in practice when considering reuse or recycling in trade and industry. Examples of application areas are:

Agriculture When breeding pigs for the food processing industry, a huge quantity of manure is generated. This manure causes serious environmental problems, since it pollutes air, water, and soil. It contributes to acidification, leaching of minerals, unacceptable nitrate concentrations, etc. Breeding farms transport the pigs to the food processing industries, and will have to dispose the manure to manure processing plants in the near future. These plants are still in an experimental phase, which makes a location study very relevant. In our problem description, the food processing industries can be considered as 'customers', the breeding farms as 'plants', and the manure processing plants as 'WDUs'.

Nuclear Power In some countries, nuclear power becomes an essential source of energy. Nuclear power plants have been and will be built near large energy-consuming industries. However, nuclear waste is hazardous and has to be stored at safe disposal sites. The distance between nuclear power plants and nuclear waste sites should be as short as possible due to the risk of accidents during transportation. On the other hand, industries are not willing to have these nuclear waste disposal sites in their neighbourhood. The location of (new) nuclear power plants and nuclear waste disposal sites has to be sorted out simultaneously, given the locations of the main energy consumers.

Packaging The responsibility to deal with product packaging shifts more and more from consumer to retailer. The retailer has to take back product packaging for reuse or collect the materials for industries that make valuable products from those materials. For example, a large consumer-electronic company sells TV-sets to its customers. The customers enjoy their new television and deliver the packaging materials to a collection center for the paper and board industry for recycling purposes. Although the distribution structure of this example differs slightly from the distribution structure of Figure 3.1, the approach will still be the same.

3.1.2 Contents

This chapter is organized as follows. Section 3.2 introduces the assumptions, notation and a general formulation of two alternative mathematical models for the problem described above. The first model formulation is an extended facility location problem (EFLP). This extension was not found in literature. The second model formulation is a flow path location problem (FPLP). It is a special case of the multi-level facility location problem. Section 3.3 reviews the literature on both the uncapacitated (UFPLP) and capacitated

(CFPLP) version of this model. Sections 3.4 – 3.6 deal with the uncapacitated extended location model (UEFLP). We analyse several lower and upper bounds that can be obtained for this problem, and carry out a computational study to test the effectiveness of these bounds. Sections 3.7 – 3.9 deal with the capacitated extended facility location model (CEFLP). We introduce the basic form of the model, analyse the linear programming relaxation strengthened by well-known valid inequalities and compare these bounds with lower bounds for the capacitated flow path location problem (CFPLP). Lagrangean relaxation is also discussed in Section 3.7. Round-off heuristics and Lagrangean heuristics to obtain upper bounds for the (CEFLP) problem are described in Section 3.8. Computational results using the approaches in the previous sections are presented in Section 3.9. Finally, Section 3.10 provides some conclusions.

3.2 Problem formulations

In the mathematical formulation of the location problem for products and by-products, we impose the following assumptions:

- Customer demand for the single product considered in the model is known, and its volume is assumed to be constant over the (single-period) planning horizon,
- Associated with each potential location of a plant or WDU fixed costs can be identified (e.g. for opening or keeping open a plant or WDU),
- Variable costs relate to the transportation of goods flows between plants and customers, and to the transportation of by-product flows from the plants to the WDUs. Variable costs are assumed to be proportional to the transported amount of flow,
- Each plant generates a quantity of by-product, proportional to the total production quantity.

The following notation is used:

Index sets:

$I = \{1,\dots,m\}$ = Set of plants
$J = \{1,\dots,n\}$ = Set of customers
$K = \{1,\dots,p\}$ = Set of waste disposal units

Parameters:

a_{ij} = product transportation costs from plant i to customer j (per unit of flow)
a^w_{ik} = by-product transportation costs from plant i to WDU k (per unit of flow)

d_j = product demand from customer j
f_i = fixed costs associated with plant i
f_k^w = fixed costs associated with WDU k
s_i = capacity of plant i
s_k^w = capacity of WDU k
e_i = by-product at plant i (as a fraction of the total production)
w_i = upper bound on by-product flow from plant i;
$w_i = e_i \sum_{j\in J} d_j$

The first model formulation uses the following decision variables:

Decision variables:

X_{ij} = flow from plant i to customer j (in units of flow)
X_{ik}^w = by-product flow from plant i to WDU k (in units of flow)

$$Y_i = \begin{cases} 1 & \text{if plant } i \text{ is open} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_k^w = \begin{cases} 1 & \text{if WDU } k \text{ is open} \\ 0 & \text{otherwise} \end{cases}$$

The extended facility location problem (EFLP) can be formulated in very general terms, such that it holds for the uncapacitated (UEFLP) problem and the capacitated (CEFLP) problem:

$$z_{EFLP} = \min \sum_{i\in I}\sum_{j\in J} a_{ij}X_{ij} + \sum_{i\in I} f_iY_i + \sum_{i\in I}\sum_{k\in K} a_{ik}^w X_{ik}^w + \sum_{k\in K} f_k^w Y_k^w \tag{3.1}$$

$$\text{subject to} \quad \sum_{i\in I} X_{ij} = d_j \qquad j \in J \tag{3.2}$$

$$\sum_{j\in J} e_i X_{ij} = \sum_{k\in K} X_{ik}^w \qquad i \in I \tag{3.3}$$

$$X_{ij} \le \min\{d_j, s_i\} Y_i \qquad i \in I, j \in J \tag{3.4}$$

$$X_{ik}^w \le \min\{w_i, s_k\} Y_k^w \qquad i \in I, k \in K \tag{3.5}$$

$$\sum_{j\in J} X_{ij} \le \min\{\sum_{j\in J} d_j, s_i\} Y_i \qquad i \in I \tag{3.6}$$

$$\sum_{i\in I} X_{ik}^w \le \min\{\sum_{i\in I} w_i, s_k^w\} Y_k^w \qquad k \in K \tag{3.7}$$

$$Y_i, Y_k^w \in \{0,1\} \qquad i \in I, k \in K \tag{3.8}$$

$$X_{ij}, X_{ik}^w \ge 0 \qquad i \in I, j \in J, k \in K \tag{3.9}$$

The objective (3.1) is to minimize the sum of total transportation costs and total fixed costs. Constraints (3.2) state that all customer demand must be satisfied. Constraints (3.3) are the flow balancing constraints, stating that all by-products or waste resulting from production be disposed of at a WDU. Each plant may generate a different waste percentage, due to technical and/or other specific characteristics of the plant (size, age, environment).

Constraints (3.4) state that total flow between plant i and customer j can never exceed the minimum of customer j's demand and the capacity at plant i. Constraints (3.5) state that the total by-product flow between plant i and WDU k can never be larger than the minimum of the capacity at WDU k, and the maximum amount of by-products or waste generated at plant i ($w_i \stackrel{def}{=} e_i \sum_{j \in J} d_j$). In the *uncapacitated* (UEFLP) model, these constraints are necessary to link the continuous flow variables with the integer plant and WDU variables. In the *capacitated* (CEFLP) model, these constraints are used as valid inequalities to tighten linear programming relaxations. These valid-inequalities are based on previous work for the single-level plant location problem (Davis and Ray [46]). Constraints (3.6) and (3.7) are the capacity constraints for plants and WDUs, ensuring that no plant or WDU produces or disposes more than its capacity. In the uncapacitated (UEFLP) model (with $s_i = s_k^w = \infty$), these constraints can be used as valid inequalities to tighten linear programming relaxations. Furthermore, constraints (3.8) are the integrality constraints on the Y and Y^w variables, and constraints (3.9) are the non-negativity constraints on the flows.

The second model formulation relies on the usual flow path formulation for the two-level uncapacitated facility location problem (e.g. Barros [13]). Under the set of assumptions stated above, this flow path location problem (FPLP) can be formulated as a mixed integer linear program, using the following decision variables:

Decision variables:

X_{ijk} = the fraction of customer j's demand supplied from plant i, with the corresponding by-product processed (or waste disposed of) at WDU k

$$Y_i = \begin{cases} 1 & \text{if plant } i \text{ is open} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_k^w = \begin{cases} 1 & \text{if WDU } k \text{ is open} \\ 0 & \text{otherwise} \end{cases}$$

Mathematically, (FPLP) is formulated as follows:

$$z_{FPLP} = \min \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} c_{ijk} X_{ijk} + \sum_{i \in I} f_i Y_i + \sum_{k \in K} f_k^w Y_k^w \tag{3.10}$$

$$\text{subject to} \quad \sum_{i \in I} \sum_{k \in K} X_{ijk} = 1 \qquad j \in J \tag{3.11}$$

$$\sum_{k \in K} X_{ijk} \leq Y_i \qquad i \in I, j \in J \tag{3.12}$$

$$\sum_{i \in I} X_{ijk} \leq Y_k^w \qquad j \in J, k \in K \tag{3.13}$$

$$\sum_{j \in J} \sum_{k \in K} d_j X_{ijk} \leq s_i Y_i \qquad i \in I \tag{3.14}$$

$$\sum_{i \in I} \sum_{j \in J} d_j e_i X_{ijk} \leq s_k^w Y_k^w \qquad k \in K \tag{3.15}$$

$$Y_i, Y_k^w \in \{0,1\} \qquad i \in I, k \in K \tag{3.16}$$

$$0 \leq X_{ijk} \leq 1 \qquad i \in I, j \in J, k \in K \tag{3.17}$$

In the objective function (3.10), which expresses that we are searching for a minimum cost solution, the constant c_{ijk} is the variable cost corresponding to the production of customer j's demand at plant i, and shipping the generated by-product to WDU k. Thus, $c_{ijk} = (a_{ij} + a_{ik}^w \cdot e_i) \cdot d_j$. Constraints (3.11) ensure that customer demand is fulfilled. Constraints (3.12) ensure that no flow exists between plant i, customer j, and any of the WDUs k, unless plant i is open. Constraints (3.13) are analogous to (3.12). These inequalities are introduced by Ro and Tcha [131] in their paper on the uncapacitated two-level location problem. They can be replaced by the much weaker set of inequalities, proposed by Tcha and Lee [150]:

$$X_{ijk} \leq Y_i$$

$$X_{ijk} \leq Y_k^w$$

Since the results for the strong formulation outrank those for the weak formulation, we will not discuss the weak formulation any further. Constraints (3.14) and (3.15) are the capacity constraints for plants and WDUs, ensuring that no plant or WDU produces or disposes more than its capacity. Finally, constraints (3.16) state that location variables are binary, and constraints (3.17) specify lower and upper bounds on the flow variables.

Note that this model is a general representation for both the uncapacitated and the capacitated flow path formulation. The *uncapacitated* flow path location problem (UFPLP) has infinite capacities ($s_i = s_k^w = \infty$). In that case, constraints (3.14) and (3.15) become redundant. In the *capacitated* flow path formulation (CFPLP), constraints (3.12) and (3.13) can be removed. However, they serve as valid inequalities to tighten linear programming relaxations.

To the best of our knowledge no literature exists on solution procedures and computational behaviour of model formulations from (EFLP). The flow path formulation (FPLP) of the location problem considered here can be related to the two-level facility location model. In the next section we briefly review the literature on this problem.

3.3 The two-level facility location model

The two-level facility location problem is NP-hard, which follows directly from the fact that the single level case is already NP-hard (see Cornuejols et al. [42]). However, medium-sized problems are still tractable from a computational point of view. A number of contributions exist on (special cases of) the two-level uncapacitated facility location model. Kaufman et al. [81] were among the first to study this model. The authors propose a branch-and-bound procedure where lower bounds are determined by solving the LP-relaxation of the model, and upper bounds are obtained by an extension of Khumawala's [84] heuristic for the single level uncapacitated facility location problem. The latter procedure is based on rounding-off non-integral variables in the solution to the LP-relaxation. Kaufman et al. were able to derive solutions for problems with up to 10 plants (first level in the distribution structure), 15–40 warehouses (second level in the distribution structure), and 50 customers. Ro and Tcha [131] consider a special case of the two-level facility location problem, in which warehouses are coupled with plants, in the sense that (a pre-specified set of) warehouses can be opened only when a (pre-specified) plant is opened. This special structure allows the authors to tighten lower bounds and to improve the overall performance of the Kaufman et al. procedure. The paper reports optimal solutions for problems with up to 10 plants, 20 warehouses, and 50 customers. Tcha and Lee [150] present computational work on an extension of the dual adjustment procedure of Erlenkotter [53] for a weaker formulation of the multi-level uncapacitated facility location problem, replacing constraints (3.12) by $X_{ijk} \leq Y_i$ (and similarly for constraints (3.13)). The resulting computation times are relatively high when compared to the results obtained by Ro and Tcha [131]. Gao and Robinson [62] present an alternative model formulation, the two echelon facility location problem. This model formulation differs from the one studied here, in that it does not account for fixed WDU opening costs at the second level, while it does account for fixed transportation costs between plants and WDUs. On a large mainframe computer their code succeeds in solving problems with up to 35 customers, and up to 25 plants and WDUs. Barros [13] discusses linear programming and Lagrangean relaxations as well as heuristics for a generalization of both the two-level and the two-echelon uncapacitated facility location problem. Computational results from this study indicate that extensions of successful methods for the one-level uncapacitated facility location problem, such as dual adjustment methods and greedy heuristics, appear to perform poorly for the two-level problem.

The two-level capacitated facility location problem is still very hard to solve. Early results by Aardal [1] indicate the importance of deriving valid inequalities for this problem.

3.4 Lower bounds for the uncapacitated location model

We analyse two lower bounding techniques for the uncapacitated location problem for products and by-products. The first one is based on the *linear programming relaxation* of the earlier stated model formulation (EFLP). The linear programming relaxation is denoted by LP(UEFLP). The second one is based on *Lagrangean relaxation.* We apply Lagrangean relaxation to the flow-balancing constraints (3.3), yielding the following Lagrangean problem LR(UEFLP):

$$\begin{aligned} z_{LR(UEFLP)}(\lambda) = \min \quad & \sum_{i\in I}\sum_{j\in J} a_{ij}X_{ij} + \sum_{i\in I} f_iY_i + \sum_{i\in I}\sum_{k\in K} a^w_{ik}X^w_{ik} \\ & + \sum_{k\in K} f^w_kY^w_k + \sum_{i\in I}\lambda_i(\sum_{j\in J} e_iX_{ij} - \sum_{k\in K} X^w_{ik}) \qquad (3.18) \\ \text{subject to} \quad & (3.2), (3.4), (3.5), (3.6), (3.7), (3.8) \text{ and } (3.9) \end{aligned}$$

where $\lambda = (\lambda_1, \ldots, \lambda_m)$ is the vector of Lagrangean multipliers corresponding to (3.3).

This Lagrangean problem LR(UEFLP) decomposes into the subproblems LR_1 and LR_2 as stated below:

$$\begin{aligned} z_{LR_1(UEFLP)}(\lambda) = \min \quad & \sum_{i\in I}\sum_{j\in J}(a_{ij} + \lambda_ie_i)X_{ij} + \sum_{i\in I} f_iY_i & & (3.19) \\ \text{subject to} \quad & \sum_{i\in I} X_{ij} = d_j & j \in J \quad & (3.20) \\ & X_{ij} \le d_jY_i & i \in I, j \in J \quad & (3.21) \\ & \sum_{j\in J} X_{ij} \le \sum_{j\in J} d_jY_i & i \in I \quad & (3.22) \\ & Y_i \in \{0,1\} & i \in I \quad & (3.23) \\ & X_{ij} \ge 0 & i \in I, j \in J \quad & (3.24) \end{aligned}$$

$$\begin{aligned} z_{LR_2(UEFLP)}(\lambda) = \min \quad & \sum_{i\in I}\sum_{k\in K}(a^w_{ik} - \lambda_i)X^w_{ik} + \sum_{k\in K} f_kY^w_k & & (3.25) \\ \text{subject to} \quad & X^w_{ik} \le w_iY^w_k & i \in I, k \in K \quad & (3.26) \\ & \sum_{i\in I} X^w_{ik} \le \sum_{i\in I} w_iY^w_k & k \in K \quad & (3.27) \\ & Y^w_k \in \{0,1\} & k \in K \quad & (3.28) \\ & X^w_{ik} \ge 0 & i \in I, k \in K \quad & (3.29) \end{aligned}$$

LR_1(UEFLP) is a single level uncapacitated facility location problem, which can be solved to optimality by DUALOC (Erlenkotter [53]). In this procedure, dual-ascent is combined with enumerative search, leading to an algorithm that is successful in solving large problem instances to optimality.

LR_2(UEFLP) is an optimization problem that can be solved efficiently, using the following simple inspection rule:

Inspection Rule (IR):

$$Y_k^{w*} = \begin{cases} 1 & \text{if } \bar{c}_k^w(\lambda) \leq 0 \\ 0 & \text{otherwise} \end{cases} \qquad k \in K$$

$$X_{ik}^{w*} = \begin{cases} w_i & \text{if } \bar{c}_{ik}^w(\lambda) < 0 \text{ and } Y_k^w = 1 \\ 0 & \text{otherwise} \end{cases} \qquad i \in I, k \in K$$

where

$$\bar{c}_{ik}^w(\lambda) \stackrel{def}{=} (a_{ik}^w - \lambda_i) \text{ and } \bar{c}_k^w(\lambda) \stackrel{def}{=} f_k^w - \textstyle\sum_{i \in I} w_i \cdot \max\{0, -\bar{c}_{ik}^w(\lambda)\}.$$

It is obvious that Y_k^{w*} and X_{ik}^{w*} are feasible. This solution is also optimal, since there exist dual variables that are feasible for the dual problem of the linear relaxation of LR$_2$(UEFLP), and for which the Complementary Slackness Theorem for linear programs holds.

It holds that $\max_\lambda z_{LR(UEFLP)}(\lambda) \geq z_{LP(UEFLP)}$, since the integrality property (Geoffrion [63]) does not hold for the single level uncapacitated facility location problem LR$_1$(UEFLP).

The complete Lagrangean relaxation procedure can now be summarized as follows:

Lagrangean relaxation procedure:

Initialisation:	Set dual multipliers $\lambda = (\lambda_1, \ldots, \lambda_m)$ equal to zero.
Step 1:	Solve LR$_1$(UEFLP) using DUALOC and LR$_2$(UEFLP) using IR.
Step 2:	If convergence conditions are satisfied, then STOP, otherwise update dual multipliers λ using the well-known subgradient optimization procedure (see Fisher [57]), and return to Step 1.

We have chosen to implement the subgradient procedure since implementation is easy, and since the subgradient procedure has shown to be very robust in a wide range of applications (see Fisher [57]). Computational results (see Section 3.6) show that it performs quite well here too.

In order to improve upon the above-mentioned lower bounding procedures, polyhedral techniques could also be used. For the uncapacitated extended location model, the lower bounding procedures perform well enough. We analyse the improvements of adding specific valid inequalities to the formulations (CEFLP) and (CFPLP) for the capacitated location model in section 3.7.

3.5 Upper bounds for the uncapacitated location model

Solving the location problem for products and by-products to optimality using enumerative procedures may become very time consuming for larger sized problem instances.

In order to overcome this difficulty, we have chosen to implement heuristic procedures. Although these procedures do not guarantee a final optimal solution to the problem, they generate good quality solutions within a reasonable amount of time. The following *construction* heuristics will be described: *(i)* Linear programming round-off heuristic (Section 3.5.1), *(ii)* Sequential facility location heuristic (Section 3.5.2), *(iii)* Cost savings heuristics (Section 3.5.3). In addition, an *improvement* heuristic will be discussed briefly in Section 3.5.4.

3.5.1 Linear programming round-off heuristic

A simple way to generate feasible solutions is to round the solution to the linear programming relaxation in a suitable way. Our round-off heuristic (RO) is summarized as follows:

Heuristic RO:

Initialisation:	Solve LP(UEFLP) and denote its solution by $(\overline{X}, \overline{X}^w, \overline{Y}, \overline{Y}^w)$.
Step 1:	Set all fractional variables $\overline{Y}$ and $\overline{Y}^w$ equal to one.
Step 2:	Compute for each customer-plant-WDU path the total transportation costs defined by c_{ijk}. Determine for each customer j a plant i^* for which $\overline{Y}_{i^*} = 1$ and a WDU k^* for which $\overline{Y}^w_{k^*} = 1$, such that total transportation costs are minimized, i.e. $c_{i^*,j,k^*} = \min_{i\in I,\, k\in K}\{c_{ijk} \mid \overline{Y}_i = 1 \text{ and } \overline{Y}^w_k = 1\}$.
Step 3:	Set $\overline{X}_{i^*,j} = d_j$ and $\overline{X}^w_{i^*,k^*} = e_{i^*} \cdot d_j$ and compute costs z_{RO} corresponding to the solution.

3.5.2 Sequential facility location heuristic

The sequential facility location heuristic (SF) is based upon sequentially solving two single level uncapacitated facility location problems. The first of them is given by $\text{LR}_1(\text{UEFLP})$, whereas the second can be considered as an extension of $\text{LR}_2(\text{UEFLP})$ (LR_2^E), formulated as:

$$z_{LR_2^E(UEFLP)}(\lambda) = \min \quad \sum_{i\in I}\sum_{k\in K}(a^w_{ik} - \lambda_i)X^w_{ik} + \sum_{k\in K} f_k Y^w_k \tag{3.30}$$

$$\text{subject to} \quad X^w_{ik} \le E_i Y^w_k \qquad i \in I, k \in K \tag{3.31}$$

$$\sum_{i\in I} X^w_{ik} \le \sum_{i\in I} w_i Y^w_k \qquad k \in K \tag{3.32}$$

$$\sum_{k\in K} X^w_{ik} = E_i \qquad i \in I \tag{3.33}$$

$$Y_k^w \in \{0,1\} \qquad k \in K \qquad (3.34)$$

$$X_{ik}^w \geq 0 \qquad i \in I, k \in K \qquad (3.35)$$

where E_i is an exogenous variable obtained from the solution to LR_1(UEFLP) and denoting the generated by-product at plant i, i.e. $E_i \stackrel{def}{=} e_i \sum_{j \in J} X_{ij}$. The reader may verify that sequentially solving LR_1 and LR_2^E yields a feasible solution to our location problem.

The heuristic is iteratively applied within the subgradient optimization procedure with different values for the dual cost multipliers λ, in order to slightly perturb the cost coefficients in the objective function.

Heuristic SF:

Initialisation:	Obtain a set of dual cost multipliers λ from the subgradient optimization procedure.
Step 1:	Solve LR_1(UEFLP) using DUALOC and denote its solution by $(\overline{X}, \overline{Y})$.
Step 2:	Compute $E_i = e_i \sum_{j \in J} \overline{X}_{ij}$.
Step 3:	Solve LR_2^E(UEFLP) using DUALOC and denote its solution by $(\overline{X}^w, \overline{Y}^w)$. Compute costs z_{SF} corresponding to the $(\overline{X}, \overline{X}^w, \overline{Y}, \overline{Y}^w)$ solution.

In the computational experiments, the upper bounding heuristic SF is executed after every 10 iterations of the lagrangean relaxation procedure.

Remark: Besides the iterative application of SF within a subgradient procedure, we also experimented with a *single-pass* version of it, in which all dual cost multipliers are set to zero. The solution obtained by this approach is denoted by z_{1SF}.

3.5.3 Cost savings heuristics

The greedy heuristics proposed here generate upper bounds to the solutions of (UEFLP). They rely upon earlier work for the single level uncapacitated facility location problem by Kuehn and Hamburger [92], and Feldman et al. [55]. The idea behind these heuristics is quite simple: at each iteration plants and/or WDUs are opened (ADDED) or closed (DROPPED) based on marginal cost savings, until no further cost savings are possible. Four different variants of this principle have been implemented. The first of them, denoted by CS_1, is summarized as follows:

Heuristic CS$_1$ (ADD plants and WDUs):

Initialisation:	Compute the costs associated with satisfying demand for all customers by a single plant-WDU combination. Open the plant and WDU for which total costs are minimal.
Step 1:	Open either one plant i', or one WDU k', depending on the largest marginal cost savings (to be defined below). If no cost savings are possible, then go to Step 2. Otherwise adapt (by-product) flows (in the way described below) and repeat Step 1.
Step 2:	Compute total costs z_{CS_1} and STOP.

In order to formally define the marginal cost savings in Step 1, we introduce I_0 as the set of closed plants, and I_1 as the set of open plants in the current solution. Similarly, K_0 (K_1) is the set of closed (open) WDUs. For all $i \in I_0$ check whether

$$\min_{k \in K_1} c_{i,j,k} \leq c_{i_c(j),j,k_c(j)} \qquad (*)$$

where $i_c(j) \in I_1$ ($k_c(j) \in K_1$) is the plant (WDU) customer j is currently assigned to. The cost function c_{ijk} is defined as in model formulation (FPLP). All customers j for which (*) holds are stored in the set S_i. The marginal cost savings for opening plant i ($mcsp_i$) are now defined as:

$$mcsp_i \stackrel{def}{=} \sum_{j \in S_i} (c_{i_c(j),j,k_c(j)} - \min_{k \in K_1} c_{i,j,k}) - f_i$$

Analogous to the computations of $mcsp_i$ for $i \in I_0$, marginal cost savings for WDUs ($mcsw_k$) can be computed for $k \in K_0$. Now, let $i' = \text{argmax}\{mcsp_i | i \in I_0\}$ and $k' = \text{argmax}\{mcsw_k | \, k \in K_0\}$. If both $mcsp_{i'} < 0$ and $mcsw_{k'} < 0$ the heuristic is halted since no local improvements (cost savings) are possible. Otherwise, either i' or k' is opened, depending on the largest marginal costs savings. Suppose i' is opened. Then, assign all customers $j \in S_{i'}$ from $i_c(j)$ to i', and reroute by-product flows running from $i_c(j)$ to $k_c(j)$ now from i' to the WDU with the largest cost savings, i.e. to $\text{argmin}\{c_{i',j,k} | k \in K_1\}$. Finally, adapt sets I_0 and I_1.

The three other costs savings heuristics rely on the same arguments as CS$_1$ but differ slightly with respect to opening and closing rules for plants and warehouses. These differences are listed below:

- Costs saving heuristic CS$_2$ (ADD plants and DROP WDUs) initially starts out with *one* plant open, and *all* WDUs open. It tries to *increase* the number of open plants, while *decreasing* the number of open WDUs, until no further costs savings are possible,

- Costs saving heuristic CS$_3$ (DROP plants and ADD WDUs) starts out with *all* plants open and *one* WDU open, and tries to *close* plants and *open* WDUs based on marginal costs arguments,

- Costs saving heuristic CS_4 (DROP plants and WDUs) starts out with *all* plants and WDUs open, and tries to *close* plants and WDUs based on marginal costs arguments.

3.5.4 Improvement heuristic

The improvement heuristic (IH) is applied to the solution obtained by the aforementioned heuristics. The idea behind IH relies on the cost savings heuristics, in the sense that plants and/or WDUs are opened (ADDED) and closed (DROPPED) based on cost savings arguments. If no local improvements (cost savings) are possible anymore, the heuristic is halted. This improvement heuristic is based on the BUMP and SHIFT routine of Kuehn and Hamburger [92]. In what follows we denote the value of the solution obtained by applying IH on a solution $z_{(.)}$ by $z_{(.)^+}$. Thus, for example, z_{RO^+} is the value of the solution obtained by applying IH to the RO solution.

3.6 Computational results for the uncapacitated location model

The quality of the proposed lower and upper bounding procedures is tested on a set of 108 problems. These problems originate from the publicly accessible library by Beasley [18] for the single level capacitated facility location problem. We have adapted problems identified in the library by category IV, VIII, and XI to the two level location problem. In these adapted datasets potential locations of plants and WDUs are generated randomly in an Euclidian square. For each plant-WDU combination by-product transportation costs are set to be proportional to the corresponding Euclidian distance. Other adaptations are made for the following four problem characteristics: *(i)* problem dimension, *(ii)* fixed costs related to plants, *(iii)* fixed costs related to WDUs, and *(iv)* waste percentages (taken from a uniform distribution). Tables 3.1 and 3.2 specify the range over which we vary the data corresponding to each of the four characteristics. For each of the nine possible parameter combinations of Table 3.1 we consider four different plant opening costs and three different WDU opening costs, depending on the magnitude of plant opening costs. The relation between fixed plant opening costs and fixed WDU opening costs is found in Table 3.2.

Table 3.1: Test problem generation

	Low (L)	Medium (M)	High (H)
problem dimension (m, n, p)	$(16, 50, 10)$	$(25, 50, 10)$	$(50, 50, 20)$
by-product percentages	10–20%	10–50%	50–100%

Table 3.2: Relation between fixed costs

		WDU opening costs ($)		
plant opening costs ($)		Low (L)	Medium (M)	High (H)
7,500	(Low (L))	2,500	8,000	15,000
12,500	(Medium (M))	4,000	15,000	25,000
17,500	(High (H))	5,500	15,000	35,000
25,000	(Big (B))	8,000	25,000	50,000

As already mentioned, the total number of problem instances that results from all parameter combinations is $9 \times 12 = 108$. The lower and upper bounding procedures discussed in Sections 3.4 and 3.5 are applied to these problem instances on a VAX/VMS V5.4 computer. For lower bounding and upper bounding procedures in which a linear program is solved, we use LINDO (Schrage [138]).

Table 3.3 (Table 3.4) presents an overview of the quality (required CPU-time) of the solution procedures. In order to investigate the influence of each of the four problem characteristics (problem size, fixed plant opening costs, fixed WDU opening costs, and waste percentage) on the overall performance of the solution procedures, we show aggregated results for each of the characteristics. For example, the data shown in rows 3–5 of the tables correspond to the (average) quality of the solutions for problem dimensions identified by L, M, and H, when aggregated over the three other problem characteristics (fixed plant opening costs, fixed WDU opening costs, and waste percentages). Average results are shown in the last row of the tables. Results for the lower bounding procedures are shown in column 2 (LP-relaxation LP(UEFLP)) and column 3 (Lagrangean-relaxation LR(UEFLP)) respectively. Results on the upper bounding procedures are shown in column 4 (Linear programming round-off heuristic RO) to column 10 (Cost savings heuristic CS_2). The solutions are compared to the optimal solution z_{UEFLP}, which is obtained by a standard branch-and-bound procedure. [1] In order to measure the quality of the procedures we define for each problem instance the (normalized) deviation between the value of the bounds and the value of the optimal solution. For lower bounds the quality is measured as $\delta z_{LB} = \dfrac{z_{opt} - z_{(.)}}{z_{opt}}$, where z_{opt} is the value of the optimal solution and $z_{(.)}$ is the value corresponding to lower bounding procedure (.). For upper bounds the quality is measured as $\delta z_{UB} = \dfrac{z_{(.)} - z_{opt}}{z_{opt}}$, where z_{opt} is the value of the optimal solution and $z_{(.)}$ is the value corresponding to upper bounding procedure (.).

[1] Except for instances with high problem dimension (H), where branch-and-bound turns out to be too time and memory consuming. Therefore, the quality of the solution for this problem category is related to the *best known* solution, rather than to the optimal solution.

Table 3.3: Quality of lower and upper bounding procedures for the uncapacitated location problem (in percentages)

	δz_{LP}	δz_{LR}	δz_{RO}	δz^+_{RO}	δz_{1SF}	δz^+_{1SF}	δz_{SF}	δz^+_{SF}	δz_{CS_2}
data aggregated according to problem dimension:									
L	2.65	3.23	1.64	0.17	8.64	0.89	1.35	0.16	0.01
M	3.53	3.92	6.70	0.26	9.02	0.46	1.11	0.33	0.39
H	4.11	4.51	3.26	0.23	12.07	2.02	1.62	0.13	0.07
data aggregated according to fixed plant opening costs:									
L	3.07	3.70	2.30	0.23	7.15	0.27	1.22	0.19	0.09
M	3.42	3.83	2.58	0.13	9.00	1.55	1.52	0.15	0.18
H	3.48	3.97	5.12	0.20	11.84	1.16	1.32	0.17	0.19
B	3.77	4.04	5.47	0.32	11.65	1.52	1.38	0.31	0.17
data aggregated according to fixed WDU opening costs									
L	1.48	1.77	1.03	0.13	9.20	0.84	0.86	0.13	0.09
M	3.43	3.94	3.78	0.31	9.90	1.24	1.40	0.25	0.17
H	5.39	5.96	6.80	0.22	10.62	1.29	1.83	0.24	0.21
data aggregated according to waste percentage									
L	3.60	3.75	4.74	0.20	4.62	0.83	0.82	0.16	0.24
M	3.74	4.33	4.83	0.19	8.58	1.04	0.99	0.26	0.13
H	2.96	3.58	2.04	0.27	16.52	1.50	2.28	0.20	0.10
av.	3.43	3.89	3.87	0.22	9.91	1.01	1.36	0.21	0.16

LP = linear programming relaxation of (UEFLP)
LR = Lagrangean relaxation (Section 3.4)
RO = linear programming round-off heuristic (Section 3.5.1)
1SF = single pass sequential facility location heuristic (Section 3.5.2)
SF = sequential facility location heuristic (Section 3.5.2)
CS_2 = cost savings heuristic 2 (ADD plants and DROP WDUs), (Section 3.5.3)
$(.)^+$ = heuristic (.) with improvement heuristic IH (Section 3.5.4)

Table 3.4 contains average CPU-times in seconds. It should be noted that *(i)* CPU-times for the RO^+, $1SF^+$, and SF^+ heuristics *do* include CPU-times for RO, 1SF, and SF respectively, and *(ii)* CPU-times for the heuristics SF, and SF^+ do *not* include CPU-times for computing the lower bound $z_{LR(UEFLP)}$.

Table 3.4: CPU times t for lower and upper bounding procedures (in seconds)

	t_{LP}	t_{LR}	t_{RO}	t^+_{RO}	t_{1SF}	t^+_{1SF}	t_{SF}	t^+_{SF}	t_{CS_2}
data aggregated according to problem dimension									
L	13.5	26.5	13.5	16.8	0.5	4.4	5.3	9.2	4.3
M	34.8	28.0	34.8	43.7	0.6	10.7	5.6	15.7	7.8
H	146.8	36.5	146.8	170.0	0.7	21.1	7.3	27.7	36.9
data aggregated according to fixed plant opening costs									
L	56.0	30.0	56.0	79.8	0.6	19.9	6.0	25.3	22.8
M	59.5	30.0	59.5	68.3	0.6	12.6	6.0	18.0	15.9
H	59.1	30.0	59.1	67.6	0.6	8.6	6.0	14.0	14.1
B	85.6	31.0	85.6	91.6	0.6	7.2	6.2	12.8	12.4
data aggregated according to fixed WDU opening costs									
L	64.3	30.0	64.3	76.5	0.6	13.3	6.0	18.7	19.9
M	73.7	30.5	73.7	86.9	0.6	12.4	6.1	17.9	15.6
H	57.1	30.0	57.1	67.1	0.6	10.4	6.0	15.8	13.5
data aggregated according to waste percentage									
L	68.6	30.5	68.6	82.3	0.6	12.6	6.1	18.1	17.5
M	52.9	30.5	52.9	65.1	0.6	14.1	6.1	19.6	17.2
H	73.6	30.0	73.6	83.0	0.6	9.5	6.0	14.9	14.3
av.	64.3	30.3	64.3	76.8	0.6	12.1	6.1	17.5	16.3

LP = linear programming relaxation of (UEFLP)
LR = Lagrangean relaxation (Section 3.4)
RO = linear programming round-off heuristic (Section 3.5.1)
1SF = single pass sequential facility location heuristic (Section 3.5.2)
SF = sequential facility location heuristic (Section 3.5.2)
CS_2 = cost savings heuristic 2 (ADD plants and DROP WDUs), (Section 3.5.3)
$(.)^+$ = heuristic (.) with improvement heuristic IH (Section 3.5.4)

From our computational experiments the following conclusions can be drawn:

Lower bounding procedures

- The lower bound resulting from LP(UEFLP) is rather tight (within 3.43% from optimality on average). The quality of the bound is sensitive to changes in problem dimension and cost structure, but appears to be rather insensitive to changes in the amount of by-products. As can be expected, the computation time required to solve LP(UEFLP) depends heavily on the problem dimension, and ranges from 13.5 seconds for small problems, to 146.8 seconds for larger sized problems (on average),
- Although, theoretically speaking, the lower bound obtained by solving the dual problem corresponding to LR(UEFLP) cannot be worse than the lower bound obtained

by solving the linear programming relaxation LP(UEFLP), in our implementation the iterative procedure for solving LR(UEFLP) is stopped after 100 iterations, yielding $z_{LR(UEFLP)} < z_{LP(UEFLP)}$ for all problem instances (thus, in fact, we never obtain the true Lagrangean bound). However, the difference between the two bounds is small (within 0.5% on average). The advantage of the Lagrangean bound is, that, compared to LP(UEFLP), CPU-times are relatively small (100 iterations take only 30.3 seconds, on average).

Upper bounding procedures

- When compared to the optimal solution and the other upper bounding procedures, the LP round-off heuristic RO performs only very modestly (with an average deviation from optimality of 3.87%). Furthermore, CPU-times are large (64.3 seconds on average) which is of course due to the fact that the LP-relaxation is solved in the first step of this heuristic,

- Although 1SF is fast (within 0.6 seconds of CPU-time), the quality of the solutions is poor when compared to the other upper bounding heuristics. Furthermore, the solutions obtained by applying 1SF are highly sensitive to all four problem characteristics. The multi-pass version SF yields much better results and is less sensitive to changes in the four problem characteristics. For this heuristic the average deviation from optimality is only 1.36%, while the average CPU-time is 6.1 seconds. Apparently the dual-cost multiplier adjustment procedure is quite effective in generating upper bounds for the type of problems studied in this chapter,

- The improvement heuristic IH yields indeed a drastic improvement to the quality of the solutions obtained by RO, 1SF, and SF. The best results are obtained by applying IH to the SF solution (average deviation from optimality is 0.21% only), however the difference in quality when compared to the solution obtained after combining IH with RO, 1SF, or SF is only very small. In other words, the performance of IH seems rather insensitive to the quality of the starting solution. Furthermore, the quality of IH seems also rather insensitive to changes in the four problem characteristics, including problem size. Finally, although CPU-times for IH are of course sensitive to problem size and quality of the starting solution, they are still acceptable (for example, *H* problems with a relative poor RO starting solution require 30 seconds only),

- Although not shown in tables 3.3 and 3.4, cost savings heuristic CS_2 outperforms the other cost savings heuristics in terms of quality of the solutions (CPU-times) on almost 89% (82%) of all evaluated problems instances. (Therefore we decided to restrict the presentation of the computational results for the cost savings heuristics to CS_2). The reason that CS_2 performs better on average than the other cost savings heuristics may be related to the way in which we generated the problem instances, especially with respect to the ratios between fixed and variable costs. For different problem instances it might very well be the case that other cost savings heuristics outperform CS_2,

- The quality of CS_2 seems to be insensitive to changes in problem size, cost structure, or by-product percentages. The solutions obtained by CS_2 do not improve upon application of the improvement heuristic IH, except for a few problem instances. The reason for the latter observation might be that both heuristics use the same type of cost savings mechanism. Furthermore, CS_2 is relatively fast (only 16.3 seconds of CPU-time are required on average), but on the other hand CPU-times are highly dependent on problem size, as well as cost structure (which is of course due to the way in which the cost saving mechanism operates),

- The quality of the solutions obtained by the relatively simple cost savings heuristic CS_2 dominates the quality of the solutions obtained by the other (seemingly more sophisticated) heuristics shown in the tables (when not combined with IH). When the other heuristics are combined with IH, their quality performance becomes comparable to CS_2. However, time requirements are in most cases favourable to CS_2.

3.7 Lower bounds for the capacitated location model

In this section, we analyse *(i)* the quality of linear programming relaxations of both model formulations (CEFLP) and (CFPLP), *(ii)* improvements of these bounds by adding valid inequalities to the relaxations, and *(iii)* Lagrangean relaxation for (CEFLP).

3.7.1 Linear programming relaxations

The linear programming relaxation for (CEFLP), LP(CEFLP), consists of the equations (3.1), (3.2), (3.3), (3.6), (3.7), (3.9) and relaxed constraints for the integer variables

$$0 \leq Y_i, Y_k^w \leq 1 \qquad i \in I, k \in K.$$

Valid inequalities (3.4) and (3.5) can be added in order to tighten the linear programming relaxation of (CEFLP). Constraints (3.4) state that total flow between plant i and customer j can never exceed the minimum of customer j's demand and the capacity at plant i. Constraints (3.5) state that the total by-product flow between plant i and WDU k can never be larger than the minimum of the capacity at WDU k, and the maximum amount of by-products or waste generated at plant i ($w_i \stackrel{def}{=} e_i \sum_{j \in J} d_j$). Furthermore, the linear programming relaxation can be tightened by another set of valid inequalities.

$$\sum_{i \in I} Y_i \geq \alpha \tag{3.36}$$

$$\sum_{k \in K} Y_k^w \geq \beta \tag{3.37}$$

Valid inequalities (3.36) and (3.37) are used to set a lower bound on the number of plants and WDUs that have to be opened in order to obtain a feasible solution to (CEFLP). In (3.36) (Christofides and Beasley [37] and Guignard and Opaswongkarn [65]) the constant α is the smallest integer number of plants (with the largest capacities) that must be open in order to satisfy all the demand ($\sum_{j \in J} d_j$). Similarly, constant β in (3.37) is the smallest integer number of WDUs (with the largest capacities) that must be open in order to dispose the minimum by-product flow ($\min_{i \in I} w_i$).

The linear programming relaxation for (CFPLP), LP(CFPLP), consists of the equations (3.10), (3.11), (3.14), (3.15), (3.17) and relaxed constraints for the integer variables

$$0 \leq Y_i, Y_k^w \leq 1 \qquad\qquad i \in I, k \in K.$$

Valid inequalities (3.12) and (3.13) can be added in order to tighten the linear programming relaxation of (CFPLP). Valid inequalities (3.36) and (3.37) are also useful for LP(CFPLP).

We compare the relative quality of LP(CEFLP) and LP(CFPLP), when adding the introduced valid inequalities. For this comparison we introduce the following notation:

- Constraint set (3.4) and (3.5) is denoted by A,
- Constraint set (3.36) and (3.37) is denoted by B,
- Constraint set (3.12) and (3.13) is denoted by C,

For example, $z_{LP(CEFLP-AB)}$ is the optimal solution value of the LP-relaxation to (CEFLP), when valid inequalities A and B are added to it. We first prove the following lemma's:

Lemma 3.1 $z_{LP(CEFLP)} = z_{LP(CFPLP)}$

Proof: The following equivalence relations hold by definition:

(a) $X_{ij} = \sum_{k \in K} d_j X_{ijk}$

(b) $X^w_{ik} = \sum_{j \in J} e_i d_j X_{ijk}$

(c) $(a_{ij} + a^w_{ik} \times e_i) d_j = c_{ijk}$

Given these equivalence relations, we prove that LP(CEFLP) is equivalent to LP(CFPLP). The objectives (3.1) and (3.10) in both formulations are equivalent:

$$\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} c_{ijk} X_{ijk} + \sum_{i \in I} f_i Y_i + \sum_{k \in K} f^w_k Y^w_k \stackrel{(c)}{=}$$

$$= \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} (a_{ij} + a^w_{ik} \times e_i) d_j X_{ijk} + \sum_{i \in I} f_i Y_i + \sum_{k \in K} f^w_k Y^w_k =$$

$$= \sum_{i \in I} \sum_{j \in J} a_{ij} \sum_{k \in K} d_j X_{ijk} + \sum_{i \in I} \sum_{k \in K} a^w_{ik} \sum_{j \in J} e_i d_j X_{ijk} + \sum_{i \in I} f_i Y_i + \sum_{k \in K} f^w_k Y^w_k \stackrel{(a),(b)}{=}$$

$$= \sum_{i \in I} \sum_{j \in J} a_{ij} X_{ij} + \sum_{i \in I} \sum_{k \in K} a^w_{ik} X^w_{ik} + \sum_{i \in I} f_i Y_i + \sum_{k \in K} f^w_k Y^w_k$$

Also, demand constraints (3.2) and (3.11) are equivalent, since for each $j = 1, .., n$,

$$\sum_{i \in I} \sum_{k \in K} X_{ijk} = 1 \Leftrightarrow d_j \sum_{i \in I} \sum_{k \in K} X_{ijk} = d_j \stackrel{(a)}{\Leftrightarrow} \sum_{i \in I} X_{ij} = d_j$$

Furthermore, flow balancing constraints (3.3) are automatically satisfied in (CFPLP), since for each $i = 1, .., m$,

$$\sum_{j \in J} e_i X_{ij} \stackrel{(a)}{=} \sum_{j \in J} e_i \sum_{k \in K} d_j X_{ijk} = \sum_{k \in K} \sum_{j \in J} e_i d_j X_{ijk} \stackrel{(b)}{=} \sum_{k \in K} X^w_{ik}$$

By the definition of *(a)* it follows that (3.6) is equivalent to (3.14), and by the definition of *(b)* it follows that (3.7) and (3.15) are equivalent. □

As a result of this lemma, it holds that $z_{LP(CEFLP-B)} = z_{LP(CFPLP-B)}$.

Lemma 3.2 $z_{LP(CEFLP-A)} \leq z_{LP(CFPLP-C)}$

Proof: It is sufficient to show that *(i)* each solution of LP(CFPLP-C) is feasible in LP(CEFLP-A) and *(ii)* there exists an instance for which the solution of LP(CEFLP-A) is not feasible in LP(CFPLP-C).

First we prove that each feasible solution to LP(CFPLP-C) is also feasible to LP(CEFLP-A). Consider an arbitrary feasible solution to LP(CFPLP-C). We know from Lemma 3.1 that $z_{LP(CEFLP)} = z_{LP(CFPLP)}$. It remains to be shown that (3.4) and (3.5) are satisfied by the solution to LP(CFPLP-C).

Constraints (3.12) can be rewritten as

$$\sum_{k\in K} X_{ijk} \leq Y_i \Leftrightarrow \sum_{k\in K} d_j X_{ijk} \leq d_j Y_i \overset{(a)}{\Leftrightarrow} X_{ij} \leq d_j Y_i$$

Two cases may occur now:

Case 1: $\min(d_j, s_i) = s_i$. Then (3.4) reduces to $X_{ij} \leq s_i Y_i$. Consequently, (3.4) is dominated by (3.6), and thus (3.4) is satisfied,

Case 2: $\min(d_j, s_i) = d_j$. Then $X_{ij} \leq d_j Y_i$ is equivalent to (3.4).

Constraints (3.13) can be rewritten as

$$\sum_{i\in I} X_{ijk} \leq Y_k^w \Leftrightarrow \sum_{j\in J} d_j \sum_{i\in I} X_{ijk} \leq \sum_{j\in J} d_j Y_k^w$$

Consider now one single plant i^*. Then

$$e_{i^*} \sum_{j\in J} d_j \sum_{i\in I} X_{ijk} \leq e_{i^*} \sum_{j\in J} d_j Y_k^w \Leftrightarrow \sum_{j\in J} d_j e_{i^*} X_{i^*jk} + \sum_{j\in J} d_j e_{i^*} \sum_{i\neq i^*} X_{ijk} \leq$$

$$\sum_{j\in J} d_j e_{i^*} Y_k^w \overset{(b)}{\Leftrightarrow} X_{i^*k}^w + \sum_{j\in J} d_j e_{i^*} \sum_{i\neq i^*} X_{ijk} \leq w_{i^*} Y_k^w \Rightarrow X_{i^*k}^w \leq w_{i^*} Y_k^w$$

The above results hold for all $i^* \in I$. Again, two cases may occur now:

Case 1: $\min(w_i, s_k^w) = s_k^w$. Then (3.5) reduces to $X_{ik}^w \leq s_k^w Y_k^w$. Consequently, (3.5) is dominated by (3.7), and thus (3.5) is satisfied,

Case 2: $\min(w_i, s_k^w) = w_i$. Then $X_{ik}^w \leq w_i Y_k^w$ is equivalent to (3.5).

Next we consider *(ii)*. We construct an example in which the solution to LP(CEFLP-A) is not feasible to LP(CFPLP-C). Consider problem instance I with three customers, three plants, and two WDUs (dimensions $m = 3; n = 3; p = 2$). Demand data are $d_1 = d_2 = d_3 = 1$. Fixed costs are $f_1 = f_2 = f_3 = 3$, and $f_1^w = f_2^w = 1$. Capacities of the plants are $s_i = 2$ for $i = 1, 2, 3$, and for the WDUs $s_k^w = 3$ for $k = 1, 2$. Variables costs are $a_{13} = a_{21} = a_{32} = 3$, and $a_{ik}^w = 1$ for all i, k. The other variable costs are zero. Finally, waste fractions equal one, i.e. $e_1 = e_2 = e_3 = 1$. LP(CEFLP-A) yields an optimal solution with $z_{LP(CEFLP-A)} = \frac{47}{6}$. The corresponding values for the location variables are: $Y_1 = Y_2 = Y_3 = \frac{1}{2}$, and $Y_1^w = \frac{1}{3}, Y_2^w = 0$. The flow variables have values

$X_{11} = X_{12} = X_{22} = X_{23} = X_{31} = X_{33} = \frac{1}{2}$, and $X_{11}^w = X_{21}^w = X_{31}^w = 1$. The other flow variables are zero. By the definition of *(a)* and *(b)*, it follows that the corresponding flow path variables equal $X_{111} = X_{121} = X_{221} = X_{231} = X_{311} = X_{321} = \frac{1}{2}$. The other flow path variables are zero. This solution violates (3.13) for $k = 1$.

We conclude that *(i)* any feasible solution to LP(FPLP-C) is feasible to LP(CEFLP-A), and *(ii)* a solution exists to LP(CEFLP-A) which is not feasible to LP(CFPLP-C). This implies that $z_{LP(CEFLP-A)} \leq z_{LP(CFPLP-C)}$ □

Lemma 3.3 *No dominance relations exist between $z_{LP(CEFLP-A)}$ and $z_{LP(CEFLP-B)}$, between $z_{LP(CFPLP-B)}$ and $z_{LP(CFPLP-C)}$, between $z_{LP(CEFLP-A)}$ and $z_{LP(CFPLP-B)}$, and between $z_{LP(CEFLP-B)}$ and $z_{LP(CFPLP-C)}$.*

Proof: Consider problem instance II with two customers, two plants, and two WDUs. Customer demands are $d_1 = 2$ and $d_2 = 3$. Transportation costs are $a_{21} = 3$ and $a_{12}^w = 3$. All other transportation costs are zero. Fixed costs for opening plants are $f_1 = 2$ and $f_2 = 3$, and for the WDUs $f_1^w = 2$ and $f_2^w = 3$. Capacities of the plants are $s_1 = 3$ and $s_2 = 5$, and for the WDUs $s_1^w = 3$ and $s_2^w = 5$. Waste percentages are $e_i = 1$ for $i = 1, 2$. Problem instance III is identical to problem instance II, except that $s_2 = 4$ and $s_2^w = 4$. The optimal solutions to these instances are presented in Table 3.5:

Table 3.5: Solutions to problem instances II and III

objective function	Instance II	Instance III
$z_{LP(CEFLP-A)}$	$7\frac{1}{5}$	$7\frac{1}{2}$
$z_{LP(CEFLP-B)}$, $z_{LP(CFPLP-B)}$	$6\frac{4}{15}$	10
$z_{LP(CFPLP-C)}$	8	8

The results for instances II and III indeed show that no dominance relations exist between $z_{LP(CEFLP-A)}$ and $z_{LP(CEFLP-B)}$, between $z_{LP(CFPLP-B)}$ and $z_{LP(CFPLP-C)}$, between $z_{LP(CEFLP-A)}$ and $z_{LP(CFPLP-B)}$, and between $z_{LP(CEFLP-B)}$ and $z_{LP(CFPLP-C)}$.
□

3.7.2 Lagrangean relaxation

As an alternative to the linear programming based lower bounding procedures, we also obtain lower bounds from Lagrangean relaxation of the flow-balancing constraints (3.3) of model formulation (CEFLP). We denote the resulting problem by LR(CEFLP). The latter problem decomposes into the subproblems LR_1(CEFLP) and LR_2(CEFLP) as stated below:

$$z_{LR_1(CEFLP)}(\lambda) = \min \quad \sum_{i \in I} \sum_{j \in J} (a_{ij} + \lambda_i e_i) X_{ij} + \sum_{i \in I} f_i Y_i \qquad (3.38)$$

$$\text{subject to} \quad \sum_{i\in I} X_{ij} = d_j \qquad j \in J \qquad (3.39)$$

$$X_{ij} \leq \min\{d_j, s_i\}Y_i \qquad i \in I, j \in J \qquad (3.40)$$

$$\sum_{j\in J} X_{ij} \leq s_i Y_i \qquad i \in I \qquad (3.41)$$

$$Y_i \in \{0,1\} \qquad i \in I \qquad (3.42)$$

$$X_{ij} \geq 0 \qquad i \in I,\ j \in J \qquad (3.43)$$

$$z_{LR_2(CEFLP)}(\lambda) = \min \sum_{i\in I}\sum_{k\in K}(a^w_{ik} - \lambda_i)X^w_{ik} + \sum_{k\in K} f^w_k Y^w_k \qquad (3.44)$$

$$\text{subject to} \quad X^w_{ik} \leq \min\{w_i, s_k\}Y^w_k \qquad i \in I, k \in K \qquad (3.45)$$

$$\sum_{i\in I} X^w_{ik} \leq s^w_k Y^w_k \qquad k \in K \qquad (3.46)$$

$$Y^w_k \in \{0,1\} \qquad k \in K \qquad (3.47)$$

$$X^w_{ik} \geq 0 \qquad i \in I,\ k \in K \qquad (3.48)$$

where $\lambda = (\lambda_1, \ldots, \lambda_m)$ is the set of Lagrangean multipliers corresponding to (3.3). Note that $z_{LR(CEFLP)}(\lambda) = z_{LR_1(CEFLP)}(\lambda) + z_{LR_2(CEFLP)}(\lambda)$.

Problem LR_1(CEFLP) is a single level capacitated plant location problem, which can be solved to optimality using a special purpose code like the one developed by Ryu and Guignard [132]. Due to the block structure of the constraint matrix, problem LR_2(CEFLP) decomposes into p independent subproblems $\text{LR}_2(\text{CEFLP})_k$ $(k = 1, \ldots, p)$. These problems can be solved as follows:

Solution procedure to $\text{LR}_2(\text{CEFLP})_k$:

Step 1: Fix $Y^w_k = 1$. Let I_k be the set of plants i for which $a^w_{ik} - \lambda_i < 0$. Next we formulate the following *bounded continuous knapsack problem* (BCKP):

$$z_{BCKP} = \max \sum_{i\in I_k}(\lambda_i - a^w_{ik})X^w_{ik}$$

$$\text{subject to} \sum_{i\in I_k} X^w_{ik} \leq s^w_k$$

$$0 \leq X^w_{ik} \leq \min\{s^w_k, w_i\} \qquad i \in I_k$$

In order to solve BCKP we apply the $\mathcal{O}(|I_k|\log|I_k|)$ solution procedure of Martello and Toth [103] (p. 84). This procedure yields solutions $\overline{X}^w_{ik}$ (to be used in Step 2 below).

Step 2: The optimal solution to $\text{LR}_2(\text{CEFLP})_k$ is obtained using the following rule: if $f^w_k + \sum_{i\in I_k}(a^w_{ik} - \lambda_i)\overline{X}^w_{ik} < 0$ then $Y^w_k = 1$, $X^w_{ik} = \overline{X}^w_{ik}$ for $i \in I_k$, and $X^w_{ik} = 0$ for $i \notin I_k$. Otherwise $Y^w_k = 0$ and $X^w_{ik} = 0$ for all $i \in I$. The costs corresponding to this solution are $z_{LR_2(CEFLP)_k}(\lambda)$.

Note that $z_{LR_2(CEFLP)}(\lambda) = \sum_{k=1}^{p} z_{LR_2(CEFLP)_k}(\lambda)$. The complete Lagrangean relaxation procedure can now be summarized as follows:

Lagrangean relaxation procedure:

Initialization:	Set dual multipliers $\lambda = (\lambda_1, \ldots, \lambda_m)$ equal to zero.
Step 1:	Solve LR_1(CEFLP) and LR_2(CEFLP) using the procedures described above.
Step 2:	If convergence conditions are satisfied, then STOP, otherwise update dual multipliers λ using subgradient optimization, return to Step 1.

The Lagrangean lower bound may dominate the bounds resulting from the LP-relaxation of CEFLP. Also, as a consequence of Lemma 3.1, the Lagrangean lower bound may dominate $z_{LP(CFPLP)}$. However, a number of computational experiments have shown that the procedure is largely outperformed by the linear programming based procedures in terms of required CPU time. The considerable effort required to compute $z_{LR_1(CEFLP)}(\lambda)$ at each iteration of the subgradient optimization procedure does not seem to be compensated by superior values for the bounds. Therefore, in our computational study we refrain from further consideration of the Lagrangean relaxation technique.

Apart from the Lagrangean relaxation of constraints (3.3), we could have experimented with Lagrangean relaxation of capacity constraints (3.6) and (3.7) of (CEFLP). The resulting (UEFLP) problems are still hard to solve to optimality (see sections 3.4 – 3.6). Therefore, we do not consider these relaxations here.

3.8 Upper bounds for the capacitated location model

In what follows we discuss two alternative upper bounding procedures: *(i)* a linear programming round-off heuristic, and *(ii)* a sequential capacitated facility location heuristic.

3.8.1 Linear programming round-off heuristic

The linear programming round-off heuristic (RO) is similar to the round-off heuristic in Section 3.5.1. Given the solution to LP(CEFLP) or LP(CFPLP) we fix the binary variables Y_i and Y_k^w to 0 or 1. The remaining problem is a minimum cost network flow problem with losses (MCNFPL), shown in Figure 3.2. This problem can be solved using an appropriate network simplex procedure or a special purpose code (in our implementation we applied the simplex procedure available from IBM [76]).

Linear programming round-off heuristics:

Step 1:	For heuristic RO(CEFLP) (RO(CFPLP)) solve LP(CEFLP) (LP(CFPLP)), yielding the (possibly fractional) solution values $(\overline{Y}_i, \overline{Y}^w_k)$ for the binary variables.
Step 2:	Fix $Y_i = 1$ ($Y^w_k = 1$) when $\overline{Y}_i > 0$ ($\overline{Y}^w_k > 0$). Otherwise, set $Y_i = 0$ ($Y^w_k = 0$).
Step 3:	Given the open plants and WDUs obtained from Step 2, design the corresponding minimum cost flow network with losses. Solve MCNFPL.
Step 4:	Compute the values $z_{RO(CEFLP)}$ ($z_{RO(CFPLP)}$) by adding fixed costs for opening plants and WDUs to z_{MCNFPL} .

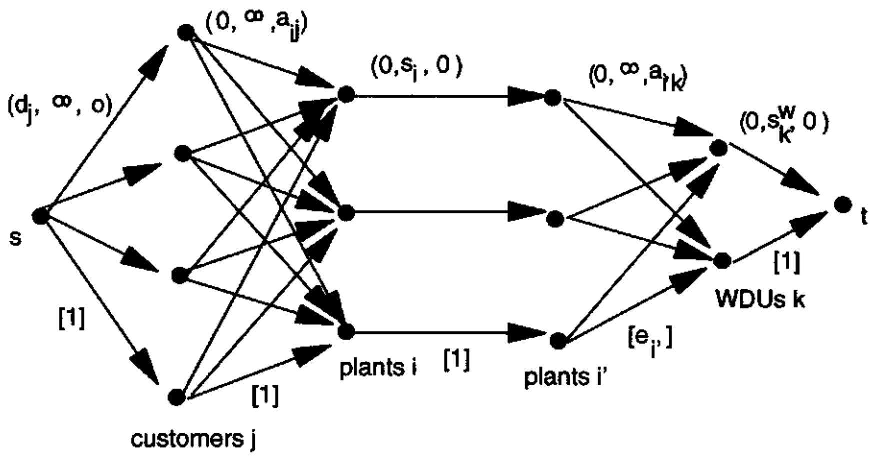


Figure 3.2: The minimum cost network flow problem with losses.

In Figure 3.2, the vector of lower bounds, upper bounds and costs corresponding to each arc from node p to node q is denoted by (l_{pq}, u_{pq}, c_{pq}). The flow-intensity corresponding to the flow between node p and q is represented by $[r_{pq}]$. Note that a fraction of $(1 - r_{pq})$ of flow is lost between node p and node q. Node s is the super source, node t is the super sink, and nodes i' are introduced in order to represent capacity restrictions on plants.

3.8.2 Sequential capacitated facility location heuristic

The sequential capacitated facility location heuristic (SF) is based on the observation that a feasible solution to the capacitated location problem can be constructed in two stages. In the first stage a single level capacitated facility location problem (between plants and customers) is solved. Given the solution to this problem, the amount of by-products at each plant is computed. In the second stage of the heuristic again a single level capacitated facility location problem (between plants and WDUs) is solved, taking into account the amount of by-products computed at the first stage. This two stage decomposition procedure is in fact similar to the decomposition that is applied within the Lagrangean lower bounding procedure (section 3.7.2). Unfortunately, the latter procedure does not yield feasible solutions automatically, as LR_2(CEFLP) does not explicitly take into account the amount of by-products generated at each plant. However, a feasible solution is constructed by replacing LR_2(CEFLP) with subproblem LR_2^E(CEFLP) as defined below.

$$z_{LR_2^E(CEFLP)}(\lambda) = \min \sum_{i\in I}\sum_{k\in K}(a_{ik}^w - \lambda_i)X_{ik}^w + \sum_{k\in K} f_k^w Y_k^w \qquad (3.49)$$

subject to

$$\sum_{k\in K} X_{ik}^w = E_i \qquad i \in I \qquad (3.50)$$

$$\sum_{i\in I} X_{ik}^w \leq s_k^w Y_k^w \qquad k \in K \qquad (3.51)$$

$$X_{ik}^w \leq \min\{s_k^w, w_i\} Y_k^w \qquad i \in I,\ k \in K \qquad (3.52)$$

$$Y_k^w \in \{0,1\} \qquad k \in K \qquad (3.53)$$

$$X_{ik}^w \geq 0 \qquad i \in I,\ k \in K \qquad (3.54)$$

where the total amount of by-products at plant i is computed as $E_i \stackrel{def}{=} e_i \sum_{j\in J} X_{ij}$. The values for the decision variables X_{ij} are obtained from LR_1(CEFLP). In principle, for each set of Lagrangean multipliers a (new) upper bound can be obtained. However, because of the considerable computational requirements of an iterative procedure we limit our computational experiments to a single iteration (with $\lambda = 0$). Heuristic SF is summarized as follows:

Heuristic SF:

Step 1:	Use the solution to LR_1(CEFLP) with $\lambda = 0$ to compute E_i for all $i \in I$. Solve LR_2^E(CEFLP) using the special purpose code by Ryu and Guignard [132].
Step 2:	Compute the value of the upper bound z_{SF} corresponding to the solution of the heuristic.

3.9 Computational results for the capacitated location model

In this section we explain how the test problems for the computational study were generated, and discuss the computational results.

3.9.1 Problem generation

We generate two sets of test problems. The sets differ with respect to the generation of fixed costs, capacities, and the ratio between available capacity and required capacity (capacity utilization) for plants and WDUs. Here, capacity utilization of plants and WDUs is defined as:

$$\rho := \frac{\sum_j d_j}{\sum_i s_i} \qquad ; \qquad \rho^w = \frac{\bar{e} \sum_j d_j}{\sum_k s_k^w}$$

where $\bar{e}$ is the average waste fraction, defined below. We now describe the specific characteristics of both problem sets (Set I and Set II).

Set I

Set I consists of 18 problem instances with 16 plants, 10 WDUs, and 30 customers. For each problem instance, fixed costs (f_i and f_k^w), and capacities (s_i and s_k^w) are varied as shown in Table 3.6. Variable transportation costs (a_{ij} and a_{ik}^w) and demands (d_j) are taken from the single level problem instances used in a computational study by Khumawala [85]. Waste fractions (e_i) are randomly generated from a uniform $U[e^{min}; e^{max}]$ distribution, where for each WDU e^{min} is the minimum waste fraction and e^{max} is the maximum waste fraction. Note that $\bar{e} = \dfrac{e^{min} + e^{max}}{2}$. In order to analyse the influence of capacity utilization on the performance of the lower bounding and upper bounding procedures, capacities of plants and WDUs and waste fractions of plants are chosen such that (expected) capacity utilization at plants (WDUs) is either HIGH with ρ=0.61 ($\rho^w = 0.65$), MEDIUM with ρ=0.30 ($\rho^w = 0.22$), or LOW with ρ=0.20 ($\rho^w = 0.06$).

Domschke and Drexl [49] and Cornuejols et al. [43] observe that the performance of their heuristics for the capacitated plant location problem is rather sensitive to high variabilities in fixed costs and capacity (utilization). In order to investigate whether this observation also applies to our lower bounding and upper bounding procedures for the problem studied here, we generate problem Set II.

Set II

Set II consists of 20 problem instances with the same number of plants, WDUs and customers as the problems generated by Khumawala (see also Set I). Capacities and fixed costs are generated as suggested by Cornuejols et al. [43]:

$$\begin{aligned} s_i &= U[3,500;56,000] \\ s_k^w &= U[2,500;40,000] \\ f_i &= U[0;90] + U[100;110]\sqrt{s_i} \\ f_k^w &= U[0;90] + U[100;110]\sqrt{s_k^w} \end{aligned}$$

Waste fractions e_i are randomly generated from a uniform $U[0;1]$ distribution. Variable transportation costs and demands are generated as in Set I.

Table 3.6: Test problem characteristics of Set I

#	f_i	s_i	f_k^w	s_k^w	e_i	ρ	ρ^w
1	7,500	5,000	2,500	1,000	$U[0.1;0.2]$	0.61	0.65
2	7,500	5,000	5,000	3,000	$U[0.1;0.2]$	0.61	0.22
3	7,500	5,000	15,000	11,500	$U[0.1;0.2]$	0.61	0.06
4	7,500	5,000	8,000	5,000	$U[0.5;1.0]$	0.61	0.65
5	7,500	5,000	12,500	15,000	$U[0.5;1.0]$	0.61	0.22
6	7,500	5,000	25,000	57,500	$U[0.5;1.0]$	0.61	0.06
7	10,000	10,000	2,500	1,000	$U[0.1;0.2]$	0.30	0.65
8	10,000	10,000	5,000	3,000	$U[0.1;0.2]$	0.30	0.22
9	10,000	10,000	15,000	11,500	$U[0.1;0.2]$	0.30	0.06
10	10,000	10,000	8,2000	5,000	$U[0.5;1.0]$	0.30	0.65
11	10,000	10,000	12,500	15,000	$U[0.5;1.0]$	0.30	0.22
12	10,000	10,000	25,000	57,500	$U[0.5;1.0]$	0.30	0.06
13	12,500	15,000	2,500	1,000	$U[0.1;0.2]$	0.20	0.65
14	12,500	15,000	5,000	3,000	$U[0.1;0.2]$	0.20	0.22
15	12,500	15,000	15,000	11,500	$U[0.1;0.2]$	0.20	0.06
16	12,500	15,000	8,000	5,000	$U[0.5;1.0]$	0.20	0.65
17	12,500	15,000	12,500	15,000	$U[0.5;1.0]$	0.20	0.22
18	12,500	15,000	25,000	57,500	$U[0.5;1.0]$	0.20	0.06

3.9.2 Computational results

Below we discuss the performance of the lower bounding procedures and the upper bounding procedures with respect to their quality as well as the computational effort required. The computational study was carried out on an IBM RISC System/6000 (Model 370) workstation.

Lower bounding procedures

The linear programming based lower bounding procedures were implemented in FORTRAN using the Optimization Subroutine Library OSL (IBM [76])[2].

[2]A preliminary study indicated that for our type of problems the primal simplex method with devex pricing outperforms interior point methods and dual simplex methods implemented in OSL.

In order to measure the quality of the lower bounding procedures we define for each problem instance the (normalized) deviation between the value of the lower bound and the value of the optimal solution as $\delta z = \frac{z_{opt} - z_{(.)}}{z_{opt}}$, where z_{opt} is the value of the optimal solution and $z_{(.)}$ is the value corresponding to lower bounding procedure (.). Here, the optimal solution is obtained using the standard branch-and-bound procedure available in OSL (see also below). For each lower bounding procedure the *average* quality (*aggregated* over all instances in Set I, respectively Set II) is denoted by $\overline{\delta z}$, the worst (best) case behaviour is denoted by δz^{max} (δz^{min}), and the variance is denoted by $\sigma^2(\delta z)$. Finally, $\bar{t}$ is the average CPU-time (in seconds) over all problem instances within the set, t^{min} (t^{max}) is the minimum (maximum) CPU time, and $\sigma^2(t)$ is the variance in CPU time. Table 3.7 provides an overview of the above performance indicators for each of the lower bounding procedures. Table 3.7a shows the quality and Table 3.7b shows the CPU-time for the lower bounding procedures. Table 3.8 provides some insights into the relationship between capacity utilization of plants and WDUs and the quality of the lower bounding procedures for instances from Set I.

Table 3.7a: Quality of the solutions of the lower bounding procedures

	Set I				Set II			
Relaxation	$\overline{\delta z}$	δz^{min}	δz^{max}	$\sigma^2(\delta z)$	$\overline{\delta z}$	δz^{min}	δ^{max}	$\sigma^2(\delta z)$
LP(CEFLP)	7.95	1.19	15.58	12.93	12.16	6.46	15.14	4.28
LP(CEFLP-B)	7.95	1.19	15.58	12.93	12.16	6.46	15.14	4.28
LP(CEFLP-A)	2.92	0.17	8.76	6.45	3.74	1.28	6.37	1.69
LP(CEFLP-AB)	2.92	0.17	8.76	6.45	3.74	1.28	6.37	1.69
LP(CFPLP)	7.95	1.19	15.58	12.93	12.16	6.46	15.14	4.28
LP(CFPLP-B)	7.95	1.19	15.58	12.93	12.16	6.46	15.14	4.28
LP(CFPLP-C)	0.36	0.00	1.48	0.14	0.23	0.00	1.94	0.22
LP(CFPLP-BC)	0.36	0.00	1.48	0.14	0.23	0.00	1.94	0.22

Table 3.7b: CPU-time in seconds

	Set I				Set II			
Relaxation	$\bar{t}$	t^{min}	t^{max}	$\sigma^2(t)$	$\bar{t}$	t^{min}	t^{max}	$\sigma^2(t)$
LP(CEFLP)	0.39	0.27	0.54	0.01	0.35	0.25	0.45	0.00
LP(CEFLP-B)	0.39	0.25	0.58	0.01	0.34	0.26	0.44	0.00
LP(CEFLP-A)	2.19	1.03	3.73	0.53	2.03	0.83	4.65	1.25
LP(CEFLP-AB)	2.18	1.05	3.70	0.53	2.04	0.83	4.58	1.24
LP(CFPLP)	2.64	1.40	4.05	0.45	2.03	1.39	2.75	0.10
LP(CFPLP-B)	2.64	1.41	4.09	0.50	1.99	1.01	2.71	0.14
LP(CFPLP-C)	121	69	189	1287	193	162	271	820
LP(CFPLP-BC)	120	69	189	1288	193	162	271	831

Table 3.8: Relation between capacity utilization and quality of the lower bounds for Set I

Relaxation	Capacity utilization of plants			Capacity utilization of WDUs		
	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH
$\delta z_{LP(CEFLP)}$	9.92	8.39	5.53	11.05	6.81	5.98
$\delta z_{LP(CEFLP-B)}$	9.92	8.39	5.53	11.05	6.81	5.98
$\delta z_{LP(CEFLP-A)}$	2.52	2.91	3.32	9.04	8.64	7.72
$\delta z_{LP(CEFLP-AB)}$	2.52	2.91	3.32	9.04	8.64	7.72
$\delta z_{LP(CFPLP)}$	9.92	8.39	5.53	11.05	6.81	5.98
$\delta z_{LP(CFPLP-B)}$	9.92	8.39	5.53	11.05	6.81	5.98
$\delta z_{LP(CFPLP-C)}$	0.28	0.35	0.46	0.42	0.20	0.47
$\delta z_{LP(CFPLP-BC)}$	0.28	0.35	0.46	0.42	0.20	0.47

From the computational results the following conclusions can be drawn:

- The CPU-time required to solve LP(CEFLP) is considerably less than the CPU-time required to solve LP(CFPLP), whereas the quality of the solution does not differ between the two model formulations (Lemma 3.1),

- Adding valid inequalities A to LP(CEFLP) and C to LP(CFPLP) turns out to be very effective in terms of lower bound improvements for problem instances from Set I as well as from Set II. However, both inequality sets cause an increase in computational effort. Comparing both sets, we conclude that set C contributes to larger bound improvements than set A (Lemma 3.2), at the expense of a considerable increase in CPU-times (both in terms of averages and variances),

- Adding valid inequalities B to LP(CEFLP) or LP(CFPLP) does not seem to affect the quality of the solutions, nor the required computational effort (Lemma 3.3),

- From a comparison of the computational results for Set I and Set II we conclude that the quality of the lower bounding procedures decreases when variability is introduced in capacities and fixed costs. Exceptions are the lower bounds $z_{LP(CFPLP-C)}$ and $z_{LP(CFPLP-BC)}$. The quality of these bounds seems to be rather insensitive to higher variabilities in capacities and fixed costs (the *average* deviation from optimality becomes even smaller for the two bounds). The influence of higher variability in capacities and fixed costs on CPU-times seems to be marginal, except for the bounds resulting from LP(CFPLP-C) and LP(CFPLP-BC),

- Furthermore, as shown in Table 3.8, capacities do influence the quality and required CPU-times of the lower bounding procedures. Higher capacitated problems (i.e. problems with higher ρ and ρ^w values) yield in general sharper lower bounds $z_{LP(CEFLP)}$ and $z_{LP(CFPLP)}$. Comparing $z_{LP(CEFLP)}$ with $z_{LP(CEFLP-A)}$ we found that valid inequalities A become more effective in case of lower capacitated problems. This effect is explained by the observation that in this case the right hand side of constraints (3.4) and (3.5) becomes highly dependent on demand d_j and maximum total waste w_i. These quantities act now as (surrogate) capacities, since they may dominate s_i and s_k^w (note that we use in fact the same arguments as in the formal proof of Lemma 3.2). The effectiveness of valid inequalities C does not seem to depend much on capacity utilization.

Upper bounding procedures

The results concerning the upper bounding procedures are shown in Tables 3.9 and 3.10. Table 3.9a shows the quality and Table 3.9b shows the CPU-time. Table 3.10 gives the relation between capacity utilization (ρ and ρ^w) and the quality of the upper bounds. Similarly to the presentation of the computational results for the lower bounding procedures, we define for each instance the quality of upper bounding procedure (.) by $\delta z = \frac{z_{(.)} - z_{opt}}{z_{opt}}$. Based on this performance indicator we compute over all instances in Set I respectively Set II the average quality for each upper bounding procedure ($\overline{\delta z}$), the worst case behaviour (δz^{max}), the best case behaviour (δz^{min}), the variance ($\sigma^2(\delta z)$), and the average required CPU-time ($\bar{t}$). Furthermore, t^{min} (t^{max}) is the minimum (maximum) CPU time, and $\sigma^2(t)$ is the variance in CPU time.

With respect to the upper bounding procedures the following conclusions can be drawn:

- The solutions obtained by RO(CEFLP) seem to be slightly better than the solutions obtained by RO(CFPLP), although the latter procedure requires considerably more CPU-time. Though the difference in CPU-times was expected (see the discussion on lower bounds), we could not find intuitively appealing arguments to explain the small quality differences,

- Adding valid inequalities A to CEFLP or C to CFPLP yields better solutions to the round-off heuristics, both for Set I and Set II. This might be expected from the results reported for the lower bounding procedures, as better lower bounds have in general fewer setup variables with a value close to zero. Due to the latter, rounding-off a 'good' lower bounding solution yields in general better solutions than rounding-off a 'bad' lower bounding solution. By the same arguments it can be explained that *(i)* RO(CFPLP-C) performs in general better than RO(CEFLP-A), and *(ii)* the results to instances in Set I are in general better than the results to instances in Set II, *(iii)* high capacitated problems yield on average better upper bounds than low capacitated problems (Table 3.10),

- SF does not seem to perform very well when compared to the other procedures. Nevertheless, a preliminary study indicated that the quality of the results significantly improves when applying the multi-pass variant of SF. The quality of these solutions is comparable to the quality of the solutions to RO(CEFLP-A). However, as indicated earlier, the multi-pass variant of SF is very time consuming, and therefore not further investigated.

Table 3.9a: Quality of the solutions of the upper bounding procedures

	Set I				Set II			
Heuristic	$\overline{\delta z}$	δz^{min}	δz^{max}	$\sigma^2(\delta z)$	$\overline{\delta z}$	δz^{min}	δz^{max}	$\sigma^2(\delta z)$
RO(CEFLP)	4.53	1.09	9.54	5.53	7.88	4.57	12.66	6.22
RO(CEFLP-B)	4.53	1.09	9.54	5.53	7.88	4.57	12.66	6.22
RO(CEFLP-A)	1.78	0.00	3.80	1.52	1.65	0.00	3.83	0.99
RO(CEFLP-AB)	1.78	0.00	3.80	1.52	1.65	0.00	3.83	0.99
RO(CFPLP)	5.51	1.34	15.87	11.93	11.33	5.96	19.58	16.60
RO(CFPLP-B)	5.51	1.34	15.87	11.93	11.33	5.96	19.58	16.60
RO(CFPLP-C)	1.30	0.00	7.36	3.35	1.52	0.00	6.59	2.90
RO(CFPLP-BC)	1.30	0.00	7.36	3.35	1.52	0.00	6.59	2.90
SF	8.47	0.97	21.91	54.55	16.77	7.50	33.05	57.62

Table 3.9b: CPU-time in seconds

	Set I				Set II			
Heuristic	$\bar{t}$	t^{min}	t^{max}	$\sigma^2(t)$	$\bar{t}$	t^{min}	t^{max}	$\sigma^2(t)$
RO(CEFLP)	1.56	0.67	2.45	0.32	1.23	0.80	1.95	0.10
RO(CEFLP-B)	1.56	0.67	2.45	0.33	1.22	0.76	2.04	0.11
RO(CEFLP-A)	5.72	3.38	10.19	2.88	6.35	1.63	10.99	7.61
RO(CEFLP-AB)	5.70	3.39	10.29	2.91	6.34	1.62	10.96	7.47
RO(CFPLP)	12.78	7.95	17.39	6.54	14.21	7.12	41.39	83.84
RO(CFPLP-B)	12.81	7.95	17.56	6.88	14.28	7.04	41.65	86.75
RO(CFPLP-C)	185	78.76	362	6776	211	177	307	1460
RO(CFPLP-BC)	184	79.00	361	6720	211	177	307	1490
SF	84.17	10.74	197	6511	35.92	3.64	160	2102

Table 3.10: Relation between capacity utilization and quality of the upper bounds

Heuristic	Capacity utilization of plants			Capacity utilization of WDUs		
	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH
$\delta z_{RO(CEFLP)}$	6.46	4.84	2.30	6.43	4.00	3.16
$\delta z_{RO(CEFLP-B)}$	6.46	4.84	2.30	6.43	4.00	3.16
$\delta z_{RO(CEFLP-A)}$	1.53	2.01	1.79	3.31	1.40	0.63
$\delta z_{RO(CEFLP-AB)}$	1.53	2.01	1.79	3.31	1.40	0.63
$\delta z_{RO(CFPLP)}$	7.89	5.60	3.03	8.31	4.48	3.73
$\delta z_{RO(CFPLP-B)}$	7.89	5.60	3.03	8.31	4.48	3.73
$\delta z_{RO(CFPLP-C)}$	1.03	1.41	1.46	2.30	0.96	0.64
$\delta z_{RO(CFPLP-BC)}$	1.03	1.41	1.46	2.30	0.96	0.64
δz_{SF}	10.85	8.59	5.96	4.12	3.18	3.13

Optimal solutions

Optimal solutions -to which we compare the solutions of our upper bounding procedures-were obtained using the standard branch-and-bound procedures available in OSL. It is remarkable that for many problem instances the optimal solutions to (CEFLP) or (CFPLP) could not be obtained within hours when valid inequalities A or C were not added. However, when the valid inequalities were added very few branches were required to prove optimality, and the CPU time was reduced to less than 6 minutes at most (see Table 3.11). This demonstrates that valid inequalities (3.4), (3.5) and (3.12), (3.13) are essential when searching for optimal solutions.

Table 3.11: CPU-time (in seconds) to obtain optimal solutions

Method	$\bar{t}$	t^{min}	t^{max}	$\sigma^2(t)$
Set I				
CEFLP-AB	36.92	4.58	177.99	2,125.20
CFPLP-BC	152.16	87.37	251.08	1,580.41
Set II				
CEFLP-AB	21.81	3.14	122.70	805.35
CFPLP-BC	208.65	162.07	345.81	7,147.27

3.10 Conclusions

In this chapter we analyse the simultaneous location problem of products and by-products. A product is produced at plants and has to be transported to customers. During the production process, a by-product is also generated. This by-product has to be transported to waste disposal units (WDUs). The problem is to find a minimum cost distribution structure which defines locations of plants and WDUs and coordinates product and by-product flows. This location problem is an extension of the well-known plant location problem. We consider both the uncapacitated and the capacitated formulation of the location problem of products and by-products.

The uncapacitated extended facility location problem (UEFLP)

- For the (UEFLP) formulation, we consider two lower bounding procedures, based on linear programming and Lagrangean relaxation. The linear programming bound is rather tight (within 3.4% from optimality on average) but requires considerable computation time. The 'Lagrangean' bound performs comparable to the linear programming bound but is, on average, much faster and less dependent on the problem dimension,

- In addition, we compare a number of new upper bounding heuristics. A simple round-off heuristic based on the linear programming relaxation performs only very modestly (within 3.8% from optimality on average). The sequential facility location heuristic solves the problem as two sequential single-level facility location problems. Solving these problems just once gives rather bad results. However, the multi-pass version, based on the multiplier adjustment principle, gives better results (within 1.4% from optimality on average) and is very fast. We conclude from our computational results that simple and fast (greedy) cost savings heuristics perform better than the other heuristics and require a very reasonable amount of computation time.

*The capacitated extended facility location problem (*CEFLP*)*

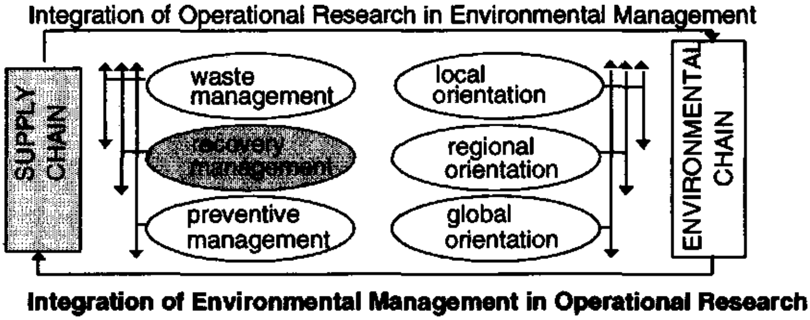
- For the (CEFLP) formulation, we compare the quality of the linear programming formulation with the linear programming formulation of the capacitated flow path location problem (e.g. Barros [13]). We show that the LP-relaxations to both formulations yield the same lower bound values. For both formulations, valid inequalities can be added to improve the quality of the lower bounds. From a computational study we conclude that valid inequalities on flow variables (based on Davis and Ray [46] and Ro and Tcha [131]) are rather effective in strengthening the LP lower bound. Empirically, we find that the valid inequalities on the binary location variables (Guignard and Opaswongkarn [65]) are not very effective in improving the LP lower bound,

- In addition to the lower bounding procedures we propose a number of upper bounding heuristics, based on *(i)* rounding-off the solutions to the LP relaxations, and *(ii)* constructing a feasible solution by sequentially solving two capacitated plant location problems. The effectiveness of the round-off strategies depends heavily on the quality of the lower bounding solution. Therefore, the most effective round-off strategies exploit the linear programming formulations *with* the appropriate valid inequalities. The sequential facility location heuristic does not yield good results in general. The quality of the solutions obtained by the single pass version is poor. The multi-pass version yields solutions of reasonable quality, but is very expensive in terms of required CPU-time. Summarizing, we advise to use the LP based round-off strategies to obtain upper bounds. Using these upper bounds, optimal solutions can be obtained relatively fast, using a standard branch-and-bound procedure.

The model formulations and solution procedures suggested in this chapter establish a first attempt at studying the coordinated control of product and by-product flows within distribution networks. Although our (computational) results are encouraging, we realize that more research is needed in this area. Future research may focus on *(i)* improving the solution procedures presented here, e.g. by developing dual-ascent procedures and implementing polyhedral techniques, *(ii)* applying the solution procedures to real-life problems, as described in Section 3.1.2, and *(iii)* modelling risk related to by-product transportation.

Chapter 4

Manure utilization in farm management



This chapter illustrates the adaptation of OR models if environmental issues are incorporated in the supply chain through recovery management.

Recovery management offers several options to recover and utilize used products and by-products. Recovery management has a large effect on production planning and scheduling. Recovery models are in general much harder to solve than models without recovery options, due to feedback loops (causing non-linearities), and uncertainty in time, quality and quantity of the supply of used products (causing stochastic processes).

We consider the effect of introducing recovery in the management of a farm. In this problem, the farmer has to determine a profit maximizing combination of farm activities (e.g. growing wheat, raising cattle) given farm constraints (e.g. acreage, labour). Recovery management translates into the choice between disposing manure or applying it for fertilizing purposes, replacing inorganic fertilizers.

4.1 Introduction

4.1.1 Problem description

One of the most important problems in the utilization of by-products is the presence of undesirable substances. In order to fulfil (environmental) quality conditions, recycling is only permitted if the concentration of problematic contents like zinc, lead, or pesticides is below a specified level. Therefore, Operational Research models for recycling or reuse have to take into account constraints and uncertainties regarding the environmental quality of the used products or by-products.

The illustrative example in this chapter focuses on the utilization of an otherwise useless by-product (manure) as a fertilizer in cattle husbandry. The Dutch government restricts the use of manure for fertilizing purposes through the introduction of environmental standards for spreading the manure in the fields. These restrictions make it difficult to develop optimal farm plans. Linear programming has appeared to be very useful in finding a profit maximizing combination of farm activities that is feasible with respect to a set of fixed farm constraints. Profits are obtained by selling e.g. milk, maize or meat. Farm constraints are acreage, the availability of labour, the demand for fertilizer and fodder etc. Introducing the choice between disposing or applying manure changes the farm management model from a linear programming formulation into a bilinear programming formulation, i.e. a model formulation of which the objective function and the constraint set are linear for one set of decision variables when the other set of variables is fixed, and vice versa. The non-linearity gives rise to, in principle, many local optimal solutions. In this chapter, we suggest a solution method for this problem.

Recovery modelling is applicable to various situations:

Iron and steel industry Penkuhn et al. [123] describe the recovery and utilization of by-products in iron and steel works. Secondary by-products like dust and sludges can no longer be stored in a landfill because of ground water pollution. Zinc elements in the dust and sludges lead to technical problems in the recycling of the by-products. The authors formulate a non-linear planning optimization model for by-product management in this industry. The most important nonlinearities result from the properties of the chemicals and processes and the recycling loops in the material flows.

Refinery The pooling problem is a classical problem in refinery modelling (Foulds et al. [59]). When crudes are supplied to the refinery, they have to be stored in tanks to be refined later. Due to the limited capacity of the storage tanks, several crudes (with different qualities) have to be pooled. The clients ask for products with a specific quality. The objective is to maximize contribution to profits, defined by sales of products minus the purchase costs of the crudes. The products arise from a mixture of the crudes, so that their quality depends on the quality of the crudes in the different tanks. This pooling procedure gives rise to non-linear programming models.

4.1.2 Contents

The sequel of this chapter is organized as follows. Section 4.2 introduces a mathematical formulation of the extended farm management problem. Section 4.3 modifies the model into a generalized bilinear problem. We compare the farm management problem with the pooling problem, one of the other applications of bilinear programs. Also, some theoretical results for the problem are given. Section 4.4 presents some classical solution methods. Section 4.5 describes the development of a branch-and-bound algorithm that makes use of theoretical results obtained for this specifically structured farm management model. Section 4.6 contains concluding remarks.

4.2 Formulation of the extended farm management problem

In this section, we introduce the utilization of manure in a traditional farm management problem (TFMP). The farm management problem has been studied for many years. The research station of horse, sheep and cattle husbandry in the Netherlands (Lelystad) was interested in solving a farm management problem that includes the utilization of manure as part of the farm activities, the extended farm management problem (EFMP).

Linear farm management models can be used to determine a profit maximizing combination of farm activities that is feasible with respect to a set of fixed farm constraints (Hazell and Norton [68]). The variable x_i represents the level of activity i, denoted by the number of hectares. The set I of activities i defines the possibilities in the farm organisation, such as the amount of cattle treated and fed in a particular way. The vector x gives the combination of activities chosen to be the farm plan. Each activity has a contribution γ_i (sales minus input costs) and some constraint parameters such as cattle density, amount of labour needed, milk production per hectare, and amount of fodder needed. The constraint parameters build the matrix A, also known as the technology set of the farm model. The set of feasible farm plans is determined by the vector of bounds b, representing e.g. total land, available labour and milk quota. The traditional farm management model formulation is:

$$\max\{\sum_{i\in I}\gamma_i x_i : x \in X\} \text{ with } X = \{x : Ax \leq b, x \geq 0\}$$

The extended farm management problem (EFMP) covers on one hand decisions on the farm plan with corresponding amounts of manure produced and demands for fertilizing. On the other hand, it covers decisions on the utilization of manure for fertilizing purposes. Choices in the farm plan determine the possibilities for the application of manure. Figure 4.1 outlines the situation.

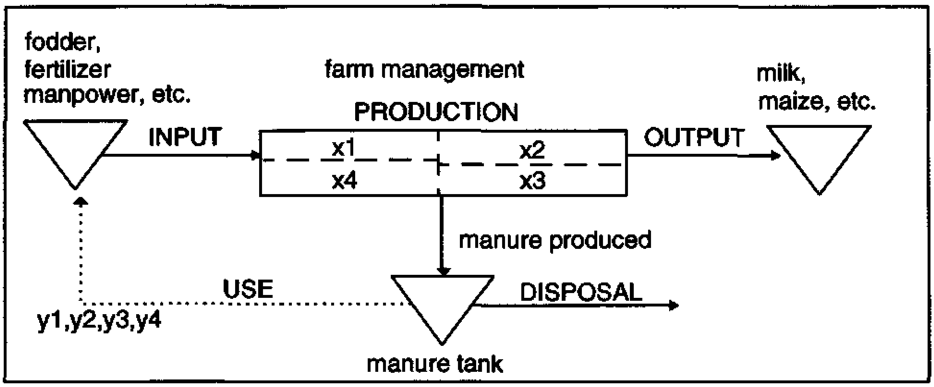


Figure 4.1: Scheme of the extended farm management problem

The following notation is used:

Indices:

$i, j \in I$ = indices for the farm activities
$k \in K$ = index for the nutrients

Parameters:

γ_i = profit per hectare using activity i minus costs of disposing manure and buying inorganic fertilizer
δ_j = costs of disposing manure and buying inorganic fertilizer for activity j
A = technology set of the farm model
b = set of feasible farm plans
q_{jk} = amount of nutrient k in manure from farm activity j (kg/ha)
d_{ik} = environmental standards for the utilization of nutrient k with farm activity i (kg/ha)

Decision variables:

x_i = number of hectares used for farm activity i
y_i = fraction of produced manure used on the land with activity i

We assume that the manure of the cattle is collected in one manure tank. The manure in the tank can be used to fertilize the land thus reducing the amount of inorganic fertilizer that has to be bought and applied on the field. Furthermore, the utilization of manure saves disposal costs. Disposal costs arise due to manure excess regulation in the intensive livestock sector. The variable y_i models the decision on the use of the manure for fertilizing the land going with farm activity i. Applied manure cannot exceed produced manure, and thus y_i is restricted by the following constraint:

$$\sum_{i\in I} y_i \leq 1$$

The cost savings of using the manure produced by activity j, instead of disposing it, is given by the parameter δ_j. These cost savings are higher if the manure contains more useful nutrients, and also if the prices of the replaced inorganic fertilizer are high. The index k represents all relevant nutrients, e.g. nitrate, phosphate and potassium. The total amount of nutrient k in the manure is given by $\sum_{j\in I} q_{jk}x_j$. The government has set standards (parameter d_{ik}) for the utilization of nutrient k on the land of activity i to reduce the contribution of the intensive livestock sector to environmental problems. The environmental legislation can be formulated as:

$$y_i \times \sum_{j\in I} q_{jk}x_j \leq d_{ik}x_i \quad i \in I, k \in K$$

The farm management problem (EFMP) is mathematically formulated as:

$$z_{EFMP} = \max \quad \sum_{i\in I} \gamma_i x_i + \sum_{i\in I} y_i \sum_{j\in I} \delta_j x_j \tag{4.1}$$

$$\text{subject to} \quad Ax \leq b \tag{4.2}$$

$$\sum_{i\in I} y_i \leq 1 \tag{4.3}$$

$$d_{ik}x_i - y_i \sum_{j\in I} q_{jk}x_j \geq 0 \qquad i \in I, k \in K \tag{4.4}$$

$$x_i, y_i \geq 0 \qquad i \in I \tag{4.5}$$

This problem is a bilinear programming problem, which occurs in the literature (see e.g. Al-Khayyal [5]). To illustrate the formulations, ideas and solution methods for the farm management problem, we introduce a simple example with two possible farm activities and environmental rules for three nutrients. The numbers in this example are completely arbitrary and have no resemblance with real data.

The model formulation for this example (EX) is:

$$z_{EX} = \max \qquad 20x_1 + 70x_2 + (y_1 + y_2)(70x_1 + 95x_2) \tag{4.6}$$

subject to

$$x_1 + x_2 \leq 10 \tag{4.7}$$

$$x_1 + 1.5x_2 \leq 12 \tag{4.8}$$

$$y_1 + y_2 \leq 1 \tag{4.9}$$

$$y_1(x_1 + 5x_2) \leq x_1 \; ; \; y_2(x_1 + 5x_2) \leq x_2 \tag{4.10}$$

$$y_1(4x_1 + x_2) \leq 5x_1 \; ; \; y_2(4x_1 + x_2) \leq 4x_2 \tag{4.11}$$

$$y_1(x_1 + x_2) \leq x_1 \; ; \; y_2(x_1 + x_2) \leq x_2 \tag{4.12}$$

$$x_1, x_2, y_1, y_2 \geq 0 \tag{4.13}$$

The objective (4.6) is to maximize the contribution of the farm activities i, including the possibility to use manure as a fertilizer. Constraints (4.7) and (4.8) define the set of feasible farm plans (e.g. upper bounds for the acreage and the production of milk). In constraint (4.9), the fraction of manure applied to the field of activities 1 and 2 is less than or equal to 1. The nutrient constraints (4.10), (4.11), and (4.12) represent the environmental regulations for fertilizing. In this example, one of the nutrient constraints, (4.10), dominates the others, i.e. if a farm plan satisfies constraint (4.10), then it also satisfies constraints (4.11) and (4.12). For example, if $y_1 \leq \frac{x_1}{x_1 + 5x_2}$, then $y_1 \leq \frac{5x1}{4x_1 + x_2}$ and $y_1 \leq \frac{x1}{x_1 + x_2}$ as long as all variables are non-negative. Specific characteristics can be derived for data instances with this property (the *one-nutrient problems*).

4.3 Analysis of the extended farm management problem

We discuss the relation with the pooling problem in Section 4.3.1 and the relation with bilinear problems in Section 4.3.2. Section 4.3.3 deals with the possibility of decomposing the problem, and in Section 4.3.4 we derive some theoretical results with respect to the optimal solutions for the extended farm management problem.

4.3.1 Pooling property

The non-linearity in (4.1) and (4.4) is caused by the fact that manure is mixed in a manure tank. The bilinearity in the constraints describing the quality of a product is called the *pooling property* (see Foulds et al. [59]). Various methods to solve the pooling problem have been studied, and most of these are based on successive linear programming.

The extended farm management problem (EFMP) has the same characteristics as the pooling problem because it is linear whenever either the decision vector x or y is fixed.

However, the pooling problem has fixed bounds on the concentrations of the end product, whereas in the (EFMP) formulation the concentrations may vary and the use of the end product is bounded by the input, i.e. the farm plan. One could say that the output (concentrations) is cyclically connected with the input (the farm plan), see Figure 4.1. The pooling problem has a linear objective function with bilinear balance restrictions whereas the problem (EFMP) has a bilinear objective function and bilinear constraints. The next section deals with this problem type.

4.3.2 The extended farm management problem as a bilinear problem

The roots of bilinear programming can be found in Nash [112], who introduced game problems involving two players. Each player must select a mixed strategy from fixed sets of strategies open to each, given knowledge of the payoff based on selected strategies. These problems can be treated by solving a bilinear program. A bilinear problem is characterised as:

$\min_{x,y\in\Omega} f(x,y) = c^T x + x^T A y + d^T y$, with Ω the feasible set for x and y.

The objective is a function of two groups of variables (x and y). The problem is linear in one group of variables if the other group is fixed, and vice versa. Bilinear problems are interesting from a research point of view, because of the numerous applied problems that can be formulated as bilinear programs (dynamic Markovian assignment problems, multi-commodity network flow problems or quadratic concave minimization problems).

In the easiest class of bilinear problems, the *traditional bilinear programs* (TBP), the feasible set Ω is the cartesian product $X \times Y$, with

$X := \{x : B_1 x \le b_1, x \ge 0\}$ and $Y := \{y : B_2 y \le b_2, y \ge 0\}$.

Global optimization algorithms to solve these problems have been developed e.g. by Falk [54] and Sherali and Shetty [141]. These algorithms guarantee finite convergence for all instances. The key property of the traditional model, used in almost all methods, is that the feasible region is expressed as the cartesian product of two polyhedra. This structure ensures the existence of an extreme-point global solution (Falk [54]).

Al-Khayyal [4] considers the feasible set $\Omega := \{(x,y) : Cx + Dy \le b,\ x \ge 0,\ y \ge 0\}$ in the *jointly constrained bilinear program* (JCBP). In this class of problems, interaction is allowed between the x and y variables in the constraints.

A further extension of the model is to include bilinear constraints, which results in the *generalized bilinear program* (GBP):

$$z_{GBP} = \min_{x,y\in\Omega} c_0^T x + x^T A_0 y + d_0^T y$$

with $\Omega := \{(x,y) : c_p^T x + x^T A_p y + d_p^T y \le b_p \, \forall p, \; Cx + Dy \le b, \; x \ge 0, \; y \ge 0\}$

The objective function of a generalized bilinear problem is a *bi-affine* function, that is affine for x and y for fixed y and x respectively. The feasible set Ω is a ***bipolyhedron***, i.e. a polyhedron in x and y for fixed y and x respectively (Al-Khayyal [5]).

The extended farm management formulation (EFMP) is a special case of the (GBP) model where constraints (4.2) and (4.3) represent the linear part and constraints (4.4) the bilinear part. Note that for this special case the jointly constrained part of (GBP) reduces to the cartesian product $X \times Y$, with

$$X := \{x : Ax \le b, x \ge 0\} \text{ and } Y := \{y : \sum_{i \in I} y_i \le 1, y \ge 0\}.$$

4.3.3 The extended farm management problem as a two step problem

The special structure of (EFMP) makes it possible to analyse the problem from the following point of view. For each x, the optimal y can be calculated. Given this optimal value for y ($y^*(x)$), we only have to solve a maximization problem in the x variables. The branch-and-bound algorithm in Section 4.5 uses this feature.

For convenience, we introduce $S(x)$ as the sum of the $y(x)$ variables. The expression $S(x)$ is in general equivalent to $\sum_{i \in I} \min_k \left(\frac{d_{ik} x_i}{\sum_{j \in I} q_{jk} x_j} \right)$ (using constraints (4.4)). The extended farm management problem in x variables, (EFMP$_x$), is:

$$\begin{array}{ll} z_{EFMP_x} = \max & (\gamma + S(x) \times \delta)^T x \\ \text{subject to} & Ax \le b \\ & S(x) \le 1 \\ & x \ge 0 \end{array}$$

For one-nutrient problems, the expression for $S(x)$ is much simpler. For the example (EX), the sum $S(x)$ can be expressed as $\frac{x_1 + x_2}{x_1 + 5x_2}$, since (4.10) is the only active constraint. This expression can be substituted in the objective function. For the resulting non-linear problem, the first-order Karish-Kuhn-Tucker conditions can be analysed as shown in Appendix A. The global maximum is $x^* = (10, 0)^T$ with corresponding optimal value $(1, 0)^T$ for the y variables and an objective value of 900. Figure 4.2 gives the graphical representation of the non-linear program for the example (EX$_x$).

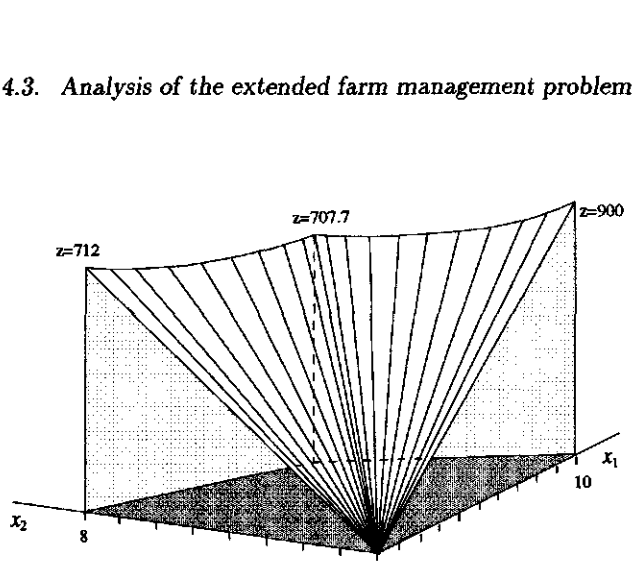


Figure 4.2: Graphical representation of (EX_x).

In the example (EX), no local optima are found in the interior of the feasible region of the variables $x_1, \ldots, x_m$. In Section 4.3.4, we show that this is a common characteristic for bilinear problems.

We define the *interior* of a bipolyhedron Ω as

$$\Omega_I := \{(x,y) : c_p^T x + x^T A_p y + d_p^T y < b_p \; \forall p, \; Cx + Dy < b, \; x > 0, \; y > 0\}$$

The *boundary* of a bipolyhedron Ω is defined as $\Omega_B := \{(x,y) : (x,y) \notin \Omega_I\}$. A *boundary solution* is a solution on the boundary of the bipolyhedron. Al-Khayyal and Falk [3] show that jointly constrained bilinear problems always have boundary solutions.

4.3.4 Boundary solutions

In this paragraph, we analyse the existence of boundary solutions for the extended farm management problem (EFMP). The property of boundary solutions can be used explicitly in branch-and-bound methods as will be outlined in Section 4.5, since this characteristic can reduce the computation time of these algorithms.

We first consider the one-nutrient problem, where one nutrient constraint (say for $k = k^*$) makes the other nutrient constraints redundant. The feasible region X is compact. The optimal value for $y_i(x)$ is $\frac{d_{ik^*} x_i}{\sum_{j \in I} q_{jk^*} x_j}$. Therefore, $S(x) := \sum_{i \in I} y_i(x)$ can be written as $\frac{d^T x}{q^T x}$, and the objective function (4.1) becomes

$$\min -(\gamma^T x + \frac{x^T \delta d^T x}{q^T x}) = \min \frac{x^T C x}{q^T x} \text{ with } C = -(\gamma q^T + \delta d^T).$$

Lemma 4.1 *Given a matrix C with at least one negative eigenvalue, and a vector q with only positive elements, consider the following problem*

$$\min\{\Phi(x) = \frac{x^T Cx}{q^T x} | Ax \leq b, \ x \geq 0\}$$

The minimum value of $\Phi(x)$, if it exists, is attained at the boundary of the polyhedron.

Proof: Let x^* be a minimum interior point. Then $\nabla\Phi(x^*) = 0$.
Define the following one-dimensional functions:

$$\begin{aligned} f(\lambda) &:= (x^* + \lambda r)^T C(x^* + \lambda r) \\ g(\lambda) &:= q^T(x^* + \lambda r) \\ \phi(\lambda) &:= \frac{f(\lambda)}{g(\lambda)} \end{aligned}$$

Since $\phi(0) = \Phi(x^*)$ and $\phi'(0) = r'\nabla\Phi(x^*)$, it holds that $\phi'(0) = 0$. The following relation between f and g can be obtained, using that $g^2(0) > 0$:

$$\phi'(0) = 0 \Rightarrow \frac{f'(0)g(0) - g'(0)f(0)}{g^2(0)} = 0 \Rightarrow f'(0)g(0) - g'(0)f(0) = 0 \qquad (*)$$

The expression for the second derivative of ϕ is

$$\phi''(0) := \frac{f''(0)g^3(0) - g''(0)f(0)g^2(0) - 2g(0)g'(0)(f'(0)g(0) - g'(0)f(0))}{g^4(0)}$$

Since $g^3(0) > 0$; $g^4(0) > 0$ (g is positive), $g''(0) = 0$ (g is affine), and using (*), it follows that $\phi''(0)$ has the same sign as $f''(0)$. We choose r such that $r^T Cr < 0$. This direction r always exists, since C has at least one negative eigenvalue. In this direction $f''(0) < 0$, and ϕ is concave in a neighbourhood of 0, which means that a better function value for Φ can be found in a neighbourhood of x^*. This counterparts the assumption that x^* is a global minimum. So x^*, if it exists, has to be a point at the boundary of the polyhedron. □

This lemma is a generalization of a lemma by Pardalos [120] on the existence of boundary solutions for indefinite fractional quadratic programming problems.

The one-nutrient problem satisfies the conditions of Lemma 4.1 if matrix C has at least one negative eigenvalue. As the vectors d, q and δ are positive, it is sufficient to have at least one positive element of the vector γ if the corresponding q-element has a strictly positive value. So, at least one farm plan should have a positive financial contribution to the profits, which is not a severe condition in practice.

The one-nutrient case is only realistic if the environmental standards for one of the nutrients dominate the environmental standards for other nutrients. If environmental legislation only holds for one nutrient (e.g. phosphate), the extended farm management problem is always a one-nutrient problem. In the near future, this will not be the case for the Dutch manure legislation as it contains standards for both phosphate and nitrogen (see also Chapter 6 of this thesis and VROM [161]). Fortunately, the existance of boundary solutions also holds for the extended farm management problem (EFMP) in general. Al-Khayyal and Falk [3] show that the solution to a (GBP) problem must be on the boundary of the $X \times Y$ space.

Lemma 4.2 (Al-Khayyal and Falk [3]) *If an optimal solution exists to the (*GBP*) problem, at least one optimal solution will be on the boundary of the bipolyhedral feasible set.*

This lemma states that the extended farm management problem (EFMP) has at least one global optimum (x^*, y^*) on the boundary of Ω. This optimum is not necessarily an extreme point (Al-Khayyal [4]). Lemma 4.3 shows that x^* of the global optimum (x^*, y^*) for (EFMP) can always be found on the boundary of X.

Lemma 4.3 *Given problem (*EFMP*) defined by (4.1)- (4.5), and $X := \{x \in \mathbb{R}^n : Ax \leq b,\ x \geq 0\}$ is a compact set, x^* of the solution (x^*, y^*) of (*EFMP*) is on the boundary of X.*

Proof: Given the optimal y^* for a (GBP) problem, (x^*, y^*) is a solution of a linear programming problem in x only. Let ($\text{EFMP}_{x|y^*}$) denote (EFMP) given the optimal value y^*. Constraints (4.4) define a cone

$$\mathcal{K} := \{x \in \mathbb{R}^n : (d_{ik}e_i - y_i^* q_k)^T x \geq 0\ ,\ i \in I, k \in K\}, \text{ with } e_i \text{ the } i^{th} \text{ unit vector.}$$

The optimal x^* can be found at a vertex of the feasible set of ($\text{EFMP}_{x|y^*}$) which is $X \cap \mathcal{K}$. Apart from the origin, $\mathcal{K}$ does not contain a vertex. If x^* is not the origin, then it is not a vertex of $\mathcal{K}$, so the solution is found on the boundary of X. □

4.4 Classical solution approaches to the extended farm management problem

4.4.1 Successive linear programming

A promising heuristic to solve a bilinear programming problem is *successive linear programming.* Starting with any $x^0 \in X$, find y^0 that optimizes the objective function over Y, then find x^1 that optimizes the objective function over X, and so on until the objective does not improve between two successive optimizations.

If the feasible set Ω is a cartesian product $X \times Y$, with X and Y convex sets and the objective function is differentiable and convex over $X \times Y$, then any limit point to this alternating procedure globally solves the problem (Wendell and Hurter [164]). If the objective function is biconvex, each limit point is a Karish-Kuhn-Tucker point (Konno [89]), but necessary conditions are needed for a limit point to be a local optimal solution to the biconvex problem.

For the (EFMP) formulation, these convergence theorems can not be used. Applying successive linear programming to (EFMP) can be very disappointing. The linear programs for (EFMP) in each iteration t are:

$$z_{EFMP_{x|y^t}} = \max \quad \gamma^T x + \delta^T x(\sum_{i \in I} y_i^t) \tag{4.14}$$

$$\text{subject to} \quad d_{ik} x_i \leq (q_k^T x) y_i^t \qquad i \in I, k \in K \tag{4.15}$$

$$Ax \leq b \tag{4.16}$$

$$x \geq 0 \tag{4.17}$$

$$z_{EFMP_{y|x^t}} = \max \quad \sum_{i \in I} y_i \tag{4.18}$$

$$\text{subject to} \quad y_i(q_k^T x^t) \leq d_{ik} x_i^t \qquad i \in I, k \in K \tag{4.19}$$

$$\sum_{i \in I} y_i \leq 1 \tag{4.20}$$

$$y \geq 0 \tag{4.21}$$

Note that a feasible solution for the y-variables can be found, given any $x^t \in X$ (e.g. $y = 0$). The reverse statement does not necessarily hold. The successive linear programming procedure is summarized as follows:

Successive linear programming procedure:

Step 1	Start with any feasible y^0, $t = 1$
Step 2	Given y^{t-1}, find x^t that minimizes $z_{EFMP_{x\|y^{t-1}}}$ over the feasible region for x.
Step 3	Given x^t find y^t that minimizes $z_{EFMP_{y\|x^t}}$ over the feasible region for y.
Step 4	If $\|y^t - y^{t-1}\| \leq \epsilon$ then STOP else $t := t + 1$ and return to Step 2.

For the example (EX), successive linear programming stops after at most two iterations. The LP solution $x^* = x^1$ is a point on the boundary of X. Only for the starting vector $y^0 = (1, 0)^T$, the successive linear programming method finds the global maximum $x^* = (10, 0)^T$. This example illustrates that successive linear programming can perform poorly for the extended farm management problem.

4.4.2 Non-linear programming: local search

Perhaps the most common method to solve problems like the farm management problem is to apply standard nonlinear programming software. As illustrated in Figure 4.2, (EFMP) may contain many local optima. The global optimum could be discovered by starting a nonlinear programming local search from various starting points. Törn and Žilinskas [148] give an overview of global optimization methods, based on local searches.

Implementation of a local search for the example (EX) with the computer package GAMS (MINOS 5.3) gives different local optima for various starting points (Table 4.1):

Table 4.1: Results of a local search for (EX)

Starting point				Local optimum				Objective
x_1	x_2	y_1	y_2	x_1	x_2	y_1	y_2	
0.0	0.0	0.0	0.0	10	0	1.00	0.00	900.0
3.0	3.0	0.2	0.2	6	4	0.23	0.15	707.7
3.0	0.0	0.0	0.0	0	8	0.00	0.20	712.0

For the starting point (0,0,0.2,0.2), MINOS could not even find a local optimum, but got stuck at the starting point. Finding the global optimum requires finding a starting point in the region of attraction of the global optimum. This is hard to verify.

4.4.3 Branch-and-bound algorithms for bilinear programs

Many global optimization problems can be solved by means of branch-and-bound. Linear programs are often used as subproblems that are solved in a partition scheme for finding global solutions. Horst and Tuy [73] provide a general framework for branch-and-bound in global optimization.

Falk [54] developed the first branch-and-bound procedure for the traditional bilinear program (TBP). It guarantees convergence to a global optimal solution in a finite number of steps. Bounds are obtained by solving linear programming relaxations and branching is accomplished by holding individual variables out of the basis for each branch when using the simplex method to solve the subproblems. Al-Khayyal and Falk [3] developed a branch-and-bound algorithm for the (JCBP) problem. The algorithm branches into four nodes based on a partition of the parent node's rectangular set $C = \{(x, y) : l_x \leq x \leq u_x, l_y \leq y \leq u_y\}$ and bounding is achieved by minimizing the convex envelope of the objective function over the subset of the feasible region, $\Omega \cap C^p$, for the p^{th} partition set considered. The same can be done for the (GBP) problem (Al-Khayyal [5]).

The next section describes a specific branch-and-bound method for the extended farm management problem, that uses the theoretical results from this section.

4.5 A new branch-and-bound algorithm

Contrary to Al-Khayyal [5], partition sets in the branching are not defined in the $X \times Y$ space, but only in the X-space using the decomposition approach described in Section 4.3.3. The rectangular partition set $C^p : [l^p, u^p]$ is defined as the p^{th} block created in the branching tree (l and u have the same dimension as x). Each partition set C^p that does not intersect with the boundary of X can be deleted, using Lemma 4.3.

Furthermore, bounds are not based on convex envelopes, but on the monotonicity of $z(x, S(x))$. At each iteration of the branch-and-bound algorithm we need to calculate the maximum of $S(x)$ over all $x \in (C^p \cap X)$. This value is not easy to find, so we try to find a good upperbound σ^p for $S(x)$ that is easy to obtain.

Section 4.5.1 presents the interior check algorithm that checks if a box intersects with the boundary of X. Section 4.5.2 discusses the calculation of the upperbound σ^p. Section 4.5.3 gives an outline of the complete branch-and-bound framework and provides results for the example (EX).

4.5.1 Interior check algorithm

To check whether a box $C^p = [l^p, u^p]$ is interior with respect to the polyhedron X, we write X as a set of linear inequalities $\{x : Ux \le v\}$, where v_i $(i = 1, \cdots, n)$ is the right-hand-side of the i^{th} linear inequality.

Interior check algorithm:

Step 0	i=1
Step 1	Calculate the vector $w = (w_1, \cdots, w_j, \cdots w_m)^T$ where $w_j = \begin{cases} l_j^p & \text{if } u_{ij} < 0 \\ u_j^p & \text{if } u_{ij} \ge 0 \end{cases}$
Step 2	If $u_i^T w \ge v_i$ then STOP; box is not interior else $i := i + 1$
Step 3	If $i = n + 1$ then STOP; box is interior else goto Step 1

4.5.2 Threshold algorithm for fractional programming

The upperbound derivation of the maximum value for S in (the feasible part of) each box C^p is as follows:

$$\begin{aligned} \max_{x \in C^p \cap X} S(x) &= \max_{x \in C^p \cap X} \left\{ \Sigma_i \min_k \frac{d_{ik} x_i}{q_k^T x} \right\} \le \max_{x \in C^p} \left\{ \Sigma_i \min_k \frac{d_{ik} x_i}{q_k^T x} \right\} \le \\ &\le \max_{x \in C^p} \min_k \left\{ \frac{d_k^T x}{q_k^T x} \right\} \le \min_k \max_{x \in C^p} \left\{ \frac{d_k^T x}{q_k^T x} \right\} \end{aligned}$$

So, we choose $\sigma^p := \min\{1, \min_k \max_{x \in C^p}\{\frac{d_k^T x}{q_k^T x}\}\}$. For each nutrient k, the fractional programming problem (FP_k) has to be solved, with the demand and supply vectors (d and q) strictly positive:

$$z_{FP_k} = \max\{\phi_k(x) := \frac{d_k^T x}{q_k^T x} : x \in C^p\}$$

Once the optimal solution for each problem (FP_k) is found, it is easy to determine σ^p. In order to solve the fractional programming problem (FP): $z_{FP} = \max\{\frac{f(x)}{g(x)} : x \in X\}$, Pardalos and Phillips [121] consider the global optimization problem (GP):

$$z_{GP} = \max\{f(x) - \lambda g(x) : x \in X\} \text{ with } \lambda \in \mathbb{R}.$$

The fundamental result, relating the (GP) problem to the (FP) problem, is:

Lemma 4.4 (Dinkelbach [48]) *x^* solves the fractional programming problem* (FP) *if and only if x^* solves the global optimization problem* (GP) *with constant $\lambda^* = \frac{f(x^*)}{g(x^*)}$.*

According to this theorem, $\lambda_k^* = \frac{d_k^T x^*}{q_k^T x^*}$ for the fractional programming problems (FP_k). For this constant λ_k^*, the global optimization problem (GP_k) is the linear programming problem

$$z_{GP_k} = \max\{\sum_{i \in I}(d_{ik} - \lambda_k^* q_{ik})x_i : x \in C^p\}$$

If $d_{ik} - \lambda_k^* q_{ik} < 0$ then it is optimal to decrease x_i as far as possible ($x_i^* = l_i^p$), and if $d_{ik} - \lambda_k^* q_{ik} \geq 0$ then it is optimal to increase x_i as far as possible ($x_i^* = u_i^p$). That is:

$$x_i^* = \begin{cases} l_i^p & \text{if } \frac{d_{ik}}{q_{ik}} < \lambda_k^* \\ u_i^p & \text{if } \frac{d_{ik}}{q_{ik}} \geq \lambda_k^* \end{cases}$$

For each k, λ_k^* can be seen as the *threshold* value, which determines in which corner of the box C^p the value x^* is obtained. An algorithm to find this x^* is described below:

Threshold algorithm:

Step 1	Fix all x_i at l_i^p and calculate the objective value ϕ_k. Initiate ϕ_k^* as ϕ_k.
Step 2	Renumber all x_i, such that $\frac{d_{1k}}{q_{1k}} \leq \frac{d_{2k}}{q_{2k}} \leq \cdots \leq \frac{d_{mk}}{q_{mk}}$. Pick up the first element of the sorted vector x.
Step 3	Put the chosen element x_i on its upper bound u_i^p and calculate the new ϕ_k. If ϕ_k exceeds ϕ_k^* then goto Step 4, else put the chosen element back to its lower bound l_i^p and STOP: ϕ_k^* is the optimum.
Step 4	Replace ϕ_k^* by the new ϕ_k and take the next element of the x vector, goto Step 3.

The upperbound for $S(x)$, to be used in the bounding strategy of the branch-and-bound algorithm, is $\sigma^p := \min\{1, \min_k \phi_k^*\}$.

4.5.3 Outline of the branch-and-bound algorithm

The algorithm starts with the smallest rectangular box C^1 that includes X as a whole ($X = \{x : Ax \leq b\ ,\ x \geq 0\}$). The interior of C^1 is strictly positive. In *Step 1*, the value of σ^1 is obtained using the threshold algorithm. A global upper bound to z_{EFMP}, z_U, is found by maximizing $z(x, \sigma^1)$ over X. For the solution x^1, we calculate the optimal y and the corresponding $S(x^1)$, solving the linear programming problem ($\text{EFMP}_{y|x^1}$) and the first lower bound $z_L = z(x^1, S(x^1))$ is found.

At each iteration, there is a list P of boxes C^p. One of these boxes is split by dividing the box into two parts of equal volume over the longest edge (bisection). This creates two new boxes (*Step 2*).

For each of these boxes C^p we check whether the box is totally interior with respect to X using the algorithm of Section 4.5.1. If the box is interior, it is discarded and we proceed with another box. If the box is not interior, we continue with *Step 3.* A new upper bound $z_u^p := z(x^p, \sigma^p)$ is calculated. A feasible solution (x^p, S^p) is obtained by solving the simple LP problem ($\text{EFMP}_{y|x^p}$), which results in a new lower bound $z_l^p := z(x^p, S^p)$. If this lower bound is higher than z_L, then $z_L := z_l^p$ and the solution x^p is saved.

In *Step 4* the list of boxes is checked: If the upper bound z_u^p of some box C^p is below the new lower bound z_L, there is no use to analyse this box C^p any further, and this box can be neglected.

We select a new box for further division by means of the highest upper bound z_u^p, which is the new z_U (*Step 5*). During the branch-and-bound process, the gap between upper and lowerbound, $|z_U - z_L|$, is decreasing. The algorithm stops if this gap is less than a preset tolerance ϵ_1, or if the list of boxes is empty. In order to guarantee convergence of the overestimate σ^p to the maximum of $S(x)$ and to speed up the algorithm, boxes that are too small (i.e. with a volume smaller than a preset tolerance ϵ_2) are also discarded.

Implementation of the branch-and-bound procedure for the example problem (EX) gives the following result. After 15 iterations, the point $x_{best} = (9.75, 0.25)$ gives the best lower bound $z_L = 855$. The best upper bound is $z_U = 919$, so these bounds enclose the optimum value $z^* = 900$ at (10,0). Only three small partition sets in the neighbourhood of $x^* = (10, 0)$ remain on the list (see Figure 4.3).

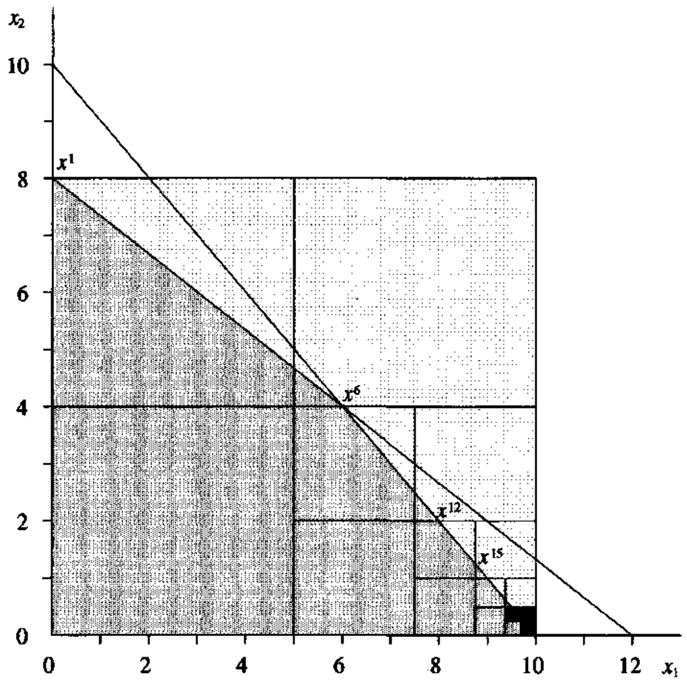


Figure 4.3: Partition after 15 iterations of the branch-and-bound algorithm

The formal branch-and-bound description is:

Branch-and-bound algorithm:

Step 0	Give tolerances ϵ_1 and ϵ_2
Step 1	The list P consists of one box $C^1 = [l^1, u^1] \supset X$ Calculate σ^1. Initiate z_U as $z_u^1 := \max_{x \in X} z(x, \sigma^1)$. The value of x corresponding to this maximum is denoted by x^1. For this x^1 initiate z_L as $z_l^1 := z(x^1, S^1)$ and $x_{best} := x^1$.
Step 2	Divide the box under consideration over the longest edge into two boxes of equal volume and for both boxes C^p goto Step 3.
Step 3	First use the interior check algorithm: If the box is interior, stop analysing the box else determine σ^p Find $z_u^p := \max_{x \in C^p \cap X} z(x, \sigma^p)$, and the corresponding solution x^p. If the box does not contain feasible solutions, stop analysing the box. If $z_u^p > z_L$ then find S^p and $z_l^p := z(x^p, S^p)$. If $z_l^p > z_L$ then $z_L := z_l^p$ and $x_{best} := x^p$. Put the box C^p in the list of boxes P.
Step 4	Delete all boxes in the list with $z_u^p < z_L$. Delete all boxes with a volume smaller than ϵ_2. If the list is empty then STOP.
Step 5	Search for the box C^p in the list P with the highest upper bound : $z_U := z_u^p$, this is the new box we consider. If $\lvert z_U - z_L \rvert < \epsilon_1$ then STOP, else goto Step 2.

4.6 Conclusions

Including the utilization of manure in a traditional farm management model gives the extended farm management problem (EFMP). This problem is a special form of a generalized bilinear programming problem (GBP) and is closely related to the pooling problem (Foulds et al. [59]). Quality conditions on the supply of substances cause nonlinearity in this type of problems, resulting in many different local optimal solutions. For the extended farm management problem (EFMP), a global optimal solution exists at the boundary of the set of feasible points.

We analyse global optimization methods for the extended farm management problem and illustrate their behaviour with an example. The successive linear programming approach for convex bilinear problems is not always satisfactory. The use of nonlinear programming codes can result in different local optima for different starting points. These codes can be applied as local optimization procedures in a multi-start method in an attempt to obtain the global optimum. The global optimum can always be obtained by a branch-and-bound procedure (e.g. Al-Khayyal [5]). Using a decomposition approach to (EFMP), the subsets used for branching can be defined in a subspace of the feasible area. In this specific branch-and-bound procedure, upper estimates are obtained by an algorithm for fractional programming on a hyperrectangle.

Efficient solution methods for the extended farm management problem are essential for research stations of cattle husbandry to stimulate the utilization of manure as an alternative for inorganic fertilizers: Successive linear programming is easy to implement and researchers are familiar with the method. However, the worst-case behaviour is very poor. More research is necessary to analyse the average-case behaviour of this approach, using real-life data. Branch-and-bound procedures for bilinear programming guarantee optimal solutions. Unfortunately, these procedures are still in development and need to be improved before they can be used in practice. Research stations need userfriendly software systems which allow for the use of efficient algorithms for special-structured problems.

Problems such as the extended farm management problem are challenging both from a practical point of view as research stations – giving advice to farmers – are not used to incorporate the utilization of manure in the development of farm plans and from an academic point of view as they require the development and improvement of new Operational Research algorithms.

Appendix A

Constrained non-linear programming problems (NLP) involve maximization of a smooth nonlinear function subject to smooth inequality constraints on a finite set of continuous variables:

$$z_{NLP} = \max \quad f(x_1, x_2, \cdots, x_n) \tag{4.22}$$

$$\text{subject to} \quad g_i(x_1, x_2, \cdots, x_n) \leq b_i \qquad i = 1, \cdots m \tag{4.23}$$

Under certain regularity conditions (see Bazaraa and Shetty [17], p. 137) the following theorem holds:

Theorem *If $\bar{x} = (\bar{x_1}, \cdots, \bar{x_n})$ is an optimal solution to (NLP) then $\bar{x} = (\bar{x_1}, \cdots, \bar{x_n})$ must satisfy the m constraints in (4.23), and multipliers $\bar{\lambda_1}, \cdots, \bar{\lambda_m}$ exist, satisfying the following Karish-Kuhn-Tucker (KKT) conditions*

$$\frac{\partial f(\bar{x})}{\partial x_j} - \sum_{i=1}^{m} \bar{\lambda_i} \frac{\partial g_i(\bar{x})}{\partial x_j} = 0 \qquad j = 1, \cdots, n \tag{4.24}$$

$$\bar{\lambda_i}[b_i - g_i(\bar{x})] = 0 \qquad i = 1, \cdots, m \tag{4.25}$$

$$\bar{\lambda_i} \geq 0 \qquad i = 1, \cdots, m \tag{4.26}$$

The non-linear programming formulation for the example is (EX_x):

$$\begin{aligned} z_{EX_x} = \max \quad & 20x_1 + 70x_2 + \frac{(x_1 + x_2)}{(x_1 + 5x_2)} \times (70x_1 + 95x_2) \\ \text{subject to} \quad & x_1 + 1.5x_2 \leq 12 \\ & x_1 + x_2 \leq 10 \\ & -x_1 \leq 0 \\ & -x_2 \leq 0 \end{aligned}$$

The optimal solution to (EX_x) must satisfy:

- $(x_1, x_2) \in X = \{x : x_1 \geq 0, x_2 \geq 0 \mid x_1 + x_2 \leq 10 \; ; \; x_1 + 1.5x_2 \leq 12\}$
- $\frac{\partial f(x)}{\partial x_j} - \sum_{i=1}^{4} \lambda_i \frac{\partial g_i(x)}{\partial x_j} = 0$ for $j = 1, 2$.
- $\lambda_1 = 0$ or $x_1 + 1.5x_2 = 12$
- $\lambda_2 = 0$ or $x_1 + x_2 = 10$
- $\lambda_3 = 0$ or $x_1 = 0$
- $\lambda_4 = 0$ or $x_2 = 0$
- $\lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_3 \geq 0, \lambda_4 \geq 0$

After some calculation we get

$$\frac{\partial f(x)}{\partial x_1} - \sum_{i=1}^{4} \lambda_i \frac{\partial g_i(x)}{\partial x_1} = 0 \Leftrightarrow \frac{90x_1^2 + 900x_1x_2 + 1230x_2^2}{x_1^2 + 10x_1x_2 + 25x_2^2} - \lambda_1 - \lambda_2 + \lambda_3 = 0$$

$$\frac{\partial f(x)}{\partial x_2} - \sum_{i=1}^{4} \lambda_i \frac{\partial g_i(x)}{\partial x_2} = 0 \Leftrightarrow \frac{-115x_1^2 + 890x_1x_2 + 2225x_2^2}{x_1^2 + 10x_1x_2 + 25x_2^2} - 1.5\lambda_1 - \lambda_2 + \lambda_4 = 0$$

Table A.1 shows the KKT-points, found by solving these equations (KKT-points for which $x \notin X$ or $\lambda \leq 0$ are eliminated).

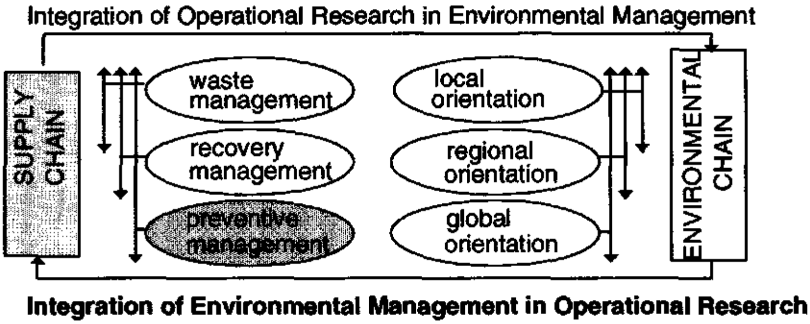
Table A.1: KKT-points to the (EX_x) problem

nr	x_1-value	x_2-value	z-value	λ_1	λ_2	λ_3	λ_4
1	0	8	712	59.3333	0	10.1333	0
2	3.5027	5.6649	692.2338	57.6862	0	0	0
3	6	4	707.6923	24.5562	41.3018	0	0
4	6.8542	3.1458	702.0794	0	70.2079	0	0
5	10	0	900	0	90	0	205

After examining the gradients of f in all directions we can conclude that *(i)* KKT-points 1 and 3 are local maxima in all feasible directions, *(ii)* KKT-point 2 is a local minimum over the boundary but is a local maximum over the line ($x_2 = \frac{5.6649}{3.5027} \times x_1$) in the interior region and KKT-point 4 is a local minimum over the boundary but is a local maximum over the line ($x_2 = \frac{3.1458}{6.8542} \times x_1$) in the interior region, and *(iii)* the global maximum is obtained in (10,0).

Chapter 5

Environmental impacts of fat blends



This chapter illustrates a 'cradle to grave' modelling approach that is necessary for preventive management *in the supply chain.*

With preventive management, firms have the flexibility to decide where and how to cut back pollution and optimize their behaviour. This approach can lead to adaptation of raw materials, product redesign and changes in the production process. Preventive management for sustainable production requires the incorporation of environmental information in the product development.

In this case study, we deal with the environmental improvement of fat blends for the production of margarines. We describe a multi-disciplinary methodology to use environmental information in the daily decision making process of formulating the fat blends. The choice of fats is usually based on costs, given a set of technical constraints. The incorporation of environmental information supports a deliberate trade-off between costs and environmental performance of the product portfolio.

5.1 Introduction

5.1.1 Problem description

Since 1992, Van den Bergh Foods (a subsidiary of Unilever) has studied the possibilities to improve the environmental performance of edible fats (margarines), a major product category of Van den Bergh Foods and of Unilever as a whole. The fatty portion of margarines usually consists of a blend of several oils. The Environmental Department of Van den Bergh Foods has been gathering environmental information for all processes, necessary to make margarines (e.g. growing oil-seeds, extracting, refining and blending the oils). This environmental information has to be combined with the product development system, used by the Production Department and the Marketing Department, that defines the optimal blend of oils in each type of margarine.

In general, preventive management requires a full environmental evaluation of products and processes in order to replace or redesign products and processes and adapt raw materials. For some years now, methods have been developed for assessing the environmental impacts of products and processes. One of the most promising instruments is life cycle analysis (LCA). The central idea of LCA is to investigate the entire life cycle of a product from cradle to grave, with all material flows that are relevant for that product. Unfortunately, most LCAs never go beyond evaluating the contribution of a product or process to a list of environmental problems, e.g. product A has a lower contribution to global warming than product B, but has a higher contribution to acidification. If the decision maker has to choose between product A and B based on total environmental performance, these results are not satisfactory. It is essential to have an unambiguous environmental index, representing the environmental performance of a product or process, in order to be able to improve the production process. Therefore, preventive management needs *(i)* an instrument such as LCA to analyse the contribution of products and processes to environmental problems, *(ii)* an instrument to determine weighing factors between different environmental problems and *(iii)* an instrument to analyse, manage and improve the full environmental performance of a product system.

Other applications of combining Operational Research with LCAs are:

Integral evaluation of air pollution Kroon et al. [91] describe a method to determine weighing factors to compare emissions in the transportation sector that contribute to different environmental problems. They develop a system for the integral evaluation of air pollution using qualitative multiple criteria decision making. This system is applied to the situation of two people moving a distance of 1000 kilometers. This tour can take place by car, by bus, by the high speed train (TGV), or by airplane. Emissions are calculated for each of the transportation modes. A quantitative statement on the most environmentally friendly way of transportation becomes possible using the integral evaluation system.

Thermoplastics Azapagic and Clift [11] couple LCA with linear programming modelling to facilitate analysing and managing the environmental performance of a complete product system. Linear programming is used to show changes in the environmental burdens which result from marginal changes in activities. Moreover, if environmental burdens are aggregated to a single environmental impact function, the LP solution can give the environmental optimum of the system. The idea behind this approach is illustrated by a simplified analysis of a system to produce thermoplastics. The LCA includes all operations and activities from the extraction of raw materials from the earth up to production of thermoplastic products. The linear programming model maximizes profit subject to constrained production of polymers to find the economic optimum or minimizes environmental burdens to find the environmental optimum.

Our approach combines LCA studies with decision support methods such as the Analytic Hierarchy Process (AHP) of Saaty [134] and linear programming to integrate environmental aspects into the decision process of formulating fat blends. Figure 5.1 shows the methodology of combining the three instruments.

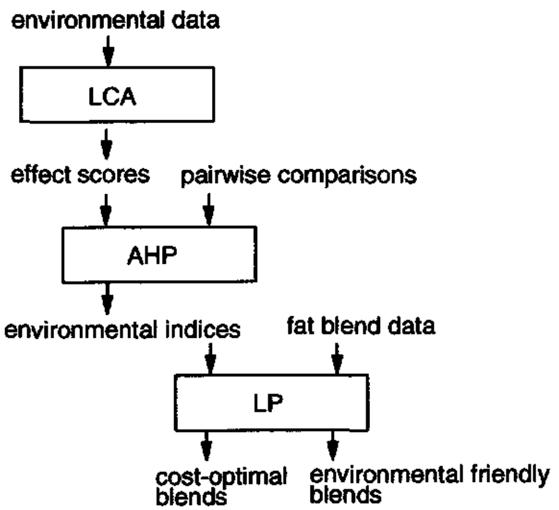


Figure 5.1: A multi-disciplinary approach for the environmental evaluation of fat blends

In order to choose oils on the basis of their environmental performance, they should have an environmental measure or index that can be used in the decision making in conjunction with costs. Therefore, we analyse the environmental effects of oils, using

LCA. We evaluate the oils using AHP, a tool for multiple criteria decision problems. This results in a one-dimensional environmental index for each refined oil. We use a linear programming blending model to optimize the environmental performance of the fat blends.

5.1.2 Contents

The organization of this chapter is as follows. The next section presents the principles of life cycle analysis and some examples of applying life cycle analyses. Section 5.3 describes briefly the Analytic Hierarchy Process method for the valuation of environmental problems and the use of linear programming for the evaluation and improvement of products. Section 5.4 describes the implementation of combining life cycle analysis with optimization methods for the environmental improvement of margarines. This case study illustrates the usefulness of integrating optimization techniques with the results from life cycle analysis studies. Section 5.5 provides some conclusions and recommendations for further research.

5.2 Life cycle analysis

Life cycle analysis (LCA) is defined as: *"a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment and to identify and evaluate opportunities to affect environmental improvements"* (SETAC [139], p. 3).

LCA has its roots as far back as the early 1960s. One of the first studies was conducted for the Coca Cola Company in 1969. The early life cycle analyses required too much data efforts for widespread application (Ayres and Cummings-Saxton, 1975). Currently, data handling is much easier and LCA is becoming a popular and effective tool for environmental analysis.

Important categories of LCA application are product improvement, product information, ecolabelling and the exclusion or admission of products from or to the market. LCA can also be applied to assess strategies on matters such as waste management. Life cycle analyses can be applied to, in principal, all types of products. Below, three classes of products will be presented where LCA's have been applied.

- *Household products*:
  Life cycle analyses for household products compare products with the same function but with a different lifetime. Well-known examples are the life cycle studies on

cotton diapers vs. paper diapers and porcelain tea-sets vs. plastic cups. The main problem with this type of LCA's is the weighing problem based on a ranking of environmental effects. Reusable products such as cotton diapers and porcelain cups add to the environmental problems of water pollution and energy use. Disposable products such as paper diapers and plastic cups add to the environmental problems of scarce resources and waste disposal. The choice for an environmentally-friendly product relates to the choice for important environmental problems.

- *Packaging materials*:
  Public attention has focused primarily on product information of types of packaging, e.g. milk packaging systems and alternatives for beverage containers. These life cycle studies do not compare different products, but different packages for the same product, basically paper, glass, or plastics. However, the influence of the type of packaging on the quality of the product is very important. The main problem with this type of LCA's is the comparability. It may easily occur that two studies on the same packaging alternatives give different outcomes based on the same data. For example, life cycle studies comparing disposable milk cartons with refillable polycarbonate bottles give different results depending on the assumption which processes are relevant and which are not.

- *Construction industry*:
  LCA's in the construction industry are usually meant for product improvement using scenario studies of the behaviour of products in different situations. Examples are life cycle studies on window-frames, glazing systems, painting systems, and floor-covering. This type of LCA's can also be used for ecolabelling or exclusion of the market (e.g. rain forest wood for furniture).

Guinée [66] identifies five steps in the process of performing a LCA:

1. goal definition
2. inventory analysis
3. classification
4. evaluation
5. improvement analysis

These five steps will be discussed below.

5.2.1 Goal definition

In the first part of a LCA the goal is determined: is the study meant for improvement of a given product, design of a new product or the granting of an ecolabel? Three major decisions have to be made.

- The *goal* of the study has to be stated, e.g. to obtain information about existing products, to analyse strategies for product improvement or to compare products.
- The intended *depth* of the study has to be stated. Will all possible environmental effects be investigated or just a selection that is particularly relevant? How many processes will be taken into account within the system boundaries?
- The *functional unit* for the LCA has to be established. This unit is defined as *"a measure of performance which the system delivers"*. Examples of functional units are: the packaging used to deliver a given volume of beverage or the amount of detergents necessary for a standard household wash (SETAC [139], p. 13).

5.2.2 Inventory analysis

In this part of the method, three elements are important: *(i)* the definition of the product system in terms of all processes necessary for the functioning of a product, *(ii)* the specification of all processes and their data, and *(iii)* the compilation of inventory tables.

The product system is subdivided into individual process steps, connected by material flows. The outflow from one process step will serve as inflow for the next one. In this way, the product system can be described as a process tree. Flows that are extracted directly from or go directly to the environment are called *environmental interventions*, e.g. energy use and emissions to water and air.

If several useful products are produced, environmental interventions have to be allocated to all products, e.g. oil-bearing crops are used for processing edible fats and oils, but also to process meal to feed livestock. Allocation is usually based on mass relations.

The result of the second step is an *inventory table*, a list with all environmental interventions belonging to the functional unit defined in the goal definition.

5.2.3 Classification

The aim of the classification is to quantify the contribution of environmental inputs and outputs of a product system to a number of generally recognized environmental problems. Data from the inventory table are grouped together according to their contribution to the environmental problems. Heijungs [69] distinguishes *(i) depletion problems* such as the extraction of abiotic and biotic resources, *(ii) pollution problems* concerned with e.g. global warming, human toxicity and acidification and *(iii) disturbance problems* which change the structure of the environmental system like the degradation of landscape (erosion). Another well-known distinction (VROM [161], p. 30) is between world-wide problems (global warming), continental problems (acidification), fluvial problems (eutrophication), regional problems (ecotoxicity) and local problems (noise, odour).

Classification factors convert environmental interventions into contributions to environmental problems, the so-called *effect scores*. The result of the classification is an *environmental profile*, a list with the quantitative contribution of the functional unit to the relevant environmental problems.

Final step of the classification is the normalization of effect scores. The effect scores obtained so far denote the contributions to well-known environmental problems. However, the meaning of these contributions is far from obvious. The effect scores become more meaningful by converting them to a *relative* contribution to the different problem types by a normalization. For example, a normalized environmental profile with the same dimension is obtained by dividing the effect scores by the total extent of the relevant effect scores for a certain area and a certain period of time (Guinée [66]).

5.2.4 Evaluation

In the fourth step, two evaluations have to be performed:

- evaluation of the environmental profile
- evaluation of the reliability and validity

If one product is better than or equal to all other product alternatives, further valuation is not necessary. A multicriteria decision problem arises if such an unweighted comparison is not possible, as is often the case. This multiple criteria decision problem can be dealt with quantitatively or qualitatively. Either way, weighing factors have to be assigned to each of the environmental effects. Combination of weighing factors and effect scores yields an *'environmental index'*.

A valuation of environmental profiles has little value without an assessment of the reliability (due to uncertainties in the data) and the validity (assumptions) of the results. Sensitivity analysis can be a useful tool here for assessing the influence of data uncertainty, assumptions and choices made (Heijungs [69]).

5.2.5 Improvement analysis

The improvement of products used to be undertaken by designers on a trial-and-error basis using empirical knowledge on environmental properties of materials and processes (Guinée [66]). The improvement analysis of a LCA can structure this process. Combined with information on costs and technological feasibility, the improvement analysis may yield options for the redesign of a product. Using optimization procedures for the identification of improvement options, LCA might become an analytic tool for eco-design supporting a continuous environmental improvement of products.

Summarizing, a complete LCA study is a multi-disciplinary process that combines knowledge from social sciences (goal definition), environmental science (classification), systems analysis (inventory analysis) and mathematical decision theory (valuation and improvement analysis).

5.3 The Analytic Hierarchy Process

The Analytic Hierarchy Process aims to choose from a finite list of alternatives using multiple criteria.

Multiple criteria decision making (MCDM) problems can be solved using several solution principles, depending on the characteristics of the problem (Korhonen et al. [90]). If only few alternatives are considered under a small list of criteria, it is possible to check all possibilities. If the problem has few criteria and many alternatives, a possible solution method can be multiple objective linear programming or goal programming (Zeleny [167]). If the problem has few alternatives and relatively many criteria, the Analytic Hierarchy Process (Saaty [134]) is a widely used method. If many alternatives are to be compared under many criteria, the problem may become too complex for analytical models.

We chose to apply the Analytic Hierarchy Process, because *(i)* this method appeared to be useful in decision making problems with 'soft' criteria such as job objectives or environmental problems (Winston [165]), and *(ii)* the method has been successfully applied to situations with relatively few alternatives such as a committee selecting the best doctoral thesis or a Board of Executives of a university choosing a new professor (Petkov [124]).

The AHP involves four steps (Zahedi [166]):

1. The structuring of the problem by breaking it down into a hierarchy of ultimate goal, criteria and alternatives;

2. The collection of input data through pairwise comparison of the criteria and scores of the alternatives for each criterium;

3. The estimation of relative weights of the criteria;

4. The aggregation of weights and scores to arrive at a set of ratings for the alternatives.

Appendix B provides a detailed description of the AHP-approach.

5.4 The case study

Margarines are emulsions of water in oil. The fatty part of the margarines is usually a blend of several fats. The choice of fats depends on costs, availability, and quality requirements. In this case study, we analyse six different fat blends with respect to their costs and environmental impact. The combination of LCA, AHP and LP results in a measure for the environmental impact of fat blends. Unilever LCA studies (a.o. Vis et al. [159]), which had been carried out earlier, provided the data.

5.4.1 Life cycle analysis for margarine fat blends

The first three steps of the life cycle analysis process (goal definition, inventory analysis and classification) result in normalized environmental effect scores for refined oils. These oils are possible inputs for the fat blends under consideration.

The functional unit of the life cycle is the production of 1000 kg refined oil. The production of the first raw material, the oil-bearing crop (or fish), defines the upstream system boundary for refined oils. The product system includes *(i)* growing of the crop, *(ii)* production of crude oil (extraction), *(iii)* refining and processing (hardening) and *(iv)* transportation. The blending of the fats defines the downstream system boundary for refined oils. Processes such as the use and the disposal of margarines are not taken into account because a change in the blend of the fats does not influence the environmental effects of these processes. Figure 5.2 presents the process tree for an arbitrary fat blend.

Raw materials for the fat blends are provided by: soy beans, sunflower, maize, safflower, rapeseed, palm fruit, copra (coconut) and fish. Environmental data for the growing of the crop mainly concern fertilizer and pesticide use. Although general recommendations are known for some crops in some countries, actual amounts used will always depend on specific circumstances. Crude oils are produced from seeds, fruits, and kernels in oil mills. Data are based on Unilever experience. We assume that Unilever has one country (or region) as the main supplier for each crude oil type. Although this is a simplification of reality, it allows us to develop an environmental index for each oil, independent of temporary price changes. The USA is the main supplier of soy bean oil and safflower oil, whereas Europe is the main supplier of sunflower oil, rapeseed oil and maize oil (in particular France, Germany, Belgium and the Netherlands). Malaysia supplies palm fruit oil, Philippines supplies coconut oil and Chili supplies fish oil.

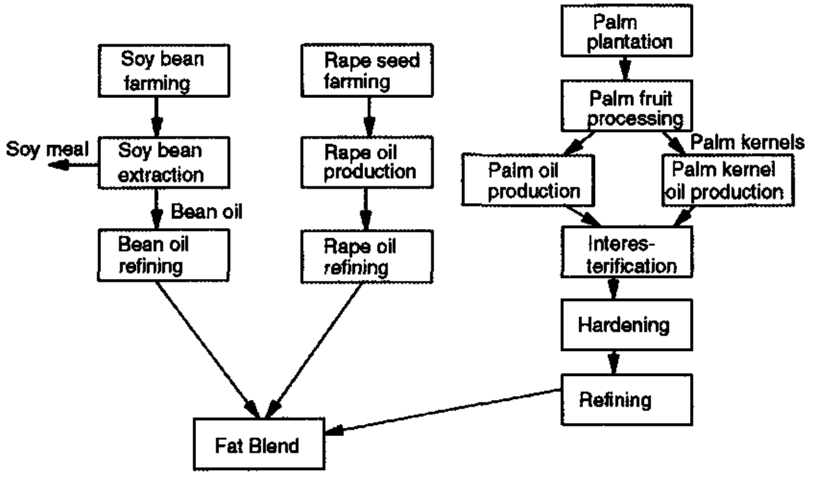


Figure 5.2: Example of a process tree for a fat blend for margarines

Refinery takes place in Rotterdam (the Netherlands). Data used are process standards from Unilever refineries. Information for the fat blend modelling, based on a six-month period in 1993, includes prices for raw materials (oils), volume of forecasted demand for the edible fats and quality requirements for the fat blends. The database package PIA [125] is used to collect and store all data in an inventory table.

For the classification step of the LCA, two sets of problems are considered (see Guinée [66]):

1. pollution problems (POL)
   - global warming (GW)
   - human toxicity (HT)
   - ecotoxicity (ET)
   - photochemical oxidant formation (POF)
   - acidification (AC)
   - nutrification (NF)
2. depletion and disturbance problems (DD)
   - energy depletion (EN)

- land use (LU)
- solid waste (SW)

The first group of problems is known to play a role for agricultural products. Table 5.1 provides a short description of these problems. The second group can be seen as a set of performance indicators rather than environmental problems.

Table 5.1: Environmental pollution problems

Problem	Short description
Global warming	An increasing amount of CO_2 in the earth atmosphere leads to an increasing absorption of heat radiation energy and consequently to an increase in temperature, often referred to as 'the greenhouse effect'. Not only CO_2, but also N_2O, CH_4, H_2S and aerosol contribute to the global warming effect. The rise of temperature will cause a rise in sea level and melting of the ice caps. Eventually, ecosystems will be threatened.
Human toxicity	Exposure of man to toxic substances will cause health problems. Exposure can take place through air, water or soil. Effect factors are mostly taken from air and water quality guidelines and represent safety levels (like the acceptable daily intake (ADI)).
Ecotoxicity	Exposure of flora and fauna to toxic substances will also cause health problems for flora and fauna. Ecotoxicity is defined for the media water and soil.
Photochem. oxidant formation	Photochemical oxidant formation takes place in the troposphere: a reaction between nitrous oxides and volatile organic compounds (VOCs) under the influence of light. It is associated with so-called 'summer smog'.
Acidification	Acidic deposition on soil and into water may lead, depending on the local buffering capacity, to changes in the degree of acidity. This might influence flora and fauna (fish extinction in Swedish lakes, decreasing quality of coniferous forests).
Nutrification	Addition of mineral nutrients to soil or water will increase production of biomass. This may lead to undesirable shifts in the number of species in eco-systems and thus to a threat of bio-diversity. In surface waters this nutrification often shows by rapid algae growth. This may cause oxygen depletion, which poses a threat to other species. The main nutrifying elements are nitrogen and phosphorus. Also emission of organic material can lead to an oxygen deficit, since oxygen will be consumed in the decomposing process. This is generally calculated as the Biological (or Chemical) Oxygen Demand BOD (COD).

5.4.2 Results from the life cycle analysis

Multiplying the inventory table (see Section 5.2.2) with the classification factors (see Section 5.2.3) results in effect scores for each product and each environmental problem.

Figure 5.3 gives an example of the effect scores for global warming (measured in global warming potentials, GWPs), for the eight oil products. The total effect scores are subdivided into contributions due to the agricultural step (farming), oil production, refinery and transportation.

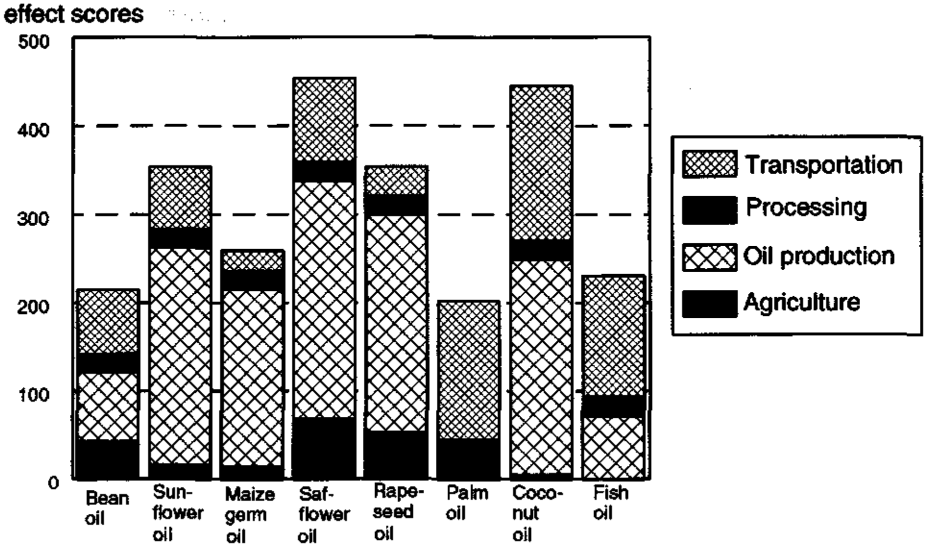


Figure 5.3: Global warming effect scores for refined oils

Fertilizers and pesticides are the main agricultural contributors to environmental problems associated with annual crops (sunflower, soybean, safflower, maize and rape seed). Use of fertilizers in the high input agriculture causes nutrification of soil and ground water. Pesticides used in agriculture contribute to human toxicity and ecotoxicity. The use of fertilizers and pesticides for more year crops like palm and coconut is substantially lower than for one year crops. Oil production and transportation are both very energy consuming processes. The production of palm oil is self supporting in energy terms because bunches and shells from the plantation are used as fuel. The production of fish oil and bean oil has a relatively low energy consumption because part of the energy is allocated to the co-products (fish meal and soy meal). Energy use for transport depends on the country of origin. Palm oil and coconut oil come from the far east, fish oil mainly from South America and soybean oil from the USA. The other oils mainly come from Europe. Where energy consumption is high, human toxicity and acidification are high too. Emissions of hydrocarbons to air cause photochemical oxidant formation. The most relevant hydrocarbon emission is hexane from the oil production process. No general remarks can be made for land use. Coconut oil and safflower oil require much land, while palm oil and maize germ oil score the lowest on land use, except, of course, for fish oil.

We normalize the effect scores to make them comparable. The normalization base is the list of effect scores of an *average oil*, defined as the average of the effect scores of the eight oil types. Table 5.2 shows the normalized environmental effect scores ES_{ij} for the eight oil types j to the environmental problems i.

Table 5.2: Normalized effect scores

Oil products	GW	HT	ET	POF	AC	NU	EN	LU	SW
Bean oil	0.71	1.21	2.30	0.54	0.77	1.08	0.73	0.52	0.17
Sunflower oil	1.21	1.57	0.07	1.69	0.33	1.48	1.05	1.17	1.06
Maize germ oil	0.89	0.74	0.55	1.44	0.23	0.54	0.87	0.51	0.95
Safflower oil	1.55	0.79	0.01	1.51	1.05	2.34	1.48	2.57	0.98
Rapeseed oil	1.21	1.12	2.43	1.74	0.39	2.24	1.14	1.20	1.15
Palm oil	0.73	0.64	0.01	0.17	1.66	0.05	0.79	0.30	0.74
Coconut oil	1.48	1.27	0.01	1.86	1.88	0.22	1.58	3.70	1.16
Fish oil	0.79	0.55	0.01	0.15	1.42	0.01	0.84	0.00	0.98

The quality of the used data differs dramatically. Data on oil processing and oil production are from Unilever experience. These data are sufficiently well understood. In other areas, especially for the agricultural steps, data reliability is poor. Some data are from oil literature. Most agricultural data are from one source and have not been compared with other sources. The use of life cycle analysis will be a strong incentive to improve the quality of these data.

5.4.3 Valuation of margarine fat blends

The multiple criteria decision making (MCDM) problem is to rank the alternative oil types (refined oils and fats) using the environmental problems as criteria. The scores of the alternatives for each criterium are obtained from Table 5.2. The relative weights of the criteria are estimated in two steps: First, we distinguish between *(i)* pollution problems and *(ii)* depletion and disturbance problems. Secondly, the relative weights of the environmental problems within each impact category are estimated.

Since the outcomes of a pairwise comparison are considered to be sensitive to the opinions of the decision maker, three alternative views are analysed. These views, *global*, *regional* and *local*, are based on the categorization of environmental problems by their spatial level. According to the *global* view, global environmental problems are the most important ones, the *regional* view emphasizes regional environmental problems, whereas local environmental problems are highlighted in the *local* view. The environmental problems mentioned in Section 5.3.1 are categorized according to SETAC-Europe [140] (Figure 52, p. 82). Global problems are global warming and energy depletion. Human toxicity, ecotoxicity, and acidification are continental problems (relevant for the *global* and the *regional* view). Regional problems are nutrification and photochemical oxidant formation. Land use and solid waste are considered as local problems.

5.4.4 Results from the Analytic Hierarchy Process

For the three views, *global*, *regional*, and *local*, the AHP approach results in environmental indices for the alternative refined oils. This approach can be interpreted as an example of the fourth phase of a complete LCA study.

Table 5.3 gives the pairwise comparison matrices corresponding to the three different views. If, for example, element a_{12} in the matrix is below 1, then problem 2 is more important than problem 1 (for more details, see Appendix B). By definition, the cross-diagonal element a_{21} has a value higher than 1. The higher the value of $\max\{a_{ij}, a_{ji}\}$, the stronger is the importance of one problem over another. For each of the matrices, the weights (w_i) are normalized eigenvectors of the pairwise comparison matrices. These eigenvectors are found using the Numerical Recipes (Press et al. [127], p. 39-45 and 405-457). First, relative weights are estimated for the pollution problems (w_{POL}) and the depletion and disturbance problems (w_{DD}) (Table 5.3a). Table 5.3b deals with the pairwise comparison matrix for the six pollution problems ($i \in$ POL) global warming (GW), human toxicity (HT), ecotoxicity (ET), photochemical oxidant formation (POF), acidification (AC), and nutrification (NU). Table 5.3c deals with the pairwise comparison matrix for the three depletion and disturbance problems ($i \in$ DD) energy depletion (EN), land use (LU), and solid waste (SW).

The environmental index EI_j of the refined oil j is defined as follows:

$$EI_j = w_{POL}(\sum_{i \in POL} w_i \times ES_{ij}) + w_{DD}(\sum_{i \in DD} w_i \times ES_{ij}) \quad (5.1)$$

Table 5.3a: Pairwise comparison matrix for environmental problem categories.

Global view				Regional view				Local view			
Problems	POL	DD	weights		POL	DD	weights		POL	DD	weights
POL	1	3	0.75	(1)	1	5	0.83	(1)	1	1/3	0.25
DD	1/3	1	0.25	(2)	1/5	1	0.17	(2)	3	1	0.75

Table 5.3b: Pairwise comparison matrix for pollution problems

Problems	Global view						
$i \in POL$	GW	HT	ET	POF	AC	NU	weights
GW	1	5	5	7	5	7	0.51
HT	1/5	1	1	3	1	3	0.13
ET	1/5	1	1	3	1	3	0.13
POF	1/7	1/3	1/3	1	1/3	1	0.05
AC	1/5	1	1	3	1	3	0.13
NU	1/7	1/3	1/3	1	1/3	1	0.05
Problems	Regional view						
$i \in POL$	GW	HT	ET	POF	AC	NU	weights
GW	1	1/5	1/5	1/7	1/5	1/7	0.02
HT	5	1	1	1/3	1	1/3	0.12
ET	5	1	1	1/3	1	1/3	0.12
POF	7	3	3	1	3	1	0.31
AC	5	1	1	1/3	1	1/3	0.12
NU	7	3	3	1	3	1	0.31
Problems	Local view						
$i \in POL$	GW	HT	ET	POF	AC	NU	weights
GW	1	1/3	1/3	1/5	1/3	1/5	0.05
HT	3	1	1	1/3	1	1/3	0.11
ET	3	1	1	1/3	1	1/3	0.11
POF	5	3	3	1	3	1	0.31
AC	3	1	1	1/3	1	1/3	0.11
NU	5	3	3	1	3	1	0.31

Table 5.3c: Pairwise comparison matrix for depletion and disturbance problems

Problems	Global view				Regional view				
$i \in DD$	EN	LU	SW	weights		EN	LU	SW	weights
EN	1	9	9	0.82	EN	1	1/3	1/3	0.142
LU	1/9	1	1	0.09	LU	3	1	1	0.429
SW	1/9	1	1	0.09	SW	3	1	1	0.429
Problems	Local view								
$i \in DD$	EN	LU	SW	weights					
EN	1	1/9	1/9	0.06					
LU	9	1	1	0.47					
SW	9	1	1	0.47					

Figure 5.4 shows the environmental indices EI_j of the eight refined oils and fats for the *global*, *regional*, and *local* views.

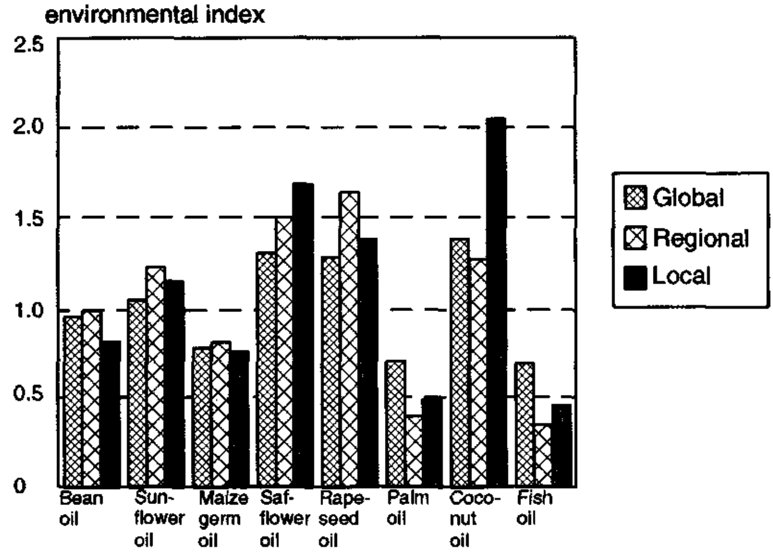


Figure 5.4: Environmental indices for the global, regional and local views

From Figure 5.4, it is obvious that the environmental indices are not very sensitive to the assumptions behind the three different views. Palm oil and fish oil have relatively low indices (due to small agricultural contributions), bean oil, sunflower oil and maize germ oil have medium environmental indices, and safflower oil, rapeseed oil and coconut oil have high indices (due to a.o. energy use and land use). Nevertheless, the ranking within the low, medium and high groups changes with the view choice, e.g. coconut oil has the highest index in the *global* and *local* views but not in the *regional* view, due to relatively low effect scores for ecotoxicity and nutrification.

Apart from the three views based on a spatial scale, an *expert* view has been developed based on the opinions of three environmental experts. The environmental indices resulting from the *expert* view have been used in the linear programming model, described in Section 5.4.5. Table 5.4 shows the weights of the problems corresponding to this view.

Combining the normalized effect scores with the weights using equation (5.1) results in environmental indices (EI_j) for the various oils, which are used in the LP model of the next section. Table 5.5 shows the environmental impact of each oil, where $--$ denotes a relatively poor impact (i.e. a high environmental index) and $++$ a relatively good impact (i.e. a low environmental index).

Table 5.4: Pairwise comparison in the *expert* view

Environmental issue	Weight
Pollution (POL)	0.67
Depletion and disturbances (DD)	0.33
Pollution	
Global warming (GW)	0.41
Human Toxicity (HT)	0.07
Ecotoxicity (ET)	0.19
Photochemical oxidant formation (POF)	0.07
Acidification (AC)	0.07
Nutrification (NU)	0.19
Depletion and disturbances:	
Energy depletion (EN)	0.64
Land use (LU)	0.26
Solid waste (SW)	0.10

Table 5.5: Environmental impacts

Oils	Environmental impact
Bean oil	±
Sunflower oil	±
Maize germ oil	+
Safflower oil	− −
Rapeseed oil	− −
Palm oil	+ +
Coconut oil	−
Fish oil	+ +

5.4.5 Improvement of margarine fat blends

Linear programming (LP) is a widely used tool for blending problems (Winston [165], p. 87-93). These are problems in which various inputs must be blended in some desired proportion to produce goods for sale. The general objective of a blending model is to minimize the costs of the blend subject to raw material availabilities, quality requirements and product demand requirements. The variables in the blending model are the levels of the various inputs (in %). A linear programming blending system can be useful for various purposes, both on the operational and the strategic level, such as purchasing raw materials, developing product formulation policies, monitoring product standards or improvement of existing products. Linear programming not only provides the costs and composition of the optimal fat blend, but gives also the sensitivity of the fat blend to changes in the component prices (reduced costs) and the savings or extra costs incurred by altering binding constraints (shadow prices).

Environmental improvement of blends is also possible, using the environmental index, obtained in Section 5.4.4. The application of linear programming for product improvement is an example of the use of mathematical tools in the final step (improvement analysis) of a complete LCA study.

5.4.6 Results from the linear programming blending models

We analyse two situations. First, the objective is to minimize costs. The optimal blend is called the *C-opt blend*. Secondly, the objective is to minimize the environmental impacts of the blend. The optimal blend is called the *E-opt blend*.

Price information is based on a six-months period in 1993. Van den Bergh Foods has about 40 different fats and oils in its assortment. In the case study, six fat blends, representing 45% of total market volume, are chosen to be environmentally improved. The remaining blends are not relevant for this study for different reasons: *(i)* the blend consists of only one oil type, *(ii)* the proportion of the raw materials is fixed due to quality or marketing conditions, or *(iii)* the market share of the blend is too small to require the use of a linear programming model.

Table 5.6 shows the results for the six E-opt blends compared to the C-opt blends.

Table 5.6: Results of the E-opt blends compared to C-opt blends

Fat blends	Cost Increase (%)	Environmental impact Decrease (%)
BLEND1	5	20
BLEND2	2	30
BLEND3	15	7
BLEND4	0	6
BLEND5	0	0
BLEND6	5	20

The 'environmentally friendly' blends suggested in this study have higher costs and better environmental impacts with respect to the 'cost friendly' blends. For some blends (e.g. blend 4 and 5) there is no or little improvement possible, because the quality restrictions do not allow for the use of other raw materials. For others, it seems possible to improve the environmental impact by 20 or 30% at cost increases of 2 to 5% (e.g. blend 1,2, and 6). The cost increase highly depends on the prices of edible oils, which fluctuate very much. Therefore, it is not possible to draw general conclusions on total cost increase resulting from the improvement of environmental impacts.

5.5 Conclusions

In this chapter, we describe a multi-disciplinary methodology to incorporate environmental information in product development. A full environmental evaluation of products requires instruments for *(i)* analysing the contribution of products to environmental problems, *(ii)* determining weighing factors between environmental problems, and *(iii)* managing and improving the environmental performance of products.

One of the market leaders in the edible fat sector, Unilever, aims to use environmental information in guiding the product development of margarines. In a case study, we propose the combination of Environmental Management tools and Operational Research tools for the environmental evaluation of the fat blends of margarines. The fat blends of margarines consist of a combination of several refined oils. If a one-dimensional environmental index is available for each oil, it is possible to compare low-cost blends with environmentally friendly blends with respect to costs, environmental impact and composition. To obtain this result, we combine life cycle analysis (LCA), multiple criteria decision making and linear programming. Life cycle analysis provides an environmental profile for the refined oils that are used in the fat blends. The Analytic Hierarchy Process, a multiple criteria decision method developed by Saaty [134], has been applied for the valuation of the refined oils. This method transforms the environmental profile into an environmental index for each refined oil. A linear programming blending model can improve the environmental impact of the fat blends using the environmental index. The use of linear programming illustrates the need to combine mathematical procedures with LCAs for an effective and efficient eco-design supporting a continuous environmental improvement of products.

Within Unilever, this method has given rise to a fruitful discussion between purchasers, producers, and marketing people on the issue of 'green' edible fats. The application of the method can still be improved. Issues which need special attention include:

- the improvement of the reliability of raw data underlying LCA's. Especially, data on the environmental impact of pesticides are lacking,
- the sensitivity of the results to the choice of using the Analytic Hierarchy Process instead of another multiple criteria decision method. Also, the scenarios determining the weighing factors are rather arbitrarily chosen. The hesitation of people to use a quantitative approach to determine weights will reduce if they are allowed to experiment with different methods and scenarios,
- the trade-off between cost optimization and environmentally friendly behaviour. We analyse only two extreme situations; optimizing costs regardless of the environmental impact and optimizing environmental impact regardless of the costs of the blends. People will become less reluctant to including environmental information

in daily decision making if they can trade off between costs and environment. This requires the use of multiple objectives in the blending model.

Nonetheless, the outcomes of the study described in this chapter show that in due course, when sufficient reliable data are available, the method is capable of ranking different alternatives on their environmental performance. The environmental index obtained is rather robust for different opinions of decision makers on the relative importance of environmental problems. Optimizing environmental impacts results in a significantly different formulation for the majority of the products. The method can be applied to all situations where various inputs must be blended in some desired proportion to produce goods for sale such as the blending of crude oils to produce different types of gasoline, the blending of livestock feeds to produce a feed mixture for cattle, and the blending of various types of paper to produce recycled paper of varying quality (Chapter 7).

This methodology study is a first step towards using environmental information in product development. Further progress is only possible if decision makers aim to reflect on how environmental aspects of products can become part of the product portfolio management, apart from common criteria such as cost, quality, price and differentiation.

Appendix B

The Analytic Hierarchy Process (AHP) is a tool that has found application in a wide range of problem areas. The decision maker must be able to make comparisons and state the strength of his or her preferences. The intensity of these preferences must satisfy the reciprocal condition: If A is x times more important than B, then B is $1/x$ times more important than A (Vargas [154]).

A simple questionnaire can be developed for pairwise comparison. The decision maker has to indicate on a 9 point integer scale the relative importance between each pair of problems on the same hierarchy level. Table B.1 gives the interpretation of the 1-9 integers (Saaty [135]):

Table B.1: The fundamental scale of the Analytic Hierarchy Process

Intensity of importance	Definition
1	problems have equal importance
3	one problem has weak importance over another
5	one problem has strong importance over another
7	one problem has demonstrating importance over another
9	one problem has absolute importance over another
2,4,6,8	intermediate values between the two adjacent judgements

This scale has been validated for effectiveness, not only in many applications but also through theoretical comparisons with a large number of other scales.

The pairwise comparisons can be collected in a pairwise comparison matrix A where each entry (a_{ij}) of A indicates the relative importance of problem i compared to problem j. If $a_{ij} = k$ then $a_{ji} = 1/k$, and A is called a *reciprocal* matrix.

Suppose that the weights $w_1, \cdots, w_n$ for the n problems are known to the evaluator, then each entry a_{ij} equals $\frac{w_i}{w_j}$. The matrix A is *consistent*, because the following condition is satisfied:

$$a_{jk} = a_{ik}/a_{ij} \quad i, j, k = 1, \cdots, n$$

How can we recover the vector of weights $w = (w_1, \cdots, w_n)$ from A? If A is consistent, it holds that $Aw^T = nw^T$. This system of equations has a non-zero solution if and only if n is an eigenvalue of A with w is the eigenvector associated with it. Now A has rank one because each row is a constant multiple of the first row. Thus all its eigenvalues except one equal zero. The sum of the eigenvalues of the matrix is equal to the sum of its diagonal elements, in this case n since $a_{ii} = w_i/w_i = 1 \ \forall i$. Therefore, n is also the largest eigenvalue of A, λ^*, and w is the principal right eigenvector of A. To make w unique, we normalize its entries by dividing by their sum such that $\sum_{i=1}^{n} w_i = 1$.

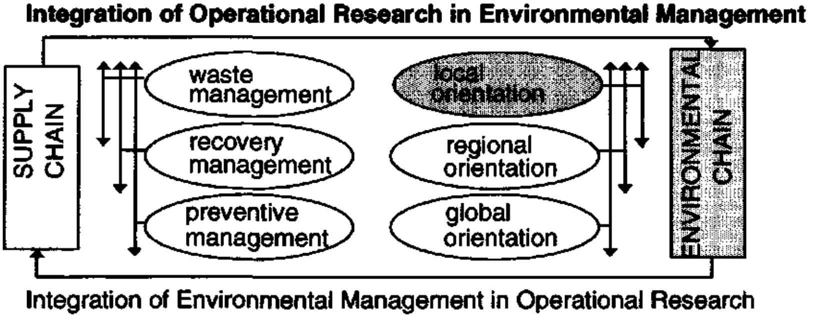
In a general decision-making environment, the actual observed matrix A often contains slight inconsistencies (that is, $\exists\ i, j : a_{ij} \neq w_i/w_j$). However, the largest eigenvalue λ^* and the corresponding eigenvector $(w_1, \cdots, w_n)$ can still be obtained. Using the theorem of Perron (1907) on the characteristics of positive matrices, we can prove that the largest eigenvalue of the pairwise comparison matrix A is always real and positive and a corresponding eigenvector can be found which contains only positive elements. Saaty [133] proved that $\lambda^* > n$ for inconsistent matrices. So, a natural consistency index is defined as $CI = \dfrac{\lambda^* - n}{n - 1}$. If CI is sufficiently small, the estimate of the weights w is acceptable.

Part III

Operational Research tools for environmental problems: some illustrative examples

Chapter 6

The mineral excess problem



This chapter illustrates the use of Operational Research in a local orientation *towards solving environmental problems.*

Optimization approaches with respect to a local policy focus on choosing from a well-defined set of end-of-pipe alternatives to correct damaging pollution. As knowledge on environmental problems is increasing and a larger number of alternatives are being developed, policy shifts also towards a more regional approach. Dynamic simulation models are used to describe the phenomena and optimization is used to determine good combinations of alternatives.

We consider the mineral excess problem in the Netherlands that has caused serious environmental problems. The problem of emission abatement is complex, because of the large number of alternatives to reduce emissions. First, we discuss optimization and simulation models, each dealing with one component of the mineral excess problem (the local orientation). Secondly, we propose a large-scale linear programming model that covers all aspects of the problem in a simplified way to develop efficient and effective strategies to abate the emissions.

6.1 Introduction

6.1.1 Problem description

One of the major environmental problems in the Netherlands is created by the manure surplus. At first, only a few people noticed the increasing growth of livestock, fertilizer use and fodder import (Frouws [61]). Nowadays, many researchers and policy makers are concerned with the manure surplus. Conferences, special issues of journals and many committees are devoted to various aspects of the problem.

The manure problem translates into (too) high emission levels of ammonia, nitrogen, and phosphorus. Measures can be taken in all phases of the mineral cycle, including fodder adaptation, emission-poor stables and covered storage, application adjustments or the processing of manure in plants. There is a high interaction between these measures. However, legislation is still very fragmented. An integrated approach is necessary to develop more effective strategies. Mathematical models turn out to be very useful to structure the problem.

The idea to develop an integrated approach to understand and analyse a complex environmental problem can also be applied to other areas:

Production Systems Lambert [94] describes how a chain description of production systems may result in mathematical models that are especially useful as a decision aid to evaluate combinations of measures applied to production systems in a strongly varying environment. An example for the pork production system shows that a large number of incomparable characteristics of a system, such as costs, emissions, and energy use, can be used in one model to obtain insight in bottlenecks and possible improvements of the system.

Slaughter by-products As a consequence of intensive animal production, not only large amounts of meat, but also large amounts of slaughter by-products are produced. Van Sonsbeek et al. [143] propose a mixed integer linear programming model to trace the optimal path from slaughter to processed feed component for animal nutrition. A path is defined by a number of decision moments, i.e. different ways of sorting, storage, transportation and processing. The model includes both process integrated measures and end-of-pipe measures to meet environmental objectives.

Policy evaluation The National Institute for Public Health and Environmental Protection RIVM (the Netherlands) developed the integrated environmental model EXPECT (Braat et al. [31]). EXPECT is a model to generate a great number of consistent, integrated environmental impact analyses of economic and environmental policy scenarios. The model consists of a number of modules which are simplified versions of state-of-the-art models of economic activity, environmental compartments and ecological, economic and social receptor systems. The system allows users to examine the costs and effectiveness of economic and environmental policies for several environmental problem areas simultaneously.

6.1.2 Contents

The first part of this chapter (Section 6.2 – Section 6.5) describes the causes of the mineral excess problem in a nutshell, discusses the measures proposed to solve the problem, and presents a survey of the quantitative models used to calculate the financial and environmental consequences of the proposed measures. Section 6.2 deals with questions like: how did the mineral excess problem originate, why is it a problem, which are the various aspects of the problem and which abatement policies exist? Section 6.3 discusses the different abatement measures in all phases of the mineral cycle, from fodder to stable and storage, in transportation, application and processing. The complex interactions in the mineral excess problem call for the development and use of mathematical models. Section 6.4 evaluates different modelling approaches advocated by the main research institutes in the Netherlands. We discuss the usefulness of these models and emphasize the need for an integrated model covering all aspects at an aggregate level. Section 6.5 demonstrates how scenario analysis can help to show decision makers the gap between political goals and the result of derived measures to reach these goals.

The second part of this chapter (Section 6.6 – Section 6.9) describes the development of a large-scale linear programming model to decide simultaneously on which measures to take in each phase in the mineral cycle, minimizing total costs of measures in the Netherlands. Section 6.6 gives the problem description for the mineral excess problem. Section 6.7 presents the mathematical formulation of the integrated optimization problem. Section 6.8 deals with the computational results for the optimization problem. We state the origin of the data and assumptions, describe the scenarios and present the results. Finally, Section 6.9 summarizes and provides some conclusions.

6.2 Description of the mineral excess problem

Although the entire intensive livestock farming is responsible for the mineral excess problem, we mainly concentrate on the manure of pigs. Pig manure has received much attention in literature due to the large number of pigs in the Netherlands and the watery character of the manure (slurry) that makes it difficult to handle. Most of the literature discussed is of Dutch origin, due to the importance of the problem in that country. No other country keeps as many pigs and poultry on such a small area.

6.2.1 Mineral cycle

The mineral excess problem in the Netherlands has three main causes: *(i)* the growth in the intensive livestock, *(ii)* a strong tendency towards specialisation in agriculture, and *(iii)* large amounts of excess minerals in fodder. Effects of mineral excess are noticeable at farms but also in nearby forests and other ecosystems.

In order to analyse and solve the mineral excess problem, it is necessary to understand the structure of the problem. We describe the mineral cycle in sequence as follows (Figure 6.1).

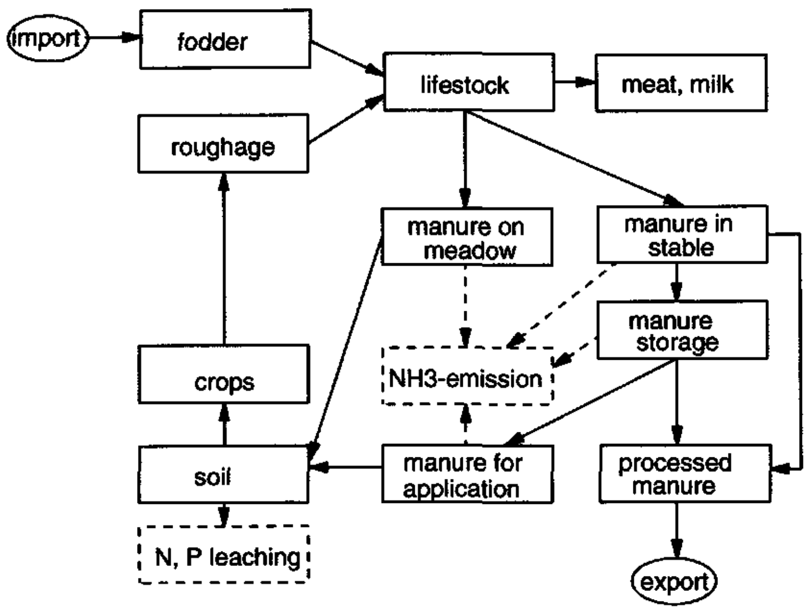


Figure 6.1: Mineral cycle (adapted from Knol et al. [87])

Fodder is one of the main requirements for the growth of pigs. The feed stuffs (e.g. tapioca, maize, soy) are largely imported from abroad (Asia, USA). More than 50% of the pigs are exported directly after slaughter. According to Van Winden at the IKC conference [78], processing after slaughter accounts for 75% of the added value in the pork sector. This value is largely realized abroad, whereas the environmental problems remain in the country. Emission of ammonia during the grazing period of cattle husbandry contributes 10% to the total ammonia emission. Emissions from stables contribute 37% to the total ammonia emission (Baltussen et al. [12] and Nijland et al. [114]). Since the manure cannot be applied immediately, due to spreading rules and crop cycles, it has to be stored for some time which results in a little more ammonia emission (1 percent). The manure can be applied on meadows that need fertilization, or be treated in a factory. During the application about 55% of total ammonia emission arises. The mineral excess that is not used by the crops disappears in soil, ground- and surface water.

6.2.2 Causes of the mineral excess

After World War II, the agricultural sector in the Netherlands experienced an explosive growth. Especially intensive livestock has increased enormously (Table 6.1). The growth of the population, the increased consumption of meat due to improved economic circumstances, new production technology and a favourable competitive relation with the neighbouring countries have contributed to this increase.

Table 6.1: Increase of intensive livestock in the Netherlands

Type	1950	1960	1970	1980	1990	1993
			(× *1,000,000*)			
Poultry	23.47	42.41	55.38	81.16	93.82	97.24
Pigs	1.86	3.00	5.53	10.14	13.92	14.96

Source: CBS [36]

In 1992, Europe had about 110 million pigs, of which about 65% are concentrated in France, Belgium, Germany, Denmark and the Netherlands. The availability of nearby harbors to import the raw materials for fodder was the main reason for the concentration of pig production in Vlaanderen (Belgium), Niedersachsen (Germany) and the Netherlands.

Another development has been the specialization of mixed agricultural farms to stock-farms and arable farms. The pig and poultry farms purchased low cost corn and corn substitutes abroad, instead of buying the cereals from arable farms in the Netherlands. This resulted in a large import of minerals. The arable farms exchanged the manure of pig and poultry for inorganic fertilizers to enrich the soil. In this way, the relationship between both kind of farms became totally unbalanced.

Intensive livestock uses only a relatively small part of the minerals in the food. The unused minerals end up in the manure. As an example, Table 6.2 provides the balance between the input (N-ingestion) and output (N-excretion) of nitrogen for pigs. Breeding pigs are kept for producing piglets (in general a sow has more than 20 piglets a year). At a weight of 23 kilogram (after 80 days) the piglets are forwarded to porker farms to be fattened to porkers with a weight of 105 kilogram. These fattening pigs are used for consumption.

The excess minerals are recognized as a principal cause of several environmental problems. The amount of nitrogen and phosphorus in the manure (and inorganic fertilizers) exceeds the quantities required by the crops. In 1990, the Dutch surplus of phosphorus was 80 million kilogram, the surplus of nitrogen 680 million kilogram and the ammonia-emission

234 million kilogram (Hoogervorst and Van der Hoek [71]). The excess minerals accumulate in soil, water and air, leading to eutrophication and acidification. Next, we describe the consequences for human beings and the environment.

Table 6.2: Nitrogen-balance of pigs in 1980 and 1990

Type		1980	1990
		kg N/animal/year	
Breeding pigs:			
	N-ingestion	41.0	43.4
	N-use	8.8	11.9
	N-excretion	32.2	31.5
Fattening pigs:			
	N-ingestion	17.7	17.8
	N-use	4.8	5.4
	N-excretion	12.9	12.4

Source: Hoste and Baltussen [74], p. 25

6.2.3 Consequences of the mineral excess

The intensive livestock sector contributes to two major environmental problems: eutrophication and acidification.

Eutrophication occurs when the concentration of minerals in the environment is so high that it disturbs ecological processes. Manure surplus can lead to a decrease in the value of nature and a decrease in quality of ground water and surface water. As a result of the latter, the quality of the drinking water will decline. The most important eutrophicating minerals are phosphorus, nitrogen and potassium. In 1993, agriculture was responsible for 87% of phosphorus accumulation and for 89% of nitrogen accumulation, due to excessive use of manure (RIVM [130]).

Acidification is the result of air pollution by sulfur dioxide, nitrogen oxide, and ammonia. Deposition of acidifying compounds can lead to a change in the chemical compositions of soil and surface water, which cause a worsening of the health of forests and the quality of surface water and ground water. Agriculture is responsible for 92% of total ammonia emission in the Netherlands (RIVM [130]). Main contributors to the agricultural part of the ammonia emission are cattle husbandry (57%), pigs (23%) and poultry (10%) (Nijland et al. [114]).

To solve the eutrophication and ammonia problem, an abatement policy has been developed. In the following, we summarize the policy of the Dutch government, compared to other European countries.

6.2.4 Abatement policies

Although the first warnings about the pollution effects of manure surpluses were published as early as the late 1960s, the development of Dutch manure legislation started only in 1987. Frouws [61] gives a broad overview of the Dutch manure policy since then. The Dutch government decided to introduce ammonia standards and phosphorus standards for the reduction of the mineral excess problem. The application standard implies an upper bound on the amount of manure (measured in phosphorus) allowed to be applied per hectare. After the year 2000 the application should equal the phosphorus absorption of the vegetation. Until then, the standards are tightened in three phases as shown in Table 6.3. Presently, policy seems to shift from the application standard to the accumulation standard, i.e. the number of kilograms of phosphate that one hectare of land can deal with, without any environmental damage such as soil and surface water pollution. In 1998, accumulation standards for phosphorus and nitrogen will be introduced. The accumulation standard for phosphorus will be tightened from 40 kg/ha/year in the year 1998 to 20 kg/ha/year in the year 2010 (VROM [161]). Equilibrium application of manure should have an accumulation standard of at most 20 kg/ha/year.

Nitrogen standards have not yet been implemented for the Netherlands. In 1998, an accumulation standard will be introduced. This accumulation standard will be tightened from 300 kg/ha/year in 1998 to 180 kg/ha/year in 2010, which is the standard for equilibrium application (VROM [161]).

Table 6.3: Phosphorus application standards

	−1991	1991 − 1995	1996 − 2000
	kg P_2O_5/ha		
Arable land	125	125	70
Grass land	250	175	110
Maize land	350	125	75

Source: Stolwijk et al. [146]

The ammonia standard is based on a reduction compared to the emission level in 1980 (224 million kg NH_3 a year, Meeuwissen [105]). In 1990, a 30% reduction with respect to the level of 1980 was required. For the year 2000 the ammonia emission should be at least 50% less than in 1980, whereas the target reduction is 70%.

The efforts to develop manure legislation have provoked great tension between the Ministries of Agriculture and Environment, between the government and the farmers' unions and also within the agricultural lobby itself. The basis for legislation is not self-evident. Dietz and Hoogervorst [47] note that *(i)* a phosphorus policy cannot solve a nitrogen emission problem, *(ii)* legislation is mainly developed to regulate production of manure, whereas the environmental problems are also related to the application of manure, and *(iii)* current manure policy is directed towards action prescriptions instead of financial incentives as a policy instrument. In other words, the Dutch legislation is still very fragmented and disputable.

Other European countries with a high concentration of livestock have their own manure regulations. In all areas, the quality of drinking water and coastal water is an important theme in the agricultural-environmental policy, especially the high nitrogen concentration related to the application of inorganic and organic fertilizers. The acidification caused by ammonia emission is an environmental problem for the sandy areas in Vlaanderen, Niedersachsen and the Netherlands. With exception of the Netherlands and Niedersachsen, the political attention for ammonia emission is low (Van Beek and Walther [20]). The phosphorus saturation in the soil receives, apart from the Netherlands, little attention. Schröder [137] compared the different forms of manure legislation in European countries with a detailed legislation on manure handling, spreading and storage. In Denmark, Germany and France the input of nitrogen per hectare is a criterion for legislation. In Belgium the legislation is based on a combination of nitrogen and phosphorus criteria (400 kg N/ha/yr as a nitrogen criterium and 150 kg P_2O_5/ha/yr on arable land, 200 kg P_2O_5/ha/yr on maize and grass land as a phosphorus criterium). Legislation restricts the permissible application rates in Denmark and Germany to an equivalent annual livestock production of 30-50 fattening pigs per ha. In the Netherlands, Belgium and France the permitted rates are equivalent to productions that vary between 40-90 fattening animals per ha, depending on land use. If legislation becomes more restrictive, as is likely in the future, livestock densities in the Netherlands will have to be reduced substantially on pig farms.

European legislation for the intensive livestock sector, as announced by the European parliament, is still far away. As Schröder concludes: "*It would be unrealistic and unwise to suggest that European legislation on the use of fertilizers and manures should be made uniform. Uniformity would deny farmers their freedom of choice of crops and crop sequence, and would disregard the existing variability in climate and soils in the different countries. It seems attractive, however, to standardize at least the reasoning on which legislation is based.*" (Schröder [137]).

6.3 Abatement measures

6.3.1 Introduction

To reduce the contribution of manure to the eutrophication and acidification problems, the following instruments can be chosen to abate emissions:

- Fodder adjustment.

- Adjustment of manure storage and accommodation in the stables.
- Enhancing the options for manure distribution.
- Processing and application of manure.
- Volume reduction, i.e. reducing the size of the intensive livestock.

To find an objective basis for manure legislation, it is necessary to link instruments directly with their effects on the mineral cycle. Figure 6.2 summarizes the abatement measures, incorporated in the mineral cycle as depicted in Figure 6.1.

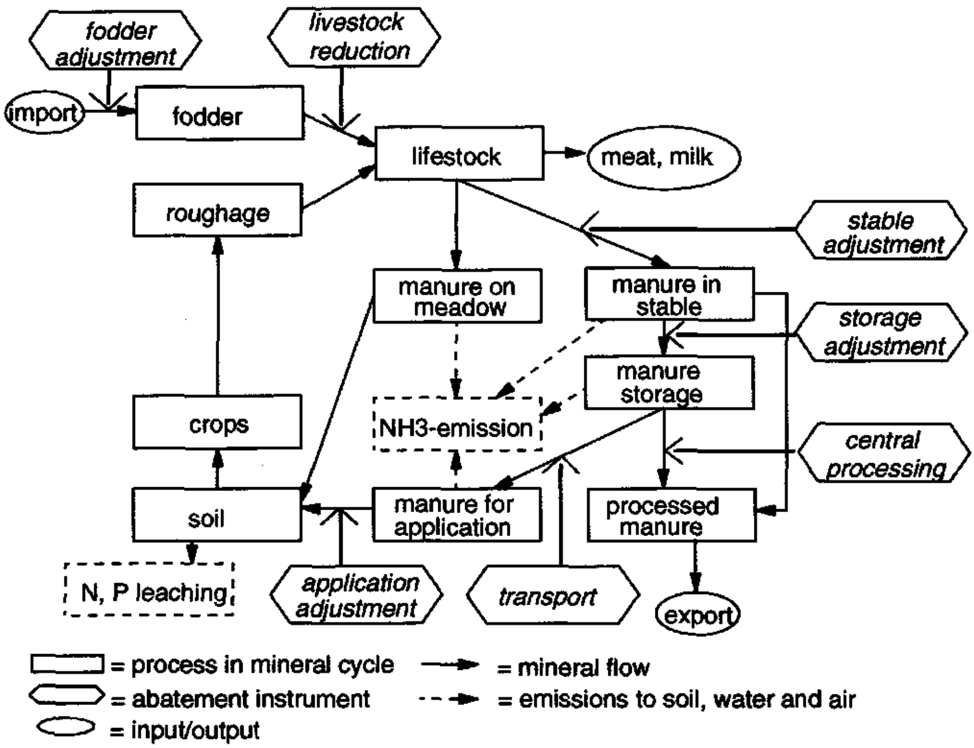


Figure 6.2: Abatement measures in the mineral cycle

A large array of abatement measures is available to satisfy environmental goals. In recent years, experimental farms, institutes and the sector itself generated a large body of knowledge about technologies to reduce the manure problem.

In the following, we discuss for each class of measures some concrete instruments to deal with the surplus of pig manure.

6.3.2 Fodder adjustment

A change in nutrition is one of the options to reduce manure and nutrient excess (Tweede Kamer [152]). Recent research has shown that this option has high potential. Fodder adjustment can be divided into two types: *(i)* those regarding the *utilization* such as multi-phase fodder systems, N-decrease and a better fodder conversion and *(ii)* those regarding the *digestibility* such as the use of phytase and other enzymes. We refer to Jongbloed and Coppoolse [80] for a review on the various ways of fodder adjustment. We only present a short description of the methods.

Multi-phase feeding:

Nowadays different types of food can be considered for different phases in the life cycle of animals. Especially for pigs, this differentiation makes sense. For fattening pigs three types of food are used: start food, growth food, and maturity food, corresponding to the decreasing need for nitrogen (Hoste and Baltussen [74]). According to Coppoolse et al. [39], the nitrogen and phosphorus contents can be reduced with 14-30%. For breeding pigs it is possible to adapt the N-ingestion during the lactation period. Again, a reduction of N-excretion with 14-30% can be obtained. Total costs of the fodder mix increase progressively with a reduction in the gap between the maximum allowable nitrogen or phosphorus level and the level of minimum required minerals.

Decreasing N-content and P-content:

If it is possible to reduce the amount of nitrogen and phosphorus, then the N-excretion and P-excretion are reduced automatically. However, too much reduction will affect the growth of the animals, because of the reduction of amino-acids which contain nitrogen. A solution is found in the addition of synthetic amino-acids. Through better knowledge about the need of phosphorus by pigs, it is possible to reduce the amount of P-excretion, without changing the growth. Unfortunately, the use of nitrogen will increase.

Digestibility:

Part of the phosphorus in fodder is contained in some poorly digestible plant elements and can therefore be found in the excrements. To satisfy the need for phosphorus, the phosphorus content of fodder has to be high. The necessary amount of phosphorus can be reduced drastically by the enzyme phytase. This enzyme decomposes some poorly digestible plant elements, so that the intestines can take up more of the phosphorus in the fodder. A positive side-effect of this measure is noticed as the element zinc is also easier to digest after adding phytase. Before that, it was necessary to add a sink-extract to the fodder.

Fodder models have been used to analyze the effects of the three types of fodder adaptation with respect to costs, N-decrease and P-decrease. These fodder models minimize the costs of the fodder package subject to a set of nutrient requirements corresponding to the specific fodder adaptation. Given the fodder package, it is possible to calculate the corresponding N-excretion and P-excretion in the manure with respect to the basic situation without fodder measures. Table 6.4 summarizes the results of this analysis.

Table 6.4: Costs and nutrients for different fodder scenarios

Scenario	Costs (mln guilders)	Increase	Phosphorus (mln kg)	Decrease	Nitrogen (mln kg)	Decrease
Base run	7108	0%	87	0%	441	0%
Multi-phase	7081	-0.4%	83	4.6%	433	1.8%
P-decrease	7141	0.5%	75	13.8%	433	1.8%
N-decrease	7132	0.3%	83	4.6%	395	10.4%
Phytase	7082	-0.4%	72	17.2%	433	1.8%

Source: Van der Veen et al. [155], Tables 1, 2, 3, and 4

Van der Veen et al. [155] conclude the following:

- Multi-phase fodder methods for pigs and poultry can reduce the amount of nitrogen in the fodder mix with 8 million kg N (1.8% decrease) and the amount of phosphorus with 4 million kg P (4.6%). The costs of the fodder mix will decrease with 27 million guilders (0.4% decrease with respect to the base situation) due to relaxed fodder requirements in multi-phase fodders.

- The decrease for nitrogen and phosphorus in the fodder will lead to higher costs. This cost increase is progressive. The costs depend heavily on the availability and costs of synthetic amino-acids.

- The use of phytase can decrease the amount of phosphorus in the fodder mix with 15 million kg (17.2%), without significant cost increase.

6.3.3 Stable and storage adjustment

Abatement measures in stable and storage aim to reduce the ammonia emission. In 1990, the Dutch government introduced a reduction plan for ammonia emission. The aim of this plan is to reach a level of ammonia emission in 2000, which is 10-50% of the level in 1980 (i.e. a reduction of 50-90%). This reduction has to be accomplished in the stable, during storage and during the application of manure.

There are two types of measures to reduce ammonia emission in the stable and during storage: *(i)* measures to reduce ammonia evaporation (*covering*), and *(ii)* measures to remove ammonia from the air (*filtering*). Verdoes [157] gave a detailed description of the various stable systems available to reduce ammonia emission. To avoid ammonia evaporation, small adaptations like roster adaptation or stench-traps are available. Large adaptations are e.g. manure slide systems. Measures to remove ammonia include bio-filters and bio-washers. Tables 6.5 and 6.6 provide some provisional results of measures for pigs, given the present technical state-of-the-art. A question mark in the table represents the situation where the measure is technically feasible, but no exact details are known.

Table 6.5: Reduction of ammonia emission from pig manure during the stable period

Type of measure	Breeding pigs		Fattening pigs	
	Reduction (%)	Costs (Dfl./year/animal)	Reduction (%)	Costs (Dfl./year/animal)
Evaporation				
- roster adaptation[1]	?	?	15	?
- stench-trap[1]	9	17	15	6
- manure channel[1]	30	92	?	17
- manure slide[1]	50-65	111	40	23
Filtering				
- bio-filters[2]	?	?	85	73
- bio-washers[2]	51	131	80	56

[1]Hoste and Baltussen [74]

[2]Baltussen et al. [12]

Table 6.6: Ammonia emission from pig manure during the storage period

Type of measure	Ammonia emission (mg NH_3/m^2/hour)				
	November-May		June-October		
	amount	reduction (%)	amount	reduction (%)	costs Dfl./m[3]
No coverage	204	0	610	0	
Covering					
- with corrugated iron	94	54	99	84	2-6
- with floating foil	56	73	35	94	"
- with tent construction	33	84	34	94	"
- with tempex	78	62	91	85	"

Source: Baltussen et al. [12]

Table 6.6 shows that the ammonia emission in winter and spring is less than in summer and fall. Low temperatures have a positive effect on the level of ammonia emissions.

Measures with respect to accommodation and storage are only useful in combination with measures on application and processing. If not, the ammonia will evaporate during the application. On the other hand, the potential ammonia emission during application depends on the measures taken at an earlier stage, since the composition of the manure influences the amount of ammonia emission.

Hoste and Baltussen [74] conclude that:

- to reduce the emission per animal per year with at least 70%, large stable adaptations such as manure slides are necessary;
- a decrease of ammonia emission causes high increases in costs, because of the high investment costs of necessary technical measures;
- the effectiveness of a package of measures including fodder adaptations decreases with an increasing reduction of ammonia emission.

6.3.4 Application adjustment

During and after application, ammonia can evaporate. These emissions can be reduced significantly by ploughing the manure into the ground immediately. The government's goal is to obtain an 80% emission reduction compared to normal surface spreading. Different measures are available for grass, arable, and maize land respectively. Table 6.7 shows the additional costs of application using these measures compared to the costs of surface spreading. Fortunately, some of these costs are covered by a reduction in the need for inorganic fertilizers. The inorganic fertilizer savings are about Dfl.2/m^3, depending on the nitrogen content in the manure. The options for application on grass land are *(i)* manure injection, *(ii)* sod fertilizing and *(iii)* manure sprinkling. For arable and maize land the 'work into the ground' option is also a reasonable measure to reduce the ammonia emission (Nijland et al. [114]).

Manure injection:
Injection is possible on all grass lands in the sandy areas, but only for half of the grass in clay and moor areas. An injector cuts a vertical groove and spouts the manure in a horizontal furrow just under the roots at 15-18 cm depth.

Sod fertilizing:
Compared to injection, sod fertilizing is less dependent on the weather. A disadvantage is the lower reduction percentage.

Manure sprinkling:
Sprinkling is similar to the situation of spreading during rainfalls. Manure rinses into the soil more easily, resulting in lower ammonia emissions. Spreading during heavy rain is not advised, because manure can easily leach into ditches contributing to eutrophication. A disadvantage of this method is an increased use of water.

Ploughing the manure:
On arable and maize land, the manure can be applied under the ground immediately or within 24 hours. The first option is more expensive.

Table 6.7: Reduction percentages and costs for application adjustments.

	Emission reduction (%)	Costs (Dfl./m^3)
Manure Injection	90	4
Sod fertilizing	80	4
Sprinkling	70	3
Ploughing	90	3.25

Source: Baltussen et al. [12], p. 47

The research on reduction of ammonia emission during application has been confronted with some complicating factors: *(i)* the amount and the location of ammonia emission is influenced by transportation, treatment and processing, *(ii)* reduction of ammonia emission during the application of the manure can lead to a greater leaching of nitrogen into the groundwater. In most of the studies, the transportation aspect has been fully ignored.

6.3.5 Central processing

Pig slurry is a material that can be processed into useful products which do not emit ammonia (e.g. pellets for fertilizing). Costs of this measure are estimated at Dfl. 10 per ton of manure as compared to application. However, the costs depend on the capacity installed. Central processing has two bottlenecks: the high cost and the absence of a market. Until now, the energy cost for the production of manure pellets is higher than the cost for inorganic fertilizer. Second generation techniques at the test plants try to make products with a higher added value from the manure. The government had plans to create a capacity of 6 million tons of manure in 1994, where in 1990 only a capacity of 0.4 million was available (ICM [77]). To reach the planned capacity, about 25 large-scale processing plants had to be located. This never happened.

Choosing locations for the processing plants appears to be a difficult problem. First, many people accuse the plants of causing problems (bad odour and traffic due to transportation of manure), and do not want such a factory in their neighbourhood, the so-called NIMBY problem (Not In My Back-Yard). Secondly, a structural approach to the location decision, including space, environmental effects, and efficiency issues, is still missing.

6.3.6 Livestock reduction

Reduction of the livestock density is considered by the government as a policy of last resort, because of the large economic consequences: unemployment and a considerable reduction in the sector contribution to GNP. However, if livestock density reduction is not feasible, a combination of only fodder and stable adaptations will cost 700 million guilders per year extra compared to the possibility of volume reduction (Meeuwissen [105]).

A livestock reduction policy has as a direct goal to reduce the production volume of manure or minerals. A reduction policy can be described as "*the direct interference of the government in the use of the amount of production means or the production itself, to prevent the negative side-effects, inherent to the production process*" (Stolwijk et al. [146]). Reduction can be implemented in three ways: *(i)* through livestock reduction, *(ii)* through manure production rights or *(iii)* through discouraging the consumption of pork. The latter is difficult to regulate since most of the consumption is abroad. Livestock reduction and manure production rights bear influence on regions with a manure surplus and can lead to relocation of animal farms (which is happening at the moment between the regions Zeeland and North-Brabant). Discouraging the consumption of pork influences the complete mineral cycle.

6.4 Manure models for the mineral excess problem

To evaluate the effectiveness of abatement strategies, a formal description of the mineral cycle is necessary. Mathematical models can be very useful to evaluate alternative abatement strategies on mineral surpluses, emission levels, etc.

6.4.1 Manure models in the mineral cycle

Mathematical models have been built to analyse each phase in the mineral cycle (see Figure 6.2). We discuss fodder models, growth models, farm and excess models, transportation models and emission models.

Fodder models

The objective of fodder models is to find a fodder mix that satisfies nutritional requirements with minimal costs. Fodder models have been developed e.g. for blending industries that sell fodder packages to farmers. These models search for fodder mixes that are optimal for the entire livestock sector. The blending model of Van der Veen et al. [155] is a linear programming model that determines an optimal blending of fodder. Costs of fodder are minimized subject to the following requirements:

- minimum and maximum requirements for nutritional value of the fodder;
- requirements on the inputs for fodder mix;
- environmental standards for the total amount of nutrients (e.g. phosphate) in the fodder mix.

Input data for the model are e.g. world trade prices of corns and corn substitutes, mineral requirements, and environmental legislation. The optimization gives the costs of the suggested fodder mix, as well as the composition of the fodder and the mineral contents.

Growth models

Growth models have been developed to obtain information on the effects of specific changes in the environmental conditions of individual animals. Simulation is a suitable tool to deal with the complexity in the relations between environmental conditions and the growth of animals. Aarnink et al. [2] developed a model to estimate the amount and composition of manure from pigs. Many factors influence the growth of pigs. The main factors are the amount of feed, feed composition, genotype, climate, housing, and stress. This model predicts the influence of e.g. a change in feed composition on the growth of pigs, the excretion of nitrogen and phosphorus in the manure and on financial results. The input to this type of growth models is a scenario description of basic feed composition, climate conditions, health and the housing situation. Given a basic scenario, the model calculates the effects of various feeding strategies on the growth of pigs. A comparable growth model is described by Dourmad et al. [50].

Farm models

De Mol and Koning [110] developed a simulation model to gain insight in the effects of legal measures for manure storage and use on farm level. Manure production is registered using the manure bookkeeping on the farm. The composition of the manure can be changed through treatment, inside or outside the stable. Since the manure cannot be applied during all months of the year, storage of manure is necessary. The need for storage depends on the constraints related to manure use and the destination of the manure. Manure has to be removed in case of *(i)* a manure excess, *(ii)* a storage deficit or *(iii)* manure exchange. Use of the manure on the farm depends among others on land use, legal constraints, user plans, personnel and machines. Farm models help to visualize the effects of investments and policies for individual farmers.

Excess models

The results of the farm model can be aggregated to obtain regional results for the Netherlands. Based on the farm model, a basic scenario can be developed with fixed storage possibilities, land use, legislation, etc. For this scenario, the manure excess, i.e. the amount of manure that cannot be disposed of at the farm itself, can be calculated. Similarly, a deficit emerges if the need for nutrients exceeds the production of manure on the farm. Excess models are used for the evaluation of environmental legislation for the entire livestock sector.

The model MESTOP (Luesink and Van der Veen [101]) is a model to calculate the manure production, manure surpluses, the number of farms with a mineral excess and the application possibilities for manure in the Netherlands. Farm level results are aggregated based on phosphorus production. This aggregation is only possible if the farm situation is given for all farms in the Netherlands (i.e. the composition of the livestock sector, the average manure production, the assignment of manure types to soils, etc.). MESTOP uses the manure production and application possibilities on a farm to calculate the amount and the regional distribution of the total national production of manure. The model can be applied to calculate the influence of e.g. various standards for the use of manure on the amount of the excess or the effects of measures to reduce the production of surpluses.

Transportation models

Transportation models support manure cooperations dealing with the distribution of manure surpluses. The goal of transportation models is to find an efficient distribution network for surplus areas and deficit areas. Simplification of the real situation is always necessary to keep the model tractable. Obvious simplifications are:

- the aggregation of farm-specific information to regional information;
- the aggregation of animal-specific information to general information for classes of animals (e.g. cows, pigs, poultry).

The distribution and processing model MESTTV (Luesink and Van der Veen [101]) determines the optimal distribution of manure surpluses while minimizing total costs on a national level. MESTTV is a large linear programming model with cost minimization as the main objective subject to available possibilities of manure application (in the region itself, transportation and application in another region, and transportation to a processing plant).

De Mol and Van Beek [110] describe a comparable model. The goal of this model is to gain a better insight into the transportation, storage and processing aspects of the distribution of manure to feasible destinations. The model is based on a processing network suitable for mixed integer linear programming. It can be extended by taking into account economies of scale and locational aspects, resulting in a large location-allocation model.

Emission models

The ammonia model of Oudendag en Wijnands [119] calculates the ammonia emission on farm level for stable, storage and application and aggregates the results to a national level. The model offers the opportunity to evaluate costs and emission reductions of abatement measures. The goal of this model is to gain insight in the relations of *(i)* the amount of ammonia emission on the regional and national levels, *(ii)* the reduction of ammonia emission by different abatement measures and *(iii)* the costs of the measures proposed.

6.4.2 Integration of the manure models

Quantitative models, based on chain analysis, can be useful to evaluate (combinations of) policy decisions in a complex system like the mineral flow system (Lambert [94]). The models described in Section 6.4.1 can be integrated into one mineral cycle system (Figure 6.3) that starts with a blending module, deciding on which food stuffs to use. Then the composition of the manure is estimated using a simulation growth module. For each type of stable and storage, the expected destination of the manure (use, treatment, removal) can be simulated in a farm module. The manure excess on farm level can be aggregated in a national manure excess module. Information on ammonia emission during the stable and storage period is not influenced by any regional decision and will be immediately forwarded to the emission module. A transportation module decides on possible manure flows between regions, such that finally the amount and composition of manure in each region will be known. Given this information, the emission module calculates the leaching of nitrogen and phosphate and the ammonia emission during application.

Evidently, the integration of the manure models is not as simple as Figure 6.3 presents it. For example, the growth models have been developed to analyse the complex effects of changes in feeding systems or stable climate on the growth of animals. These models can and must deal with a high level of detail.

Fodder models, delivering the input for the growth models and farm models, depending on the output of the growth models, cannot deal with the detailed information stored in the growth models. Therefore, aggregation and simplification are necessary to integrate these models. Excess models, developed for the evaluation of national manure legislation, need the information from the preceding models on an aggregated level. The same aggregation problems arise while gathering the information for emission models. Pig farms deliver the data on the emission in stables, whereas arable farms deliver the data on the emissions generated during application. Moreover, the transportation model is only useful if the number of processing techniques, treatment possibilities and application adjustments is reduced to only a relative small set of alternatives.

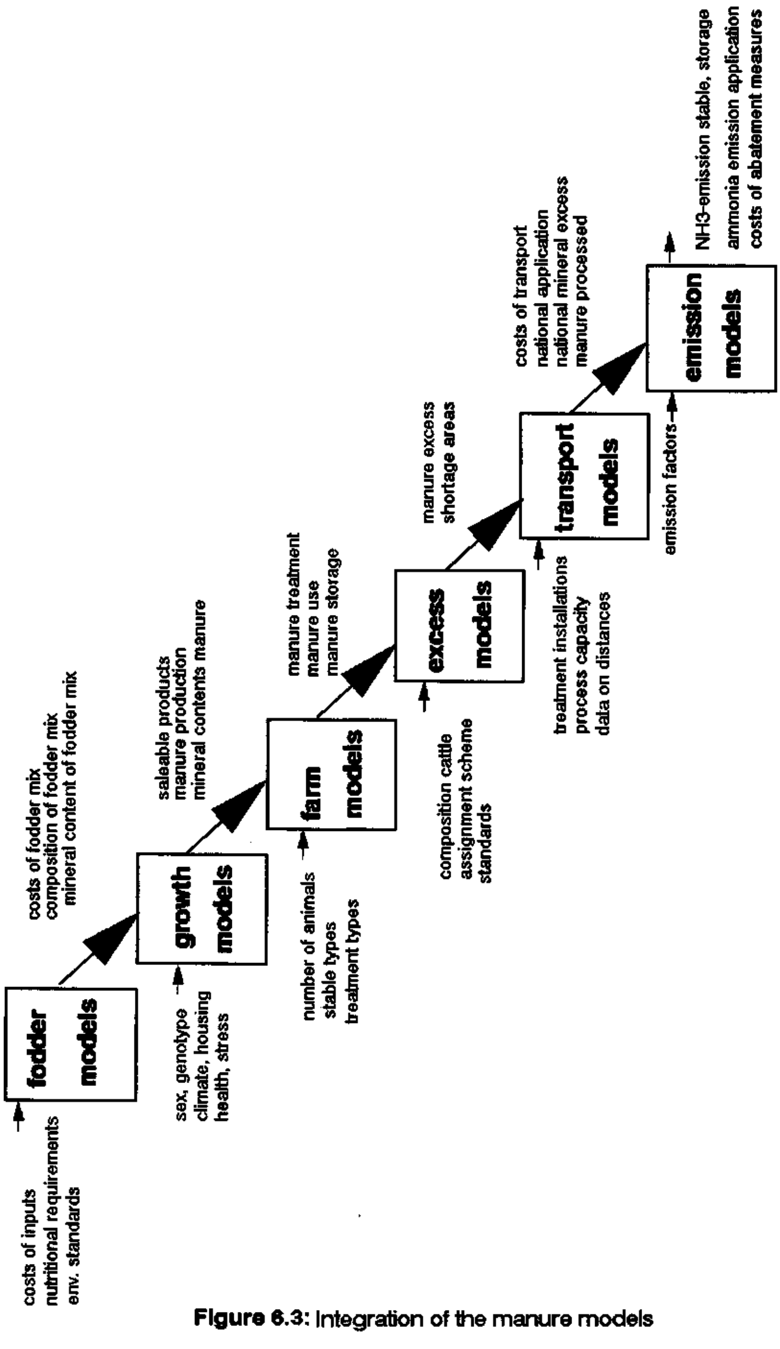


Figure 6.3: Integration of the manure models

The integration of excess models, transport models, and emission models easily leads to a conflict between the level of detail that can be dealt with by the simulation models, and the simplifying assumptions, necessary for the optimization models.

6.5 Scenario analysis based on an integrated cycle approach

Integrated modelling is necessary for environmental scenario analysis and impact assessment (Braat et al. [31]). Knol et al. [88] demonstrate the need for an independent tool to compare goals, measures and effects of the three main interest groups regarding the manure problem, i.e. the government, the agricultural sector and the environmental NGOs. We shortly introduce the basic ideas of the government, the agricultural sector and the environmental NGOs, and the scenarios based on these ideas.

Government

As mentioned in Section 6.2, the Dutch government introduced ammonia standards and phosphorus standards which are equal for each region in the country. Furthermore, the amount of manure will be reduced by introducing manure production rights, forcing the farmers to decrease their livestock. The governmental scenario is a compromise between end-of-pipe technical solutions (central processing, spreading rules) and source-oriented solutions such as volume reduction.

Agricultural sector

The largest representive of the agricultural sector in the Netherlands is the 'Landbouwschap'. According to Kok, General Secretary of the Landbouwschap, the actual policy of the government with respect to manure and environment has to be adjusted when possible (IKC [78]). Large-scale farming is necessary to satisfy the demands of the markets and the requirements of the environment. Only large-scale farms can guarantee the quality of food required by the customers. In spite of all measures the pig sector has taken, the legislation allows no development possibilities for farms. Kok emphasized that the resistance of the livestock owners is not against environmental goals, but against the way the government deals with them. The plans for reducing the number of livestock have to be adjusted, so that farms that want to extend and have the possibility to satisfy the standards, can do so.

The essential elements of the approach of the Landbouwschap are:

- farms have to define environmental goals;
- levies and production right restrictions should apply only to individual farms, and should not be of a general nature applicable to all farmers irrespective of their compliance with environmental goals;
- farmers must have access to land if they reach an equilibrium in mineral use or apply manure somewhere else in a sustainable and responsible way.

The agricultural scenario is based on end-of-pipe technical solutions such as application improvements and manure processing, without major changes for the agricultural sector.

Environmental NGOs

The environmental pressure groups are convinced that far-reaching measures are needed. These measures cannot be delayed, since that would cause unacceptable harm to the environment. In the year 1998 a sustainable agriculture has to be reached. 'Stichting Natuur en Milieu' (SNM), a major environmental NGO in the Netherlands, appreciates technical solutions like processing plants, but is extremely skeptic about their contribution to the ultimate solution of the problems. Therefore, SNM chooses an approach where levying of mineral-losses forces the farmers to adapt their farm management. Theoretically, this approach can solve the whole problem. However, since it takes quite some years to implement, in the meantime the production capacity has to be decreased (Logemann [99]). The environmental scenario represents a source-oriented approach based on large fodder and stable improvements.

Table 6.8 shows the package of abatement measures proposed by the three groups.

Table 6.8: Comparison of three scenarios for the year 2000.

Measure	Government	Agriculture	Environment
Application grass land on clay and moor (kg N/ha/year)	350	420	350
Application maize on sand (kg N/ha/year)	130	350	130
Minimal reduction concentrated fodder (%)	20	15	25
Manure processing (million ton/year)	20	20	3.5
Reduction NH_3 emission for			
- stables (%)	45	35	68
- application (%)	70	60	75

Source: Knol et al. [88]

Each group has defined standards for the ammonia emission levels in 2000 and 2010 and the nitrogen-leaching into the soil in 2010. Furthermore, an allowable decrease in income of the agricultural sector has been chosen.

Given the scenarios, Knol et al. [88] calculated the emissions if the selected measures were to be implemented. The gap between the goal and the results of the scenario analyses is given in Table 6.9. For N-leaching and agricultural income no preset goals have been defined.

Table 6.9: Results of scenario analyses

Criterium	Government		Agriculture		Environment	
	reduction percentages with respect to 1985					
	goal	Knol et al.	goal	Knol et al.	goal	Knol et al.
Emission NH_3 in 2000	65	60	50	55	80	79
Emission NH_3 in 2010	85	68	70	60	90	83
N-leaching to soil 2010	-	90	-	62	-	92
Agricultural income	-	28	-	13	-	53

Source: Knol et al. [88]

The analysis of the governmental scenario shows that the goal in 2010 can not be realized without further measures. In the environmental scenario, agricultural income declines enormously due to a production volume reduction policy and a low percentage of manure processing. In all scenarios grass and arable land are exchanged for maize land.

Summarizing, in order to analyse the effects of measures, it is necessary to keep in mind the total package of measures. Furthermore, without integrated modelling, it is hard to estimate the overall result of combined abatement measures. The marginal costs of additional measures depend heavily on the contents of the package of abatement measures that has already been chosen and the emission-reduction obtained with that package. Therefore, there is a need for quantitative models with the capability of choosing an efficient and sufficient package of abatement measures for the mineral cycle that leads to lower costs and larger emission reductions.

6.6 Integrated modelling

For the mineral excess problem, integrated modelling can be useful to find good combinations of measures to abate water, air and soil pollution. Optimization models can be helpful or even required to support determining such combinations. Because of the complexity in the mineral cycle, it is not easy to build a model that deals with all the aspects of the problem. Due to the interrelationships between the measures, it is not very likely that emissions of a combination of measures can be found by simply adding the emissions of each measure. Leneman et al. [95] show that the effects of combinations of measures on the emission of nitrate, phosphate and ammonia indeed have no additive structure. Measures to reduce emissions at one source (e.g. storage) have to be considered in conjuntion with reduction measures in other phases in the mineral cycle (e.g. application). If not, the net effect of a measure is unclear. Therefore, it is necessary to decide simultaneously on which measures to take in each phase of the mineral cycle.

The effects of combinations of fodder adaptations, volume reduction, stable or storage adaptions and application adjustments on the amount of emissions have been measured on farm level. Baltussen et al. [12] describe a linear programming optimization model to choose which combination of measures to take on a farm to reduce emissions while minimizing costs. Although this model was mainly developed for ammonia evaporation, it can easily be generalized for nitrogen and phosphorus accumulation. The model is used to obtain an optimal combination of measures on a farm, given a certain target reduction of ammonia emission. Reduction is possible by adapting fodder, using new stable or storage types and adapting application techniques. Decision variables are related to activities, that represent a combination of possible measures.

Policy makers, however, are interested in the effects of measures on a national level. Since Baltussen et al. [12] do not take into account the interrelationships between farms, aggregate results cannot be obtained just by aggregating the results of farm level optimization models. Interrelationships between farms do occur e.g. when the surplus of manure is transported to areas with a mineral deficit. These manure flows affect the level of ammonia emission during application. Also, the effects of policy making of livestock reduction, employment and the financial situation of the pig sector have to be modelled in a national abatement model.

6.7 Integrated optimization of the abatement problem

As a first attempt to integrated modelling of the entire mineral cycle in the Netherlands, we develop an integrated optimization model for the mineral excess abatement problem (MEA). The model is a support tool to decide on which combination of measures to take on a national level (in this case the Netherlands) (Section 6.7.1). Section 6.7.2 gives the mathematical formulation of the model (MEA), and Section 6.7.3 discusses some of the characteristics of the model.

6.7.1 Model description

The mineral excess abatement problem (MEA) is a regional problem. Some regions have a large surplus of manure, and therefore of minerals (the surplus areas), whereas others have a mineral deficit (the deficit areas). Therefore, the country is divided into a relatively small number of regions, such that each region is rather homogeneous with respect to farm types, soil types, etc. Each region is free to choose the combination of measures that fits with the characteristics of that region, but the overal objective of the model is to minimize the costs of a mineral excess abatement policy for the pig sector of the Netherlands as a whole. We distinguish nitrogen accumulation, phosphorus accumulation and ammonia evaporation as the three relevant environmental problems for the pig sector. The pig sector is subdivided in farms for fattening pigs and breeding farms. This subdivision is necessary, since the effects of instruments are different for fattening pigs and breeding pigs (see Section 6.3).

The optimization problem (MEA) can be described as follows: find the optimal combination of measures in each region of the Netherlands, such that the standards on nitrate, phosphate and ammonia are met and total costs for the pig sector are minimized. Feasible combinations of measures consist of seven types of instruments (see Figure 6.2): *(i)* fodder adaptations, *(ii)* stable adjustments, *(iii)* storage adjustments, *(iv)* application adaptations, *(v)* processing, *(vi)* transportation and *(vii)* livestock reduction.

For the integrated optimization model, we distinguish four groups of instruments:

1. *farm level instruments*: using the ideas of Baltussen et al. [12], we define a (vector) set M containing all feasible combinations of instruments on farm level, such that if $m \in M$ then m defines a combination of fodder adaptations, stable adjustments, storage adjustments, and application adaptations. The option of 'business as usual' (no abatement measures) is also a feasible combination of instruments.

2. *regional instruments*: processing is treated separately from the farm level instruments, because processing requires regional processing capacity (processing plants) and infrastructure.

3. *transportation*: manure from surplus regions can be transported to other regions where it can be applied. Transportation of manure results in a shift of evaporation emission and nitrate and phosphate leaching in the soil from one region to another.

4. *national instruments*: we assume that structural measures such as livestock reduction will only be taken on a national level. Therefore, livestock reduction is defined as an external parameter of the model.

We treat the mineral excess abatement problem as a decision tree (see Figure 6.4) from manure generated at the pig farms to manure spread at arable farms or processed in processing plants. Each phase in the mineral cycle is modelled as a separate branch in the decision tree to explicitly deal with the interrelationships between the effects of the abatement instruments.

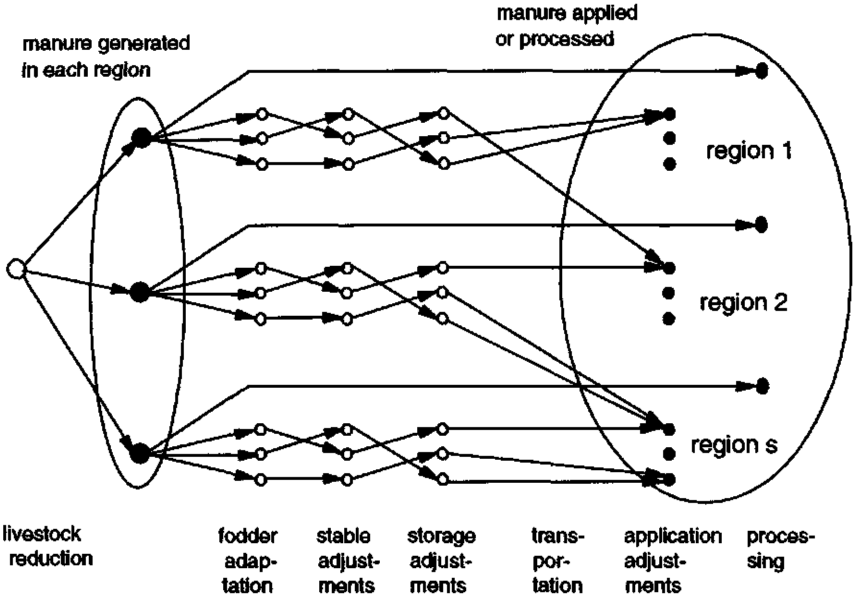


Figure 6.4: Decision tree for the mineral excess abatement problem

The optimization model (MEA) can be stated as follows:

Minimize Costs of abatement policy for the Dutch pig sector

Subject to
- total amount of pig manure generated in a region should be applied in some region or transported to a processing plant;
- the nitrogen and phosphorus accumulation due to applied pig manure in a region may not exceed the nitrogen and phosphorus standards;
- total ammonia emission of pig manure (from stable, storage and application) in the Netherlands may not exceed the ammonia standard.

6.7.2 Mathematical formulation

First, we impose the following assumptions:

- Processing plants can only be located in those regions where manure is generated,

- Nitrogen and phosphorus standards are expressed in kg/ha since they refer to the application of manure on land (see Section 6.2.4). The ammonia standard for pigs is a national standard since it refers to all ammonia emitted to the air during the stable, storage and application periods,
- Available hectares for the application of pig manure are defined by the available hectares cultivated area for manure application times the contribution of pig manure to total manure in the Netherlands in 1990. First, maize land will be used to apply the manure. If all maize land is already used, pig manure will be applied on arable land,
- Regions are free to choose each convex combination of feasible measures as their abatement strategy,
- Livestock reduction is defined as an exogenous decision variable,
- It is possible to follow each unit of manure through all branches in the decision tree.

The following notation is used:

Indices:

$s, t \in S$	=	regions in the Netherlands
$m \in M$	=	feasible combinations of farm level instruments

Parameters:

γ_m^f, γ_m^b	=	annual costs if measure combination m is applied to manure from fattening and breeding pigs (Dfl./m^3 of manure)
θ_{st}	=	transportation costs from region s to region t (costs per ton-km times distance)
π^f, π^b	=	annual costs of processing manure from fattening and breeding pigs (Dfl./m^3)
τ_m^f, τ_m^b	=	required number of hectares for applying one m^3 of manure from fattening (breeding) pigs treated with measure combination m, such that both the nitrogen and phosphorus standards are not exceeded (ha/m^3)
μ_m^f, μ_m^b	=	ammonia emission of manure from fattening (breeding) pigs during the stable and storage period with measure combination m (kg NH_3/m^3)
ν_m^f, ν_m^b	=	ammonia emission of manure from fattening (breeding) pigs during the application period with measure combination m (kg NH_3/m^3)
ω^f, ω^b	=	ammonia emission of manure from fattening (breeding) pigs if the manure is processed in a processing plant (kg NH_3/m^3)
$\overline{v}_s^f$, $\overline{v}_s^b$	=	amount of manure from fattening (breeding) pigs generated in region s (m^3)

$\overline{h}_t$ = available number of hectares for application of pig manure in region t (ha)

$\overline{a}$ = standard for annual ammonia emission from pig manure (kg NH_3)

Decision variables:

XF_{stm} = amount of manure from fattening pigs (in m^3) with measure combination m, transported from region s to region t

XB_{stm} = amount of manure from breeding pigs (in m^3) with measure combination m, transported from region s to region t

XFP_s = amount of manure from fattening pigs (in m^3) processed in region s

XBP_s = amount of manure from breeding pigs (in m^3) processed in region s

Mathematically, (MEA) is formulated as a linear programming problem:

$$z_{MEA} = \min \sum_{s\in S}\sum_{t\in S}\sum_{m\in M}(\gamma_m^f + \theta_{st})XF_{stm} + \sum_{s\in S}\sum_{t\in S}\sum_{m\in M}(\gamma_m^b + \theta_{st})XB_{stm} + \pi^f\sum_{s\in S}XFP_s + \pi^b\sum_{s\in S}XBP_s \quad (6.1)$$

subject to

$$\sum_{t\in S}\sum_{m\in M} XF_{stm} + XFP_s = \overline{v}_s^f \qquad s\in S \quad (6.2)$$

$$\sum_{t\in S}\sum_{m\in M} XB_{stm} + XBP_s = \overline{v}_s^b \qquad s\in S \quad (6.3)$$

$$\sum_{s\in S}\sum_{m\in M} \tau_m^f XF_{stm} + \sum_{s\in S}\sum_{m\in M}\tau_m^b XB_{stm} \leq \overline{h}_t \qquad t\in S \quad (6.4)$$

$$\sum_{s\in S}\sum_{t\in S}\sum_{m\in M}(\mu_m^f + \nu_m^f)XF_{stm} + \sum_{s\in S}\sum_{t\in S}\sum_{m\in M}(\mu_m^b + \nu_m^b)XB_{stm} + \omega^f\sum_{s\in S}XFP_s + \omega^b\sum_{s\in S}XBP_s \leq \overline{a} \quad (6.5)$$

$$XF_{stm},\ XB_{stm},\ XFP_s,\ XBP_s \geq 0 \quad (6.6)$$

The objective (6.1) is to minimize the costs of farm level abatement measures m, processing costs and transportation costs for manure from fattening pigs and breeding pigs. Constraints (6.2) and (6.3) are balancing definitions between the amount of manure that is generated in a region and the amount of manure that is applied somewhere in the Netherlands or processed in the same region. Constraints (6.4) ensure that the amount of hectares asked for by the applied manure does not exceed the available number of hectares in that region. The required number of hectares τ_m^f and τ_m^b are defined as follows:

$$\tau_m^f := \max\{\frac{en_m^f}{\overline{n}}, \frac{ep_m^f}{\overline{p}}\},$$

$$\tau_m^b := \max\{\frac{en_m^b}{\overline{n}}, \frac{ep_m^b}{\overline{p}}\},$$

with

en^f_m, en^b_m	=	nitrogen emission of manure from fattening and breeding pigs treated with measure combination m (in kg N/m^3)
ep^f_m, ep^b_m	=	phosphorus emission of manure from fattening and breeding pigs treated with measure combination m (in kg P/m^3)
$\overline{n}$	=	nitrogen standard (in kg N/ha)
$\overline{p}$	=	phosphorus standard (in kg P/ha).

Constraints (6.5) ensure that the total ammonia emission from stable, storage, application and processing does not exceed the national ammonia standard for pigs. Finally, constraints (6.6) state that the manure flow variables are non-negative.

6.7.3 Structure of the model

The way of modelling the feasible combinations of instruments has large consequences for the structure of the model. It contains many variables and relatively few constraints (i.e. a *flat* model). For example, if we consider 30 regions, three possible fodder adaptations, three stable adjustments, three storage adjustments and three application adjustments for fattening pigs and breeding pigs, the number of variables is almost 146.000 ($30^2 \times 3^4 \times 2 + 30 \times 2$), whereas the number of constraints (except for the non-negativity constraints) is less than 100 ($3 \times 30 + 1$). Solving the linear program with a simplex method means finding a small number of basis variables (i.e. equal to the number of constraints that satisfy the complementary slackness relations).

Many variables can be removed by preprocessing before solving the problem, since it is unlikely that they are chosen in the optimal solution. We give two examples of preprocessing for the mineral excess problem:

- Leneman et al. [95] compared the effectivity of combinations of measures on farm level with the annual costs of these combinations. They conclude that some stable and storage instruments by themselves are not effective compared to fodder adaptations. Therefore, these individual measures can be excluded from the set M.
- Manure from a surplus area will not be transported to another surplus area. The same holds for transportation from a deficit area to another deficit area and for transportation from a deficit area to a surplus area. Excluding these combinations from the transportation matrix substantially reduces the number of variables.

6.8 Computational results

The objective of using the model (MEA) is not to find one optimal solution with minimal costs, but to obtain more knowledge on preferable combinations and the robustness of these combinations with respect to changes in policy ideas. We solve the model for one static situation (the *start scenario*) using realistic data. Because of the large amount of data necessary for the model it is inevitable to make use of different sources in the literature. Data are, as much as possible, from the same year (1990). Based on the start scenario, a what-if analysis identifies the effects of various policy orientations such as changes in environmental standards, livestock reduction, and a relocation of pig farms.

6.8.1 Data and assumptions

The start scenario is defined as follows:

The nitrogen standard is 170 kg/ha (i.e. recommended standard in the European Parliament), the phosphorus standard for maize and arable land is 125 kg/ha (Dutch standard for the second phase in the manure policy, see Table 6.3), and the ammonia standard is 50% reduction with respect to the level of total ammonia emission in the year 1980. The ammonia standard for pigs is based on the contribution of pig manure to the total level of ammonia emission (see Section 6.2.3).

The Agricultural Economics Research Institute (LEI-DLO) provided the necessary data on regions, manure amounts, and areas of cultivated land. The Netherlands are subdivided into 31 regions (the so-called LEI regions) from which 10 are considered as surplus regions, 11 regions are considered as deficit regions, and the remaining regions are considered as transition regions (regions that can use manure for fertilizing but do not have a mineral deficit). Figure 6.5 shows the subdivision in regions. From Figure 6.5 it is obvious that the eastern and southern parts of the Netherlands are surplus areas, whereas the northern, north-western and south-western parts are deficit areas. The distances between all regions are known. Transportation costs are Dfl.0.06 per m^3/km (Luesink and Van der Veen [101]). For each region, the annual manure production for fattening pigs and breeding pigs is given as well as the available hectares of maize, grass land and arable land.

Data on costs and emissions for combinations of measures are obtained from Leneman et al. [95]. Tables C.1 and C.2 in Appendix C summarize their findings with respect to costs and emissions on a farm level. The emissions are subdivided into nitrogen leaching, phosphate leaching, ammonia emission in stable and storage, and ammonia evaporation during application. Nitrogen and phosphorus emissions are defined as the accumulation of nitrogen or phosphorus in the soil below one meter under the surface. In fact, this is the amount of nitrogen and phosphorus not absorbed by the vegetation. Without any measures, the nitrogen accumulation is about 200 kg N/ha, whereas the phosphorus accumulation is about 125 kg P/ha. Unfortunately, the available environmental standards for nitrogen and phosphorus are still application standards, i.e. standards for the amount of nitrogen or phosphorus when the manure is applied on the land. However, these standards can still be used as upper bounds for (still non-existing) leaching standards. First experiments show that an application standard of 150 kg P/ha can be compared with an accumulation standard of 70 kg/ha. We apply a sensitivity analysis to changes in the nitrogen and phosphorus standards in Section 6.8.2 to investigate the robustness of the results to the possible differences between application standards and accumulation standards.

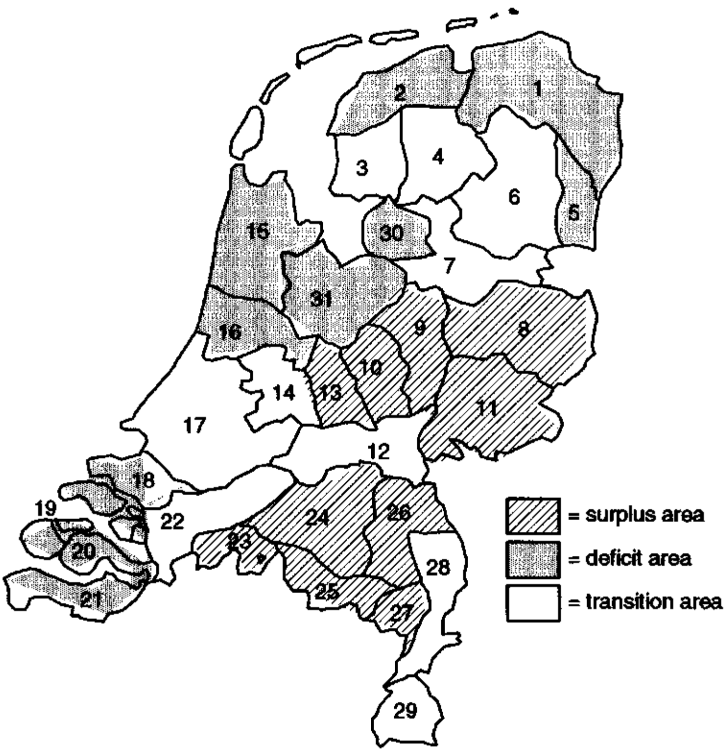


Figure 6.5: Manure regions in the Netherlands

Combinations that are dominated by other combinations (i.e. with less costs and higher reduction percentages) have already been removed in advance. The result is a list of 16 feasible measure combinations for fattening pigs and breeding pigs. These costs and emissions can easily be translated into costs and emissions per m^3 of manure. Leneman et al. [95] estimate the annual average production of manure on farms for fattening pigs to be 946 m^3, and the annual average production of manure on breeding farms 745 m^3.

Manure processing is considered as a special type of measure, since it can only be executed on a regional base. The costs for manure processing are estimated at Dfl. 50/m^3. During processing, no emissions of nitrate or phosphate take place. Ammonia emissions only occur during the stable period of the pigs.

The following assumptions have been made:

- *Regions:* Within a region, the manure is transported from pig farms to arable land. We assume the distance between these points to be five kilometers. No transportation flows are allowed from deficit areas or to surplus areas. This assumption reduces the number of possible transshipments from almost 1000 (31^2) to 441,

- *Applications:* Pig manure can be applied on maize land, and if necessary on arable land. Pig manure is not suited to apply on grass land. An average amount of 43 m^3 of manure can be applied at one hectare land. This assignment is based on the relation between annual pig manure production in the Netherlands (about 86 million m^3 in 1990) and the area of cultivated land in the Netherlands (about 2 million hectares). About 23% of the cultivated area has to be assigned to manure from fattening pigs and breeding pigs (about 20 million m^3 in 1990) divided in all maize land (201,810 ha) and 37% of arable land (254,058 ha). An alternative assignment could be based on e.g. the relation between annual production of phosphates and available cultivated land. Some studies introduce the acceptance level for application on vegetation types in each area (e.g. Luesink and Van der Veen [101]). This level represents the willingness of farmers to accept manure from other regions. We assume this level to be 100%. We examine the effect of a lower acceptance level in the sensitivity analysis,

- *Costs:* Without any binding emission standards, it is obvious that the optimal solution consists of *multi. feed. (N-%)* (3) for all fattening pigs, and *business-as-usual* (1) for all breeding pigs, because this combination has the lowest costs (see Tables C.1 and C.2). Feeding fattening pigs with multi-phase fodder is cheaper than feeding them with standard fodder since fattening pigs need less food if this food is adapted to their growth-phase. The costs for this optimal solution are negative (about -73.5 million guilders). To avoid negative costs in the objective function, total costs are increased with this fixed amount. In other words, we assume that if measures save money, all farmers will implement these measures.

The what-if analysis contains the sensitivity of the results for:

- (WI1) NITROGEN AND PHOSPHORUS STANDARDS
  In this scenario, the nitrogen standard varies from 60 kg/ha to 200 kg/ha while the phosphorus standard is either 125 kg/ha (standard for the second phase of the

Dutch manure policy) or 75 kg/ha (standard for the third phase of the Dutch manure policy). The ammonia standard is the same as in the start scenario.

- (WI2) THE AMMONIA STANDARD
  In this scenario, we assume no nitrogen and phosphorus standards. In this way, the separate effect of the ammonia standard can be measured. First, the ammonia standard is fixed at 100% of the emission level of the year 1980, then the ammonia standard is tightened in steps of 5%.

- (WI3) AVAILABLE HECTARES FOR THE APPLICATION OF PIG MANURE
  Based on the available hectares in the start situation, we can decrease the number of available hectares until no feasible solution for the mineral excess problem can be found, or increase the number of available hectares until it is no longer necessary to transport manure from one region to another. The range of available hectares between the two extremes (no feasible solution, no transportation) gives information on the elasticity of the results. We assume no ammonia standard in this scenario (ammonia emission is allowed up to 100% of the emission level of the year 1980), nitrogen and phosphorus standards are equal to those in the start scenario.

- (WI4) A UNIFORM LIVESTOCK REDUCTION
  The number of pigs in each region is increased step-by-step to 120% of the number of pigs in the start scenario, and reduced step-by-step to 50%. All standards are the same as those in the start scenario.

- (WI5) RELOCATION OF PIG FARMS
  In this scenario it is allowed to move pigs from one region to another, as long as the total amount of fattening pigs and breeding pigs does not change. The costs of a relocation are not included in the model. All standards are the same as those in the start scenario.

- (WI6) LOCAL OPTIMIZATION BY THE DEFICIT AREAS
  The deficit areas choose measure combinations that save money (i.e. the relevant fodder measures). They are reluctant to invest in costly measures that are attractive for the pig sector in the Netherlands as a whole.

6.8.2 Results

Start scenario

Three manure combinations are chosen in the optimal solution for the start scenario, the combination *multi. feed. (N-%), small stable changes and ploughing* (14) for fattening pigs, and the combinations *multi. feed. (N-%) and small stable changes* (10), and *multi. feed. (N-%) and bio-washers* (12) for breeding pigs. About 76% of the breeding farms chooses combination (10), and 24% chooses combination (12). Region 11 is the only region that uses both combinations. Breeding farms in the other regions use either combination (10) or combination (12). The optimal combinations contain rather expensive measures to reduce the ammonia emission in the stable. About 20% of the manure from fattening pigs is transported from one region to another. Manure from surplus areas in the middle of the Netherlands (regions 10, 13 and 14) is transported to nearby regions in North-Holland (regions 16 and 31). Manure from surplus areas in North-Brabant (regions 24, 26 and 27) is transported to nearby regions in Zeeland and Limburg (regions 12, 22, 28 and 29).

Meeuwissen [105] indeed conclude that the combination of fodder and stable adaptations is better than other combinations, if volume reduction is not a feasible instrument. Recent research studies from LEI-DLO show the same results. This indicates that the simple integrated optimization model gives reasonable solutions for the start-scenario, despite a lower level of detail included in the model, compared to other models (like the ones described in Section 6.4.1).

(WI1) Sensitivity to nitrogen and phosphorus standards

In this scenario, we examine the sensitivity of the results to changes in nitrogen standards, while the phosphorus standard and the ammonia standard remain unchanged. Figure 6.6 shows the costs figures of a change in the nitrogen standard if the phosphorus standard is 125 kg/ha.

Total costs of abatement instruments increase progressively if the nitrogen standard is reduced from 200 kg N/ha to 60 kg N/ha. Optimal farm measures (fodder, stable, storage, and application) remain optimal, if the nitrogen standard is above 80 kg/ha. Below this level, processing is also chosen. If processing is one of the optimal instruments, some of the expensive stable and application measures to reduce nitrogen and phosphorus accumulation in the soil can be avoided; the contribution of measure *multi. feed. (N-%)* (3) increases both for fattening and breeding pigs. This explains the decreasing cost function for farm measures after the introduction of processing. Transport costs increase until processing is introduced. If some of the manure can be processed, less manure has to be transported from surplus areas to deficit areas.

If the phosphorus standard is tightened to 75 kg P/ha, total costs for the optimal solutions for a nitrogen standard of 200 kg/ha increase with 5 %. Between a standard of 200 kg/ha and 70 kg/ha total costs increase with less than 5%. Below the standard of 70 kg/ha, total costs are the same as if the phosphorus standard is 125 kg/ha.

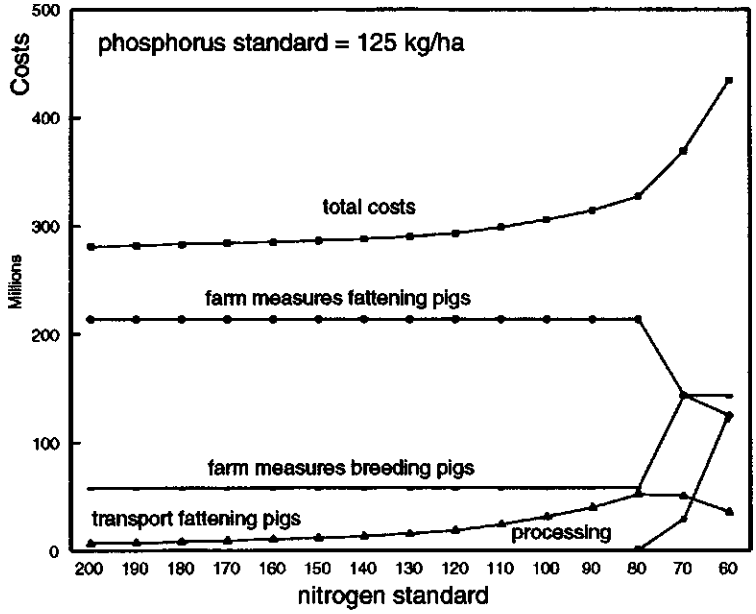


Figure 6.6: Sensitivity analysis with respect to the nitrogen standard

(WI2) Sensitivity to ammonia standard

Without any binding emission standards, the optimal solution for fattening pigs is *multi. feed. (N-%)* (3), and *business-as-usual* (1) for breeding pigs. Figure 6.7 shows the increase of measures if the ammonia standard is tightened from no reduction to 85% reduction compared with the level of 1980. For the fattening pigs, first ploughing is added to the fodder adjustments, then stable changes are added to the package of optimal measures. For the breeding pigs, stable changes are chosen before ploughing is introduced. Comparing Tables C.1 and C.2, it is obvious that ploughing is more effective for fattening pigs than for breeding pigs. Figure 6.7 presents the contribution of each combination to the optimal solution. The results give also information on the regional distribution of the various combinations. In general, it holds that a surplus area (e.g. North-Brabant) implements expensive measures earlier (i.e. at a lower reduction level) than a deficit area (e.g. Friesland).

(WI3) Sensitivity to available hectares cultivated land

In this scenario, the available hectares land for application of pig manure are step-wise reduced to 20% of the amount in the start-scenario. If the available hectares are reduced from 100% to 50% of the basic amount, only additional transportation is necessary. From 50% to 40% fodder measures for the breeding pigs are added (*multi. feed. (N-%)* (3). From 40% to 20%, also processing is introduced as a necessary instrument. It is difficult to forecast the effect of reducing available hectares for the pig sector based on the results of this scenario, since we do not take into account the relations between pig manure, available hectares and manure from other animals (cattle, poultry).

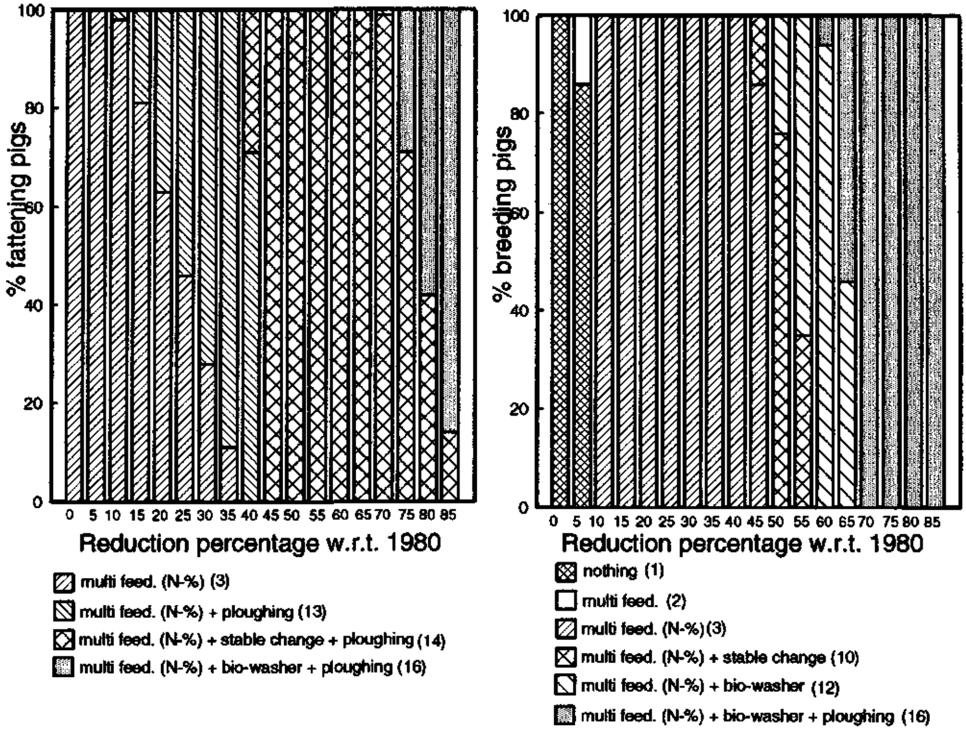


Figure 6.7: Optimal measure combinations with different ammonia standards

(WI4) Sensitivity to uniform livestock reduction

If the volume of pig manure is step-wise reduced to 50% of the amount in the start-scenario, total costs decrease step-wise linear to 15% of the original costs. A reduction to 90% of the current livestock volume saves already 24% of the costs for abatement measures. An increase of livestock from 100% to 120% results in a cost increase of 50%. From 120% to 90% the shape of the total cost function is based on a decrease in costs of farm measures for fattening pigs and breeding pigs together with a decrease in transportation costs. From 90% to 50%, the shape of the total cost function is based on a decrease in costs of farm measures for fattening pigs. Other cost categories remain stable.

(WI5) Sensitivity to relocation of pig farms

The optimal solution for this scenario suggests to relocate fattening pigs from surplus areas to deficit areas: the large pig concentrations in the regions (8-13) and (23-27) disappear. The pigs are relocated to regions 6 and 7, the South-west (regions 18-21) and Flevoland (regions 30-31). Breeding pigs are relocated to region 1 (65%), region 5 (8%) and region 18 (27%). Total costs for the optimal solution are 2.3% below the costs for the optimal solution in the start-scenario.

(WI6) Sensitivity to local optimization by the deficit areas

Although the deficit areas contribute to only 2.4% of the manure of fattening pigs and 3.1% of the manure of breeding pigs, their cooperation has a relevant impact on the behaviour of other regions. If the deficit areas refuse to invest money in other instruments than the cheapest ones (i.e. *multi. feed. (N-%)* for fattening pigs and *business-as-usual* for breeding pigs), total costs for the Dutch pig sector increase with 2% compared to the start-scenario. Costs for farm measures for fattening pigs decrease with 3%, whereas the costs for farm measures for breeding pigs increase with 16%. More farms are forced to implement *multi. feed. (N-%) and biowashers* (12), instead of the cheaper option *multi. feed. (N-%) and small stable changes* (10). Also the transportation costs increase with 16%. If the deficit areas do not invest in application adjustments, surplus manure (with a high concentration of nitrogen and phosphorus) can no longer be transported to these areas and has to be transported to areas that do invest in application adjustments.

6.9 Conclusions

The mineral excess problem in the intensive livestock sector is very complex. The most relevant reasons for this complexity are:

- the late recognition of the problem;
- conflicting goals of the manure legislation;
- the large number of combinations of measures to abate emissions.

In order to analyse and solve the mineral excess problem, we study the above reasons for complexity and suggest a quantitative modelling approach based on chain-analysis to deal with this complexity.

The main causes of the mineral excess problem are:

- the increase of the intensive mineral production due to the increase of population, better economic circumstances and improvement of technology;
- the import of corn substitutes and inorganic fertilizer due to a high level of specialization, the low-cost corn substitutes (tapioca) from Thailand, and the low-risk aspect of inorganic fertilizer (availability, quality).

As a result, mineral excretion is far above the mineral requirements of crops. The excess of minerals leads to eutrophication and acidification, recognizable by decreasing forest quality and groundwater and surface water quality.

The environmental drawbacks of a large-scale agricultural production require large reductions of emission levels. These reductions cannot be obtained only by adaptations of the production process, such as fodder adjustments and application measures. Structural measures such as a decrease of the livestock will have a large effect on the agribusiness in particular, but also on the export position of the Netherlands in general. A chain analysis that includes all components of the problem can be a valuable tool to develop an acceptable manure legislation that copes with these conflicts. Important components in the mineral chain are feeding, growth, stable and storage, transportation, application and processing. Models have been developed to evaluate scenarios of abatement strategies with respect to individual components of the manure problem. Conclusions based on these evaluation studies are that:

- integration of abatement measures is necessary to satisfy the required reduction levels,
- the effect of a combination of measures, a policy mix, is hard to estimate 'by hand' or intuitively. A significant gap has been found between the ultimate goals beforehand and the final results after implementing a chosen scenario.

Based on these conclusions, we develop an optimization model that can be used as a tool to evaluate scenarios with respect to all effects on the mineral cycle in the first place, but that can also be used to find reasonable proposals for scenarios, given the necessary emission reduction levels. This linear optimization model is only a first attempt to integrated modelling. It does not include other manure categories (cattle, poultry) that do influence the effects of abatement instruments on emissions. However, for a start-scenario with given standards for nitrogen, phosphorus and ammonia, the model gives the same recommendations as acknowledged research institutes do (e.g. Meeuwissen [105]). From the sensitivity analysis we conclude that:

- sharpening the nitrogen standard increases the amount of necessary manure transportation,

- sharpening the ammonia standard requires additional changes in the stable and during application of the manure,
- the cooperation of deficit areas (areas that can receive minerals) is essential in solving the mineral excess problem. If they refuse to invest in adaptations in the mineral cycle, the costs of emission abatement increase considerably.

The advantages of this integrated model are *(i)* additional information obtained from sensitivity analysis, *(ii)* differentiation of policy among regions, and *(iii)* integrated solutions that combine all instruments that affect the mineral cycle as a whole; farm measures (fodder, stable, storage and application), transportation, central processing, but also livestock reduction and relocation.

Appendix C

Leneman et al. [95] considered packages of abatement measures to study the effects of combining abatement measures on the emission reductions for nitrogen and phosphorus. Tables C.1 and C.2 present a summary of the results of this study.

Table C.1: Costs and emissions for measure combinations for fattening pigs

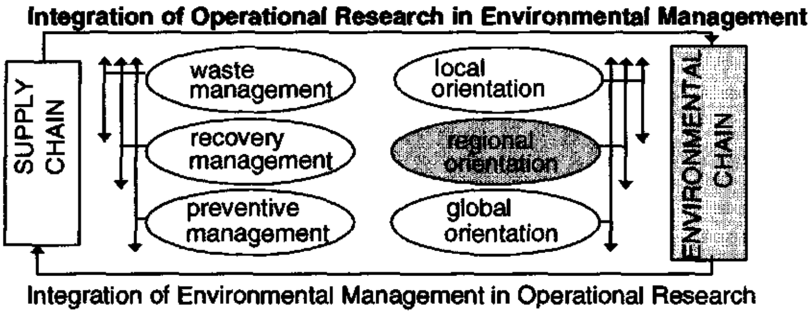
No.	Combinations fattening pigs (640 animal places)	Annual farm costs (Dfl./year)	Emissions nitrogen (kg N)	Emissions phosphorus (kg P)	Emissions ammonia stable/ storage	Emissions ammonia application
1	Business-as-usual	0	2024	1343	1477	1208
2	Multi. feed.	-2487	1943	1195	1436	1168
3	Multi. feed. (N-%)	-6294	1639	1061	1249	1007
4	Small stable change	3840	2105	1061	1208	1289
5	Large stable change	14400	2186	1061	940	1396
6	Bio-washer	21424	2186	1061	430	1208
7	Covering curr. iron	1669	2105	1061	1235	1289
8	Covering tent	2050	2105	1061	1181	1316
9	Ploughing	13192	2611	1061	1235	188
10	Multi. feed. (N-%) + small stable change	-2532	1680	1061	1020	1101
11	Multi. feed. (N-%) + large stable change	8028	1741	1061	779	1181
12	Multi. feed. (N-%) + bio-washer	15130	1639	1061	376	1020
13	Multi. feed. (N-%) + ploughing	6820	2105	1061	1047	161
14	Multi. feed. (N-%) + small stable change + ploughing	10660	2206	1061	806	161
15	Multi. feed. (N-%) + large stable change + ploughing	21220	2328	1061	564	188
16	Multi. feed. (N-%) + biowasher + ploughing	28244	2105	1061	161	161

Table C.2: Costs and emissions for measure combinations for breeding pigs

No.	Combinations breeding pigs (120 sows)	Annual farm costs (Dfl./year)	Emissions nitrogen (kg N)	Emissions phosphorus (kg P)	Emissions ammonia stable/ storage	Emissions ammonia application
1	Business-as-usual	0	840	843	1017	524
2	Multi. feed.	290	680	826	925	493
3	Multi. feed. (N-%)	956	689	733	848	447
4	Small stable change	2004	865	843	801	601
5	Large stable change	7309	890	843	593	670
6	Bio-washer	12706	840	843	231	524
7	Covering curr. iron	1514	857	843	909	570
8	Covering tent	1843	857	843	894	570
9	Ploughing	10618	991	843	901	85
10	Multi. feed. (N-%) + small stable change	2976	714	733	670	501
11	Multi. feed. (N-%) + large stable change	8296	731	733	670	501
12	Multi. feed. (N-%) + bio-washer	13606	689	733	185	447
13	Multi. feed. (N-%) + ploughing	11457	748	733	747	69
14	Multi. feed. (N-%) + small stable change + ploughing	14508	832	733	570	77
15	Multi. feed. (N-%) + large stable change + ploughing	18654	907	733	385	92
16	Multi. feed. (N-%) + biowasher + ploughing	24107	748	733	100	69

Chapter 7

Recycling of waste paper in Europe



This chapter illustrates the use of Operational Research in a regional orientation *towards environmental problems.*

This type of policy approach is often used if emission in one country may effect the environmental quality in other countries. OR supports in the evaluation and improvement of policies.

We consider European policies to reduce environmental impacts of the pulp and paper sector through waste paper recycling. Recycling is only one of the available methods to reduce environmental impacts. The question arises if forcing maximal paper recycling is the best policy to optimize the environmental impact of the pulp and paper sector. We explore this question combining life cycle analysis and optimization techniques. We use the model to analyse scenarios with different recycling strategies. Qualitative criticisms and opinions on recycling strategies can be underpinned using this quantitative approach.

7.1 Introduction

7.1.1 Problem description

The paper and pulp sector is a very large and capital-intensive part of industry. Apart from oil and gas, it is the biggest industry measured in terms of world-trade. For some countries, pulp and paper trade is essential for the economy. For example, the export of Swedish pulp and paper covers 20% of total export value of that country.

The principal environmental impacts of the European pulp and paper sector are associated with *(i)* its consumption of raw materials, including virgin resources, *(ii)* its emissions to air and water during the production of paper and pulp (especially pulp bleaching is a very polluting process), and *(iii)* the existence of waste paper. In Europe, waste paper comprises about 35% of total household waste volume (Virtanen and Nilsson [158]). There is also a major induced impact on forest ecosystems arising from the demand for pulpwood. These impacts contribute to a wide range of environmental and human health problems of local, regional and global significance.

Policies are being implemented at European (EU) and national levels to promote particular measures in the pulp and paper sector (especially recycling) even though there is no scientific consensus on their environmental impacts.

"Driven by demands for more efficient and environmentally-friendly resource management and the problems of waste disposal, governments in Europe have been setting tougher standards governing the recovery and re-use of paper products, forcing pulp and paper producers to embrace recycling as an integral part of their operations..." (Financial Times [56]).

Because of their high potential impact, policy measures must be consensual, transparent, consistent as well as efficient. For this, an assessment methodology is needed that satisfies these same criteria. Such a methodology would permit more systematic policy making based upon a comprehensive assessment of the potential environmental improvements given available technologies and prospective new technologies in the future. Scenario analysis (e.g. Virtanen and Nilsson [158]), although very useful, is limited because it depends upon an exogenously specified instrument and because the instrument cannot be evaluated in terms of its contribution to achieving an overall policy goal. Our modelling approach starts with the policy goal in order to co-ordinate policy actions. It combines life cycle analysis (LCA) and optimization techniques.

The approach described above is not only applicable to paper recycling. Other examples of application areas are:

Plastics Since 1991 Germany has an environmental policy stating that 80% of produced plastics must be collected. From the collected plastics, 80% must be recycled. Recycling of plastics is not always the best way to dispose of plastic waste. Recovery of raw materials or even incineration can be better for the environment and moreover for the economy. The plastics manufacturers use these results to criticise the policy making both in Germany and in the European Union.

Solid waste in India Van Beukering [21] describes recovery methods for urban solid waste (glass, paper, plastics and non-ferrous metal) in Bangalore (India). Three categories of recovery are distinguished: *(i)* reuse and repair, *(ii)* recycling, and *(iii)* energy recovery. He states that from an environmental view, limiting energy recovery can generally be considered beneficial, as incineration of urban solid waste often generates toxic emissions. Therefore, the primary goal of solid waste managers should be to maximize recycling activities. The results from this study are contrary to the German study on plastics. A quantitative modelling approach is very useful to place this type of statements in the right perspective by analysing whether the effect of recycling in developed countries is different from its effect in developing countries.

7.1.2 Contents

In Section 7.2 we discuss environmental policy making in the European pulp and paper sector and pose some basic research questions. Section 7.3 outlines the modelling approach and covers data sources, underlying assumptions and constraints. The modelling approach minimizes the environmental impact of the pulp and paper industry. Costs (such as market prices of pulp, paper, and waste paper, and investment costs for technical improvements) are not included in the model. We describe the life cycle optimization model in Section 7.4. In Section 7.5, we assume one paper type representative of the 'average' of all paper and board types produced. This assumption enables us to carry out a sensitivity analysis on the environmental impacts of the paper and pulp processes. In Section 7.6 we delete this simplification and observe all paper types. For five scenarios on recycling policies, we give the results with respect to environmental impacts, market shares, etc. Section 7.7 concludes with a summary of the main results and their implications for policy making.

7.2 Environmental policy and the pulp and paper sector

Environmental concern over the paper and pulp sector has until recently been focused on emissions to air and water from pulping, bleaching, and paper making processes.

The combination of policy instruments (mostly emission ceilings) and industry responses (end-of-pipe and process-integrated emission controls) has reduced emissions to air and water substantially. Chlorine and chlorine-compound emissions were specifically targeted (Rajotte [128]) and elemental chlorine has begun to be phased out as a bleaching agent. By developing systems for the recovery and reuse of its wastes, the industry has reduced its draw on raw materials, including fossil energy. Nowadays, concern is mostly for the sector's effect on forest ecosystems and its generation of solid waste. Environmental policy is shifting accordingly. Future policies will likely include (following Capps and Devas [35]):

- *timber certification.* Certificates will only be granted to pulp, paper, and board products made from timber produced from sustainable managed forests.
- *eco-labelling.* Several eco-labelling schemes have been proposed or are currently operating at the EU and national levels. Only one scheme, Britain's 'Brands-Eco' scheme, offers a label to paper and board products produced from virgin pulp. All other schemes give labels only to paper and board products made from recycled pulp. The German 'Blue Angel' label is awarded only to paper products that contain 100% recycled pulp. The EU's eco-label will exclude all products based on virgin pulp, implicitly providing market advantages to recycled pulp (Rajotte [128]).
- *eco-taxes.* The Belgium government has proposed a tax of BF 10/kg on paper and board products failing to meet specified recycled pulp content. The threshold proposed for magazines is 60%. The tax would be halved if the products were made from chlorine-free pulp.

Current waste management methods comprise recycling, energy recovery, and landfill disposal. The EU Member States agreed in 1993 that the environmental validity of each method should be based on scientific evidence (Club de Bruxelles [38]). In practice, the Member States have their own preference towards instruments. For instance, regulatory instruments, like mandated waste paper recycling, are favored in Germany. However, such 'command-and-control' type of instruments may easily lock out better future alternatives and may even 'require the impossible' by mandating technically non-feasible recycling levels. The French Eco-Emballages scheme, on the other hand, appears to move away from the focus on recycling. Its principal objective is energy recovery from used materials through incineration. However, this view appears to be making little headway with the environmental lobby in Europe.

European policy makers seem persuaded of the benefits from recycling, but many analysts consider these benefits ambiguous. Some argue that recycling may reduce some environmental impacts while increasing others (Udo de Haes [153]). The emphasis on recycling also raises suspicion that environmental policy may be manipulated to serve (national) industry and trade policy objectives or to shift environmental problems from one place or type to another. Since different activities and places involved in the life cycle of pulp and paper products are linked, actions to reduce environmental impacts in one place may have serious implications for activities that occur elsewhere. A very high imposed percentage of recycling, which helps reduce Western Europe's solid waste problem, would adversely affect the Nordic industry. Scandinavia, Europe's main producer of virgin pulp, would be unable to generate sufficient recycled paper by recovery from its relatively low population. The only solution would be to import waste paper, which would generate an environmental impact of its own, particularly from the energy used for transportation (Financial Times [56]). France, Spain, the UK and other countries have had to face considerable flows of untreated paper at very low prices from Germany, where high recycling standards were decreed without the necessary treatment capacity. Such mishaps could lead EU Member States to adopt protectionist measures.

Policy choices should be rational and consistent. A scientific basis for preferring one technology over another can be found in an explicit evaluation system. Such a system is also essential for understanding the rationale for policy choices, verifying the consistency of environmental policies. Apart from evaluation, environmental optimization is necessary to search for efficient and robust policies. The possibility of different environmental optima based on some set of assumptions, implies that policy makers should search for robust development pathways for the sector through time.

Our methodology of combining life cycle analysis with an optimization model addresses the following basic questions to evaluate and improve policy making.

- By how much can environmental performance be improved in the short and longer term ?
- What product life cycle and sectoral configurations will minimize the overall environmental impact of the sector ?
- What kinds of policy measures would be most effective in reducing environmental impacts in the short term and the longer term ?
- What do the different configurations imply for the aggregate material balances of the sector, for individual countries, and for trade ?

7.3 Methodology of life cycle optimization

The overall model combines a linear programming network flow model of the European pulp and paper sector with life cycle analysis. The methodology of life cycle analysis is extensively described in Chapter 5. LCA provides a tool for tracking flows of materials through the life cycle from one place or process to another. It combines objective information about the environmentally-relevant characteristics of processes with a subjective evaluation of the relative importance of different types of environmental damage. The environmental index that results from the LCA is used as a coefficient to build the objective function for the linear programming model. The output of this model is a life cycle configuration with its corresponding environmental impacts. The configuration entails a pattern of production, consumption, waste management, and transportation. The flows imply the geography and the technologies of the sector including levels of raw materials demand, production, and international trade.

To test the methodology, we have specifically focused on fiber recycling, since this allows us to reduce the scale of the modelling task while addressing the concerns identified above. Changes in recycling rates do not affect the environmental impacts of manufacturing paper and board products. Therefore, paper production is ignored while minimizing environmental impacts. Processes upstream of pulp production – forestry, lumbering, wood transportation – are subsumed within the process of virgin pulp production. The processes considered in the model are *(i)* virgin pulp production and bleaching, *(ii)* recycling, *(iii)* incineration with energy recovery, and *(iv)* transportation of pulp, paper and waste paper.

7.3.1 Evaluation system for environmental performance

The inventory analysis in LCA results in an inventory table for each relevant process. Table 7.1 lists the broad categories of environmental impacts for each major process and indicates which are negative, positive, and ambiguous. We distinguish four types of primary pulping (bleached sulphate, unbleached sulphate, bleached sulphite and bleached thermomechanical pulp (TMP)) that represent the main pulping techniques. Several bleaching technologies are possible: chlorine, chlorine-dioxide, oxygen, and peroxide. Although different types of recycled pulp are produced in Europe, we distinguish only one (aggregated) type of recycled pulp, since *(i)* only aggregated data are available (Virtanen and Nilsson [158]) and *(ii)* the environmental differences between the recycled pulp types are relatively small compared to the environmental differences between primary pulp types. The inventory tables for virgin pulp and transportation are based on BUWAL [33] and those for recycling and incineration on Virtanen and Nilsson [158].

The classification step prepares the environmental profile from the inventory tables. The environmental impacts are converted to effect scores for seven environmental problems that are relevant to the pulp and paper sector: global warming, human toxicity, ecotoxicity, photochemical oxidation, acidification, nutrification, and solid waste.

Table 7.1: Environmental impacts of pulp and paper processes

Inputs	Impact	Outputs	Impact
Primary pulping:			
wood	?	emissions to air/water/land	−
chemicals	−	energy recovery	+
energy	−	carbon sinking	+
Recycling:			
scrap paper	?	emissions to air/water/land	−
chemicals	−		
energy	−		
Incineration:			
scrap paper	?	energy recovery	+
		emission to air/land	−
Transport:			
fuel/energy	−	emissions to air	−

\+ positive environmental impact
− negative environmental impact
? ambiguous

Table 7.2 gives the environmental profiles for the selected processes, expressed in a damage potential per unit product (Heijungs [69]). For example, global warming is expressed in GWPs (global warming potentials), whereas acidification is expressed in APs (acidification potentials).

Table 7.2: Environmental profiles in the paper and pulp sector

Process	Global warming	Human toxicity	Eco-toxicity	Photo. oxydation	Acidi-fication	Nutri-fication	Solid waste
(for 1000 metric tons)							
Pulp/sulphate/bl.	140	11	0.0008	1.4	4.5	0.7	61
Pulp/sulphate/unbl.	59	9	0.0003	1.3	3.1	0.4	40
Pulp/sulphite/bl.	496	26	0.001	4.1	8.5	2.4	61
Pulp/TMP/bl.	887	11	0.0005	1.4	4.9	0.3	70
Recycled pulp	296	3	0	0.04	2.2	0.4	76
Incineration	-1319	-11	0	-0.2	-8.4	-0.1	32
Transport/truck	0.07	0.003	0	0.0004	0.001	0.0001	0
Transport/ship	0.03	0.0004	0	0.00004	0.0002	0	0

The effect scores are normalised using the effect score of the largest contributor as a reference level. So, the process with the largest contribution to e.g. acidification gets a normalised effect score of 100 for acidification. Table 7.3 gives the normalized environmental profiles in the pulp and paper sector.

Table 7.3: Normalized environmental profiles in the paper and pulp sector

Process	Global warming	Human toxicity	Eco-toxicity	Photo. oxydation	Acidi-fication	Nutri-fication	Solid waste
(for 1000 metric tons)							
Pulp/sulphate/bl.	16	42	79	35	53	31	81
Pulp/sulphate/unbl.	7	33	32	31	36	17	52
Pulp/sulphite/bl.	56	100	100	100	100	100	80
Pulp/TMP/bl.	100	43	52	35	58	13	92
Recycled pulp	33	11	0	1	26	19	100
Incineration	-149	-43	0	-6	-99	-5	42
Transport/truck	0.008	0.01	0	0.01	0.02	0.005	0
Transport/ship	0.004	0.002	0	0.001	0.003	0	0

In the evaluation phase, weights are assigned to the different kinds of problems to reflect their relative importance to society. In our base runs, we ascribed equal importance to the problems. For each process, the average of normalized effect scores provides the environmental index. Table 7.4 presents these indices.

Table 7.4: Environmental indices for the pulp and paper sector

Process	Index
(for 1000 metric tons)	
Pulp/sulphate/bl.	48.147
Pulp/sulphate/unbl.	29.744
Pulp/sulphite/bl.	90.909
Pulp/TMP/bl.	56.104
Recycled pulp	27.079
Incineration	-37.025
Transport/truck	0.0078
Transport/ship	0.0013

The improvement analysis translates here into a life cycle optimization, using the environmental indices in the objective function of a linear network flow model to minimize total environmental impact.

7.3.2 Life cycle optimization

The model includes six regions within Europe: Scandinavia (Finland, Sweden), Germany, France, UK, Italy, and Iberia (Portugal and Spain). These regions account for more than 80% of Europe's virgin pulp and paper production and consumption (Table 7.5).

Table 7.5 also shows that Europe has a net import of about 14% of virgin pulp and a net export of about 4% of paper. The model assumes that all virgin pulp import is from North

America (Canada and USA). The net export of paper has no influence on the system as we consider it.

We assume that the environmental impacts of the individual technologies are the same in each region (i.e. the environmental impacts of the best available technoly (BAT)). Therefore, the environmental index for the different virgin pulp types applies to all six European regions.

Table 7.5: Virgin pulp and paper production and consumption in 1990

Region	Virgin pulp				Paper			
	prod.	%	cons.	%	prod.	%	cons.	%
	(in 1000 metric tons)							
Scandinavia	11,682	(37)	14,901	(41)	17,381	(28)	3,560	(6)
Germany	2,233	(7)	5,428	(15)	11,873	(19)	14,643	(25)
France	2,203	(7)	3,621	(10)	7,049	(11)	8,760	(15)
UK	595	(2)	2,176	(6)	5,056	(8)	9,743	(16)
Italy	591	(2)	2,551	(7)	5,582	(9)	7,014	(12)
Iberia	2,868	(9)	1,740	(5)	4,225	(7)	5,091	(8)
Others	11,498	(36)	5,629	(16)	11,062	(18)	10,935	(18)
Europe	31,670	(100)	36,046	(100)	62,228	(100)	59,746	(100)

Source: OECD [117]

The model tracks the flow of raw materials, mass commodities, products, and wastes between processes and regions. In addition to the four virgin pulp types, the model differentiates seven paper and paperboard types, waste paper, and recycled pulp. Basically, there are two general product groups for which paper and board are used: *graphic* products (newsprint 14%, printing quality paper 36%), and *paper and board* products (liner 12%, fluting 9%, boxboard 9%, household 5% and special grades 15%). A distance matrix gives shortest road or sea routes between regional capitals. Transportation between regions is differentiated by ship and truck. Internal (within region) transportation is not considered.

The objective of the flow model is to find the sectoral configuration that minimizes overall environmental impact given feasibility conditions and policy scenarios. We assume that the environmental impacts of the individual pulping technologies are the same in each region; i.e. the same environmental profile for the virgin pulp types applies to all six European regions. The decision variables include the level of recycling and energy recovery, production of virgin pulp by type, and transportation flows. By implication, these specify the technological and geographical configuration of the sector.

A feasible configuration is defined by:

- *a fixed paper production and consumption pattern in Europe.*
  We assume that paper production and consumption are fixed at their current levels

in each region (OECD [117]). This implies that total pulp demand (virgin pulp plus recycled pulp) and waste paper supply are fixed. In Section 7.6.3 we allow for relocation of paper production. Virgin pulp producers in the Nordic countries argue for this relocation:

"From the producers' point of view, the best solution is to place the plants using heavy proportions of recycled pulp close to the markets where the waste paper is readily available ('urban forests') ... This strategy means that plants in the Nordic area will continue to concentrate on using the virgin pulp that is available locally." (Financial Times [56]).

- *capacity bounds for virgin pulp making* (OECD [117]).
  The capacities for total virgin pulp production are assigned to the four pulping techniques in accordance with the production of pulp in a region. For example, the capacity for sulphate bleaching in Germany is zero since Germany uses mainly mechanical pulping techniques.

- *fiber furnish conditions.*
  We assume a fixed balance of virgin pulps for each paper type. With increasing recycling, recycled pulp displaces virgin pulp of different types proportionally and up to a fixed maximal recycled pulp level that differs among the paper types. The furnish profile for these paper types is slightly different between Scandinavia and Central Europe (Table 7.6).

Table 7.6a: Furnish shares in Central Europe

Pulp type	News-print	Printing	Liner	Fluting	Box-board	House-hold	Special grades
Sulphate bl.	0.12	0.43	0	0	0.66	0.54	0.77
Sulphate unbl.	0	0	1	1	0.16	0	0
Sulphite bl.	0.03	0.11	0	0	0.18	0.13	0.19
TMP bl.	0.85	0.21	0	0	0	0.33	0.04
Additives	0	0.25	0	0	0	0	0

Source: Virtanen and Nilsson [158]

Table 7.6b: Furnish shares in Scandinavia

Pulp type	News-print	Printing	Liner	Fluting	Box-board	House-hold	Special grades
Sulphate bl.	0.10	0.44	0	0	0.56	0.63	0.60
Sulphate unbl.	0	0	1	1	0.14	0	0
Sulphite bl.	0.01	0.11	0	0	0	0.07	0.07
TMP bl.	0.89	0.20	0	0	0.30	0.30	0.33
Additives	0	0.25	0	0	0	0	0

Source: Virtanen and Nilsson [158]

In addition to pulp, varying amounts of different additives are used for paper and board manufacturing (e.g. chalk, clay, and coatings). However, their relative mass is very small in comparison with fibers except for printing-quality papers, for which they are currently estimated to have a furnish share of about 25%. Following Virtanen and Nilsson [158], 900 kg pulp is needed for 1000 kg of paper.

- *a maximum recycled pulp recovery potential.*
  Overall recycled pulp use is limited by the coefficients for collection rate and fiber recovery yield. Collected waste paper not used for recycling is assumed to be incinerated. Incineration releases heat energy which may be recovered. The maximum share of recycled pulp in paper products depends on the quality conditions (printing paper can only have 50% recycled pulp) and also on the collection rate of paper. The availability of waste paper depends on paper usage. The highest possible collection rate is 90% (Virtanen and Nilsson [158]). For household and special grades the collection rate is at most 50%. About 24% of the printing papers consists of books that have a long lifetime. Also 18% of the special grades has a long lifetime. Household paper is disposed of through sewage for 50% (toilet paper, tissues), so only 50% of this paper is available for collection. A large amount of potential waste paper for recycling is lost because of the inordinate costs of separating it from other household waste.

- *flow balances.*
  There are flow balances for virgin pulp, recycled pulp, paper and board products and waste paper requiring production plus import to equal consumption plus export. We assume that recycled pulp is not transported between regions, since it is immediately used in the paper making process. If a region has a high demand for recycled pulp, it can import waste paper.

7.4 The network flow model

Figure 7.1 gives a graphical representation of the life cycle optimization for Scandinavia. Virgin pulp can be produced or bought to be used for consumption or export. Each paper type needs a specific furnish of pulp types. Recycled pulp can only be used in the paper making process if it is available in the region itself. Waste paper will be disposed of in the region itself, or used for the making of recycled pulp within Europe. Each region will decide on a level of virgin pulp production, paper production, and paper recycling that is consistent with minimizing environmental impact of the life cycle as a whole. The optimization can be represented by a network flow model. Section 7.4.1 introduces the notation, Section 7.4.2 the mathematical formulation.

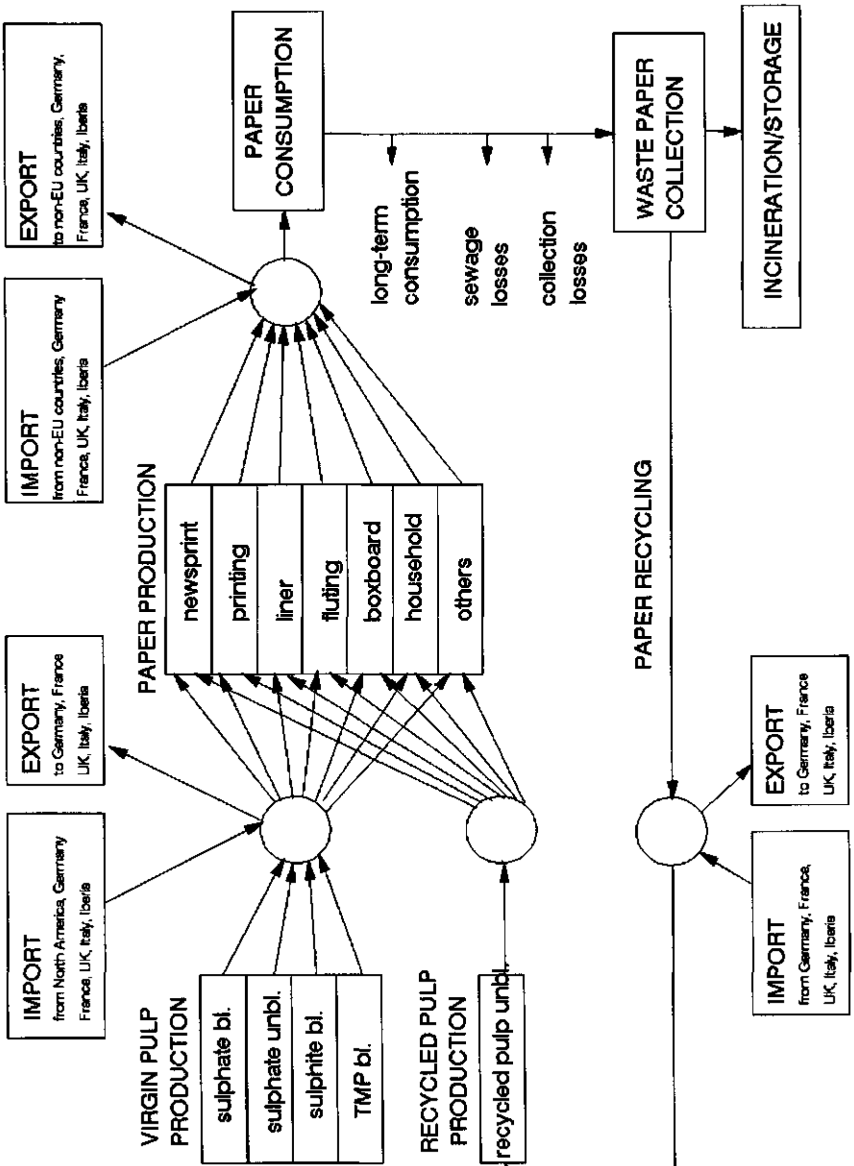


Figure 7.1: Flow chart of the network flow model for Scandinavia

7.4.1 Notation

Decision variables are in capitals, exogenous variables (fixed in advance) and other parameters (coefficients) are in small letters.

Indices:

$i, j, k \in I$ = indices for the six regions
$v \in V$ = index for the four virgin pulp types
$p \in P$ = index for the seven paper types

The set $I^+ := I \cup \mathrm{NA}$ relates to the OECD-Europe regions plus North America.

Decision variables:

VP_{iv} = virgin pulp production of type v in region i
VT_{ijv} = virgin pulp transportation of type v, from region i to region j
VD_{iv} = virgin pulp demand in region i of type v
RP_i = recycled pulp production in region i
RD_i = recycled pulp demand in region i
PT_{ijp} = paper transportation of paper type p, from region i to region j
WT_{ij} = waste paper transportation, from region i to region j
WI_i = waste paper incinerated in region i
WP_i = waste paper 'production' for recycling in region i
WD_i = waste paper demand for recycling in region i
Λ_{ip} = share of recycled pulp in furnish of paper type p in region i

Exogenous variables:

vs_i = virgin pulp wood supply in region i
pp_{ip} = paper production of paper type p in region i
pd_{ip} = paper demand for paper type p in region i
ws_i = waste paper supply for recycling or incineration in region i
pe_{ip} = paper export from region i to non-EU countries
pi_{ip} = paper import from non-EU countries to region i

Other parameters:

ev_{iv} = environmental impact of virgin pulp production of type v in region i
er_i = environmental impact of recycled pulp production in region i
ei_i = environmental impact of incineration of waste paper in region i
et_{ij} = environmental impact of transportation from region i to region j
ρ_p = total share of pulp in the inputs of paper type p (yield of paper from pulp)
μ_{vp} = furnish rate of pulp type v wrt to total virgin pulp share in paper product p
λ_p^{max} = maximum share of recycled pulp in the furnish of paper type p
δ_p = long-term consumption rate for paper type p

σ_p = sewage rate of waste paper originating from paper type p
γ_{ip} = collection rate of waste paper originating from paper type p in region i
ω = estimated fiber yield of waste paper

Waste paper supply for either recycling or incineration in region i is defined as follows:

$$ws_i := \sum_{p \in P} (1-\delta_p)(1-\sigma_p) \times \gamma_{ip} \times pd_{ip}$$

7.4.2 Mathematical formulation

The paper recycling problem (PR) can be formulated as a linear program:

$$\begin{aligned}
z_{PR} = \min \quad & \sum_{i \in I^+} \sum_{v \in V} ev_{iv} VP_{iv} + \sum_{i \in I} er_i RP_i + \sum_{i \in I} ei_i WI_i + \\
& \sum_{i \in I^+} \sum_{j \in I} et_{ij} \sum_{v \in V} VT_{ijv} + \sum_{i \in I} \sum_{j \in I} et_{ij} (\sum_{p \in P} PT_{ijp} + WT_{ij}) && (7.1) \\
\text{subject to} \quad & \sum_{v \in V} VP_{iv} \leq vs_i && i \in I^+ \quad (7.2) \\
& \sum_{i \neq j \in I^+} VT_{ijv} + VP_{jv} = VD_{jv} + \sum_{k \neq j \in I} VT_{jkv} && j \in I, v \in V \quad (7.3) \\
& RP_j = RD_j && j \in I \quad (7.4) \\
& VD_{iv} = \sum_{p \in P} \mu_{vp}(1-\Lambda_{ip}) \times \rho_p \times pp_{ip} && i \in I, v \in V \quad (7.5) \\
& RD_i = \sum_{p \in P} \Lambda_{ip} \times \rho_p \times pp_{ip} && i \in I \quad (7.6) \\
& \Lambda_{ip} \leq \lambda_p^{max} && i \in I, p \in P \quad (7.7) \\
& pi_{jp} + \sum_{i \in I, i \neq j} PT_{ijp} + pp_{jp} = pd_{jp} + \sum_{k \in I, k \neq j} PT_{jkp} + pe_{jp} && j \in I, p \in P \quad (7.8) \\
& ws_i = WI_i + WP_i && i \in I \quad (7.9) \\
& \sum_{i \in I, i \neq j} WT_{ij} + WP_j = WD_j + \sum_{k \in I, k \neq j} WT_{jk} && j \in I \quad (7.10) \\
& RP_i = \omega \times WD_i && i \in I \quad (7.11)
\end{aligned}$$

The objective (7.1) is to minimize environmental impacts of virgin pulp production (both in Europe and North America), recycled pulp production, waste paper incineration, and transportation. Constraints (7.2) are the capacity constraints for wood pulp. Constraints (7.3) and (7.4) define flow conditions for virgin pulp and recycled pulp. Constraints (7.5) define the allowable share of virgin pulp in order to satisfy quality conditions for paper types. Constraints (7.6) define the allowable share of recycled pulp in order to satisfy quality conditions for paper types. Constraints (7.7) represent the natural bound on the share of recycled pulp in the overall furnish of paper products. Constraints (7.8) define flow conditions for paper. Constraints (7.9) define the destination of collected waste paper to be either incineration or recycling. Constraints (7.10) define flow conditions for waste paper. Constraints (7.11) consider the yield from waste paper for recycled pulp.

7.5 Results for the simplified paper recycling problem

We assume one paper type representative of the 'average' of all paper and board grades produced and consumed. This average paper is produced using a combination of 'average' virgin pulp and recycled pulp. The environmental index for average virgin pulp is the weighted average of the environmental indices of the four virgin pulp types (see Table 7.4) where the weights are the contribution of each type to total virgin pulp production (Table 7.5). We need this simplification to carry out sensitivity analyses on the environmental indices of the four main processes: pulping, recycling, incineration and transportation. In Section 7.6 we relax this assumption, and run the model with four virgin pulp types and seven paper types.

In the optimal solution for the simplified paper recycling model (SPR) the contribution of virgin pulp is 15% and the contribution of recycled pulp is 85%. These percentages are quite different from current contributions (on average 60% virgin pulp and 40% recycled pulp). The large amount of recycled pulp requires considerable transportation of waste paper. Comparing current technologies on the basis of our evaluation methodology, the average environmental indices of virgin pulp (about 77) and recycled pulp (about 27) give the latter a clear advantage. This is already reflected in the inventory tables for these processes and would likely prevail whatever evaluation methodologies were applied. This result justifies the current policy emphasis on recycling. The potential environmental gain from energy recovery in waste incineration is insufficient to offset the difference between the environmental impacts of virgin and recycled pulp production. A shift to this optimal solution would have major implications for trade and industry. This is inevitable because the optimal solution involves maximum recycling while the current recycled pulp share in aggregate paper production is only 40%. Some of the implications for markets and for shifts in the geography of pulp production are illustrated in Figure 7.2. The figure shows the split between virgin and recycled pulp in the total pulp market and the shares for each of the different national pulp producers.

Interestingly, were one to shift to the optimal life cycle configuration (thus shifting the mix of virgin and recycled pulp use in the sector), Scandinavia would supply all Europe's residual need for virgin pulp. Scandinavia would produce and use virgin pulp to export paper with high virgin pulp furnishes (graphic products). The major consuming countries would in turn focus on recovering these pulps from post-consumption wastes, making paper and board grades that would allow the complete substitutability of virgin by recycled pulp (paper and board products). Essentially, the optimal solution entails specialisation of production and of products because it minimizes the environmental impacts of transportation.

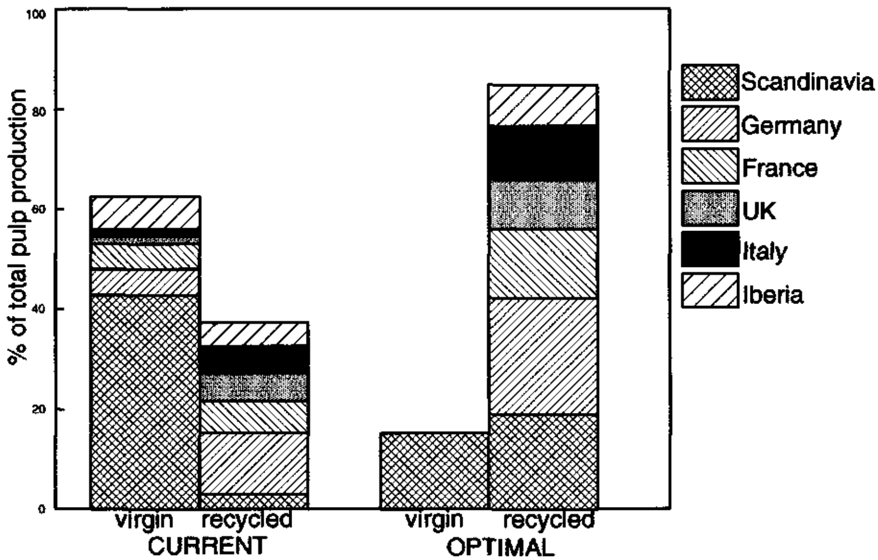


Figure 7.2: Market shares in total pulp production for problem (SPR).

A policy to increase progressively the use of recycled pulp may be simplistic. Given the relative environmental indices of the existing process technologies, maximal recycling is profitable. But, would this profit still hold if the environmental indices for the unit processes were different from those that now apply? How much would they have to differ for the optimum life cycle configuration to be inconsistent with maximum recycling?

To deal with this question, we did a sensitivity analysis on the environmental indices of virgin pulp and incineration. These processes are the most likely to change in the future because of better bleaching technologies and an increasing capacity for energy recovery. The optimal configuration appears to be sensitive to the environmental index for average virgin pulp (now 77). An increase in recycling from its current level is only warranted if the index for virgin pulping exceeds a level of 33. The sensitivity analysis shows that there is a limit to the environmental improvement that can be achieved through recycling, and that more improvement can be made via cleaner virgin pulping technologies. A comparable analysis is done for incineration. An environmental index of -35 would define a switching point. These results indicate the degree to which environmental optimality depends on the environmental performance of the different technologies and thus on prospective technological progress. The relative balance between the environmental impacts of recycling, incineration, and virgin pulp production is critical to the determination of the optimum recycling level and, by implication, to whether recycling is the best route to improved environmental performance. The results also point to the technological improvement needed if clean pulp production plus incineration were to prove a preferred route compared to higher recycling percentages.

The optimal solution implies geographical division and specialisation of tasks. How stable is this outcome to changes in the environmental indices? Figure 7.3 shows the sensitivity of the optimal life cycle configuration to changes in the environmental index for virgin pulp. With each change in the environmental index, we run the simplified paper recycling model (SPR) to define a new optimal life cycle configuration for the sector as a whole . Each of these configurations can be characterised by the proportion of recycled pulp in the aggregate paper furnish.

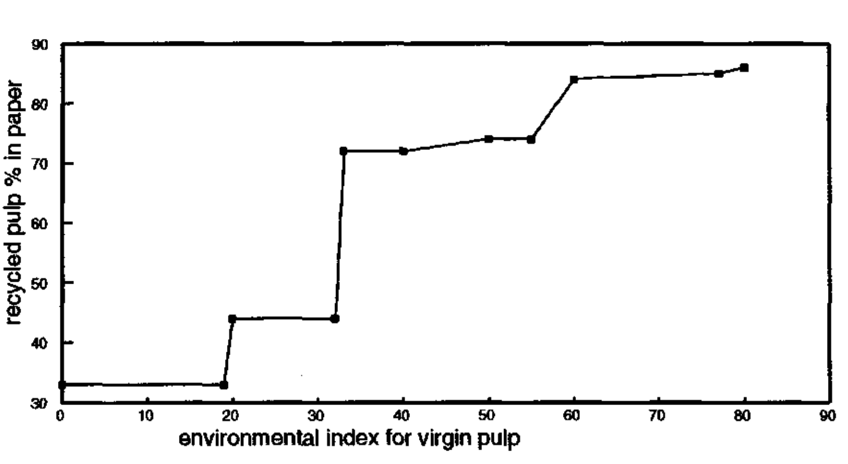


Figure 7.3: Sensitivity of the secondary pulp share to the virgin pulp index

Figure 7.3 shows that the relation between the environmental index for virgin pulping and the market share for recycled pulp is a step-function. The most significant step occurs at the point where the environmental index for virgin pulp production drops from 33 to 32. This minor shift brings about a major shift in the recycled pulp share from 72% to 44%. If the environmental index of producing virgin pulp is just above the threshold level of 33, we have a relatively stable solution. Production of virgin pulp is minimized to reduce overall environmental impact, and remaining production would be a Scandinavian monopoly. At the threshold level, the geography of production of the optimum configuration changes completely. This is because the relative environmental impacts of recycling vis-a-vis virgin pulp production and incineration are in perfect balance. The optimal configuration is determined by the only remaining factor of relevance, the overall transportation level. This configuration is consistent with maximising self-sufficiency subject to capacity constraints. At this point, all countries would return to virgin pulp production. Below the threshold level, transportation rapidly becomes irrelevant since there is a clear advantage in the virgin pulp and incineration combination. There is no longer an impetus to maximise the materials productivity of pulps within the system, and therefore no reason to constrain the throughput of virgin pulp. As a result, virgin pulp dominates the pulp market.

What would the result be if some producers had significantly cleaner technologies than their competitors. In respect to the last situation (below the threshold level), when recycling no longer offers any environmental advantage, the solution is sensitive only to the balance between the respective environmental performance of the pulping technologies of different producers and transportation costs. If the difference between the environmental performance of the different technologies of pulp production were sufficient to offset the environmental impact of transporting virgin pulp, the cleaner producers would export virgin pulp. The next section deals with (a.o.) this statement.

7.6 Results for different policy scenarios

In this section, we discuss the results of the complete model with four virgin pulp types and seven paper types. Five scenarios are used to address the policy questions formulated in section 7.2. The first scenario describes the current situation with 1990 recycled pulp shares. In the second scenario regions are free to set their own recycled pulp share in order to minimize environmental impacts. The third scenario investigates the consequences of mandating policies of individual regions, whereas the fourth and fifth scenario deal with mandating policies for Europe as a whole.

These five scenarios are analysed in three different situations: *(i)* the current situation with fixed paper production locations and partial energy recovery (Section 7.6.1), *(ii)* an advanced situation with full energy recovery and fixed paper production locations (Section 7.6.2), and *(iii)* a utopian situation with full energy recovery and possibility for relocation of paper production within Europe (Section 7.6.3). Section 7.6.4 deals with the question: what is an optimal (mandated) recycled pulp share for Europe as a whole given these three situations?

In the first situation (Section 7.6.1), it is not technically possible to use all collected waste paper for energy recovery. Virtanen and Nilsson [158] estimate that 26% of the collected waste paper can be incinerated. The remaining 74% is stored somehow. We assume that this storage does not induce additional environmental impacts. This combination of incineration and storage leads to a change in the environmental index for incineration to -9.626 (i.e. 26% of the value mentioned in Table 7.4). Note that in the utopian situation (Section 7.6.3) the network flow model becomes non-linear if production quantities are variable. The variable 'paper production' (pp_{ip}) is multiplied with the variable 'recycled pulp share' (Λ_{ip}) in constraints (7.5) and (7.6). In order to keep the model linear, recycled pulp share is set at a chosen value λ_{ip} and the paper production is allowed to vary.

A short description of the five scenarios follows:

1. (CUR) CURRENT SITUATION
   In this scenario we fix the recycled pulp share of each paper product at the level of 1990 as found in Virtanen and Nillson [158]. The average recycled pulp share over Europe is close to 30% but differs over the paper products, i.e. 25% for newspaper (except for Scandinavia where it is negligible), 7% for printing paper, 70% for liner and fluting (except for Scandinavia: 5%), 47% for boxboard, 64% for household paper and 28% for the remaining paper products. Collected waste paper not used for recycling can be used for energy recovery.

2. (FREE) NO MANDATORY RECYCLED PULP SHARES
   All regions are free to change their recycled pulp share for the paper products they produce, in order to find a paper and pulp configuration for OECD-Europe with a minimum environmental impact.

3. (GER) 100% RECYCLED PULP SHARE IN GERMANY
   Although recycled pulp use targets in Germany are already high (51%), there are plans to increase them further by the year 1996. All paper products, used in Germany, should contain 100% waste paper, except for graphic products (40%).

   In order to model this scenario, we add a group of 0-1 variables to the model:

   $$Y_{ijp} = \begin{cases} 1 & \text{if paper type } p \text{ produced in region } i \text{ satisfies the legislation of region } j \\ 0 & \text{otherwise} \end{cases}$$

   The following two sets of constraints are added to allow region i to supply region j with paper type p:

   $$PT_{ijp} \leq ps_i Y_{ijp} \qquad \forall i,j \in I, p \in P \quad (7.12)$$
   $$Y_{ijp} \leq \Lambda_{ip} + (1 - \lambda_{jp}^{min}) \qquad \forall i,j \in I, p \in P \quad (7.13)$$

   with

   ps_i : paper supply in region i
   λ_{jp}^{min} : mandated recycled pulp share for paper type p consumed in region j.

4. (EU60) MANDATORY RECYCLED PULP SHARE OF 60% ON EU LEVEL
   Suppose that the EU parliament decides that all paper and board products have to contain 60% recycled pulp if technically possible. (This percentage is consistently used in EU directives (Club de Bruxelles [38])). Since graphic products can only have a 50% recycled pulp share, due to strength and optical requirements, the mandated level is 30%.

5. (EU100) SCENARIO ON EU LEVEL
   The German plans applied to all European regions.

7.6.1 Fixed production/partial recovery

The results of the five scenarios are summarized in Figures 7.4 and 7.5. Figure 7.4 gives the environmental impact of the optimal life cycles in each scenario, together with the contribution of the four unit processes to this environmental impact. Figure 7.5 shows the regions' contribution to the supply of virgin pulp and recycled pulp. Table 7.7 shows the reduction of environmental impacts in each scenario compared to the current situation.

Table 7.7: Reduction of environmental impacts

Scenarios	Environmental impacts	Reduction (%)
(CUR)	1,884,916	0
(FREE)	1,538,052	18.4
(GER)	1,555,760	17.5
(EU60)	1,718,607	8.8
(EU100)	1,632,776	13.4

In the scenario (CUR), virgin pulp production is the largest contributor to the environmental impact. Since recycled pulp use is only in a starting phase, there is also a large amount of paper that is incinerated or stored. About 70% of the pulp production consists of virgin pulp. Scandinavia is the most important supplier of virgin pulp.

If we allow all regions to have a recycled pulp share that leads to an environmentally optimal life cycle configuration for Europe (FREE), the total environmental impact can be reduced by 18.4% compared to the current situation (CUR). This improvement is achieved by using more recycled pulp in all regions. The aggregated European use of recycled pulp is doubled compared to the current situation. Scandinavia, Germany, and Iberia reduce their virgin pulp production significantly. Scandinavia keeps its number one position in the virgin pulp market since it has the cleanest mix of virgin pulp producing technologies. The larger use of recycled pulp results in waste paper transportation from Germany and France to Scandinavia. The Nordic population cannot generate sufficient waste paper for recycling. This result justifies the current policy emphasis on recycling, given the technological capacity limits on energy recovery. The environmental gain from energy recovery is still insufficient to offset the difference between the environmental impacts of virgin and recycled pulp production.

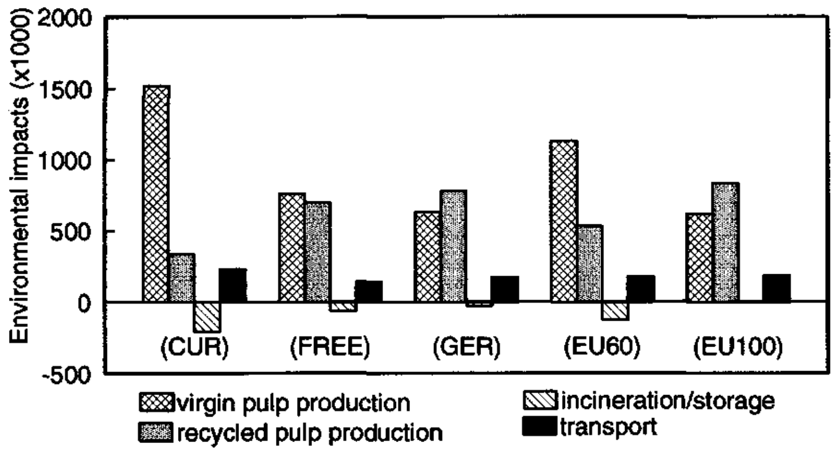


Figure 7.4: Contribution to environmental impact

The German plan of full recycling (GER) leads to a small increase in environmental impact of 1.2% compared to (FREE) but performs still 17.5% better than (CUR). Recycled pulp production is now the main contributor to the environmental impact. More waste paper transportation is necessary. Germany and Scandinavia profit from the regulation. France looses market share on the recycled pulp market.

A mandated pulp share of 60% (EU60) over Europe results in an increase of total environmental impact of 11.7% compared to (FREE). Only 47% of the pulp production consists of recycled pulp. This is due to the relatively low recycled pulp share (30%) for newspaper and printing paper. These two paper types represent 50% of the paper market. In the (FREE) scenario the recycled pulp share in newspaper and printing paper is 50% in all regions.

A mandatory fiber share as in (EU100) has a lower environmental impact than (EU60). The total environmental impact increases by 6% compared to (FREE). This result can be explained by the higher recycled pulp share in newsprint and printing paper. All regions except Iberia export waste paper to Scandinavia.

For each feasible solution, the contribution to the seven individual environmental problems can be calculated by multiplying the amount of production, recycling, incineration and transportation by the numbers in Table 7.2. Table 7.8 gives the total environmental profiles for the five scenarios. The minimum impact for each environmental problem is given in bold character.

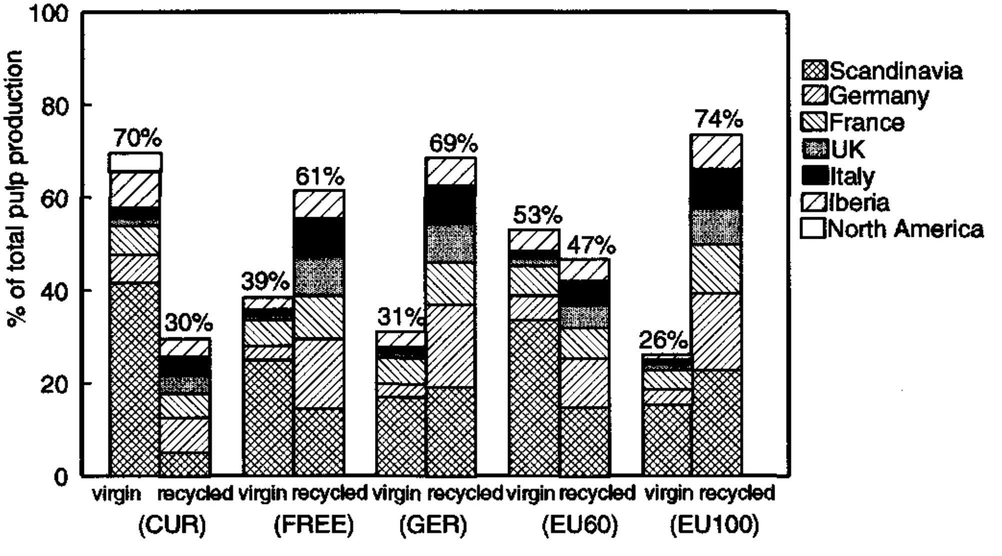


Figure 7.5: Market shares in pulp production with fixed production/partial recovery

Table 7.8: Ecoprofiles of the pulp and paper sector for the five scenarios

	Global warming	Human toxicity	Eco toxicity	Phot. oxydation	Acidi-fication	Nutri-fication	Solid waste
(CUR)	**10,365,542**	423,111	18	59,917	165,129	29,482	**2,897,964**
(FREE)	12,678,654	**291,384**	9	32,887	**140,483**	**23,232**	2,925,128
(GER)	14,286,998	292,178	**7**	30,636	148,318	23,604	2,963,890
(EU60)	11,663,709	356,275	13	46,011	153,222	26,739	2,930,341
(EU100)	16,523,440	299,482	**7**	**29,687**	157,429	24,498	3,065,359

Finding the best life cycle for all seven environmental problems requires optimizing over seven goals. Of course, there is no guarantee that a solution exists with an overall best performance. In our approach, the average of all contributions is used to minimize. This may result in a solution that has minimum impact for some of the problems but not for all. The (CUR) scenario has the lowest contribution to global warming and the solid waste problem. (FREE) performs the best for human toxicity, acidification and nutrification. For the remaining two problems, ecotoxicity and photochemical oxydation, the (EU100) scenario has the lowest contribution.

Although our approach has the drawback of a one-dimensional optimization, the results show that the (FREE) scenario performs better than the (CUR) scenario for all problems except global warming and solid waste. The latter is a consequence of the assumption in this section that only 26% of the potential energy recovery can be used.

Summarizing, given that energy recovery is only partly available, a policy towards more recycling is attractive. The environmental performance of the (FREE) scenario is optimal, using the one-dimensional environmental index as performance measure. The paper and pulp configuration that results from the (FREE) scenario also performs better than the (CUR) scenario for five out of seven environmental problems, with improvements varying from 15 to 50%. Mandated recycled pulp shares or self-protecting policies do restrict the possibilities to obtain the best environmental performance. Life cycles with mandated recycled pulp shares perform worse than life cycles with region-dependent policies. Both scenarios (GER) and (EU60) have a worse performance than the other scenarios.

7.6.2 Fixed production/full recovery

In the second situation, we consider the scenarios with the possibility of full energy recovery and fixed paper production. For each scenario with a fixed recycled pulp share the optimal configuration does not change when the incineration coefficient is altered from 26% to 100%. Obviously, the environmental performance of each configuration changes. For (FREE) and (GER) full energy recovery results in a different optimal life cycle configuration. Table 7.9 shows the change in environmental impacts.

Table 7.9: Changes in environmental impacts with recovery

Scenarios	Fixed production partial recovery	Fixed production full recovery	Change (%)
(CUR)	1,884,916	1,300,109	-31
(FREE)	1,538,052	1,202,608	-22
(GER)	1,555,760	1,246,646	-20
(EU60)	1,718,607	1,354,047	-21
(EU100)	1,632,776	1,614,299	-1

The environmental impact of the current situation decreases with 31%. This means that the extension of technology and capacity for energy recovery will yield a large improvement in environmental performance without any changes in recycled pulp policy. The model results justify the increasing focus on energy recovery in regions like France and the UK.

In the (FREE) scenario, the market share for recycled pulp decreases from 61% to 31%. The possibility of energy recovery outweighs the environmental advantage of recycled pulp over virgin pulp.

This result confirms the growing consensus among researchers that the virtues of recycling, in particular of glass and paper, are not always clear-cut in the long term. They depend largely upon the possibilities for alternatives such as energy recovery by burning paper.

Scandinavia produces no recycled pulp, but has 65% of the virgin pulp production which is still 45% of total pulp production. Virgin pulp production shifts partly from sulphite bleached to TMP bleached which is much cleaner.

For (GER) the market share for recycled pulp decreases to 36%. Scandinavia still produces no recycled pulp but looses 4% market share in the total pulp production compared to (FREE). The German market share of total pulp increases from 13% in (FREE) to 22% in this scenario. It is therefore not surprising that some countries protest against individual legislation that differs from the general policy in Europe.

7.6.3 Relocation of paper production/full recovery

In the third situation, we consider the five scenarios with the possibility of full energy recovery and relocation of paper production within Europe. For each of the five scenarios the recycled pulp shares, λ_{ip}, are set at their optimal values in the fixed production/full recovery situation (Section 7.6.2). With these values, the relocation of paper production is considered.

Table 7.10 compares the environmental impacts of the life cycle configurations for each scenario, with and without relocation.

Table 7.10: Changes in environmental impacts with relocation

Scenarios	Fixed production/ full recovery	Relocation/ full recovery	Change (%)
(CUR)	1,300,109	1,241,237	-4.5
(FREE)	1,202,608	1,152,167	-4.2
(GER)	1,246,646	1,192,788	-4.3
(EU60)	1,354,037	1,277,481	-5.7
(EU100)	1,614,299	1,485,245	-8.0

Relocation gives a reduction of environmental impact between 4 and 8% compared to fixed paper production. It has a large impact on the paper market and transportation flows. For scenarios (CUR) and (FREE) paper production is relocated from Germany to Scandinavia (mainly liner, fluting, boxboard and special grades). In these scenarios, the demand for virgin pulp in paper and board products is quite high. Since Scandinavia has the largest virgin pulp capacity and the cleanest mix of virgin pulp producing technologies, paper production shifts towards Scandinavia. In scenario (GER), about 50% of the production of newspaper shifts from Scandinavia towards Germany, the UK, and Italy. Market share also shifts from France to Germany. Scandinavia has to share its first position in the paper production industry with Germany. For scenarios (EU60) and (EU100) the market share for Scandinavia is substantially reduced whereas Germany, France, and the UK benefit from this shift. Due to the high recycled pulp share in these scenarios, it is better to relocate paper production to those regions with a high waste paper recovery potential. This means that paper production shifts towards regions with a high paper consumption. Especially (EU100) illustrates this phenomenon; the configuration of paper production converges to the configuration of paper consumption (see Table 7.5). Table 7.11 shows the new market shares for paper production.

Relocation of paper production reduces transportation (in ton-km). For (CUR), (FREE) and (GER) reductions of 11-20% are obtained whereas for (EU60) and (EU100) the reductions are 42% and 70% respectively.

Table 7.11: Market shares of paper production before and after relocation (in%)

	before	after relocation				
	relocation	(CUR)	(FREE)	(GER)	(EU60)	(EU100)
Scandinavia	34	38	31	29	15	10
Germany	23	12	16	29	28	30
France	14	15	15	10	17	17
UK	10	13	14	11	16	19
Italy	11	12	14	11	14	14
Iberia	8	10	10	10	10	9

Summarizing, recycling offers rapid improvement in environmental performance in the short term, i.e. if there is not enough capacity or technology for full energy recovery. If energy recovery capacity is available, the suggested recycled pulp share is much lower and very close to current recycled pulp shares.

7.6.4 Optimal mandated use of recycled pulp

Is environmental gain a linear function of the percentage share of recycled pulp? Figure 7.6 shows that it is not. The figure shows three environmental impact curves associated with the three different situations *(i)* fixed production/partial recovery, *(ii)* fixed production/full recovery, and *(iii)* relocation/full recovery. For each, the overall environmental impact has been calculated for a step-wise increase of recycled pulp use for all countries in Europe. (The figure was generated by making discrete runs from 30% to 100% of the maximum share of recycled pulp in the furnish of paper types (λ^{max}) at 10% increments.) In the first situation (upper curve), the current pattern of paper production is assumed to be fixed. In the second situation (middle curve), full energy recovery is technically possible. In the third case (lower curve), overall paper production is fixed but the geography of paper production is allowed to vary within constraints imposed by current installed capacities.

The figure shows that as the percentage share of recycled pulp increases, diminishing environmental returns to recycling set in. The decrease in marginal environmental gain is due to an increase in transboundary waste paper shipment. In the first situation, a mandated recycle share of 90% is optimal. This is not a surprising result, given the optimal recycling levels of (EU60) and (EU100). However, for the second and third situation, the optimal recycle share is about 40%. This is very close to the current average recycled pulp share in Europe. It is remarkable that the suggested European recycle share of 60% is never optimal.

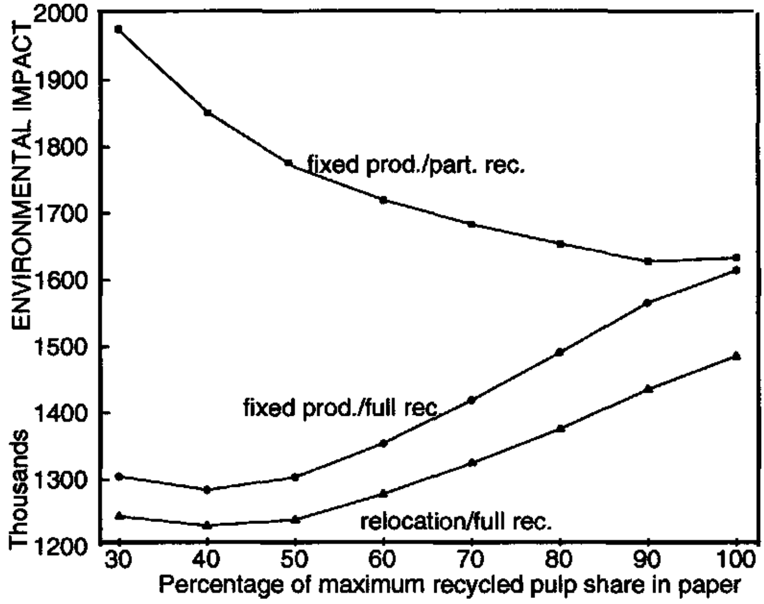


Figure 7.6: Environmental impact with fixed recycle share

7.7 Conclusions

The European pulp and paper sector can reduce its contribution to environmental damage in different ways, such as more recycling, energy recovery and cleaner pulping and bleaching. It is not obvious that one method outperforms the others in the long term although policy makers already implement and promote the option of more recycling.

We show in this chapter that an integral (optimization) methodology is necessary to define consistent environmental policies. With the developed life cycle optimization model, we can derive environmental policies that are defendable and predictable, and we can explore the potential for reducing the environmental impact of a sector. The life cycle optimization model consists of a life cycle analysis of the paper and pulp sector and a network flow model for the optimization of pulp, paper and waste paper flows in Europe. Although the life cycle analysis and the network flow model are oversimplified in many respects, it is possible to demonstrate the kinds of policy implications that we can achieve with this approach.

- *Single minded focus on recycling is myopic.*
  A high level of recycling will deliver short-term environmental impact reductions as long as full energy recovery is not available. Investment in technology and capacity for energy recovery has a large potential for environmental impact reductions, without disturbing international trade relations. Apart from energy recovery, a higher level of recycling in those regions with a large supply of waste paper gives a further improvement of the environmental impact of the sector.

- *Command and control instruments limit environmental impact reductions.*
  We demonstrate that policies such as regulated levels of recycled pulp are less effective than flexible policies. The potential for environmental impact reduction is reduced by regulation. Regions with a large production of high-quality graphic papers should be able to focus on cleaner virgin pulp production.

- *Policies on paper recycling have major international trade implications.*
  A high recycling level can easily lead to the transportation of waste paper from regions with a high population to Scandinavia. The dominant place of Scandinavian virgin pulp will be replaced by recycled pulp produced in Germany or France. This will have high impacts on forestry (renewable resource).

- *National legislation can easily result in protectionist actions.*
  National mandated levels of recycling have a large impact on market shares of other regions. National legislations can also lead to an increase in total transportation flows.

- *Relocation of the paper industry has major economic implications.*
  A reduction of environmental impact of 4–8% is possible with relocation. However, the paper production configuration changes considerably and converges to the configuration of paper consumption as the recycling level increases.

Although our first results are encouraging, much research remains to be done to assure a reliable support of policy making. Data for the inventory tables for unit processes are probably insufficiently accurate for realistic analysis. Especially the assumption that the environmental impact of a process does not depend on the country where it takes place disregards differences in technological skills. The network model assumes no changes in paper consumption. Moreover, the impact of changing market prices for paper, pulp and waste paper on the market shares for pulp is not included. Future research in this area may focus e.g. on the effects of prices for paper and pulp on the market shares for virgin pulp and recycled pulp, or on the impact of new and cleaner pulping and bleaching techniques which are currently in a laboratory phase. Finally, improving the possibilities for energy recovery is also a priority issue.

Chapter 8

Major conclusions

Environmental issues have come to play an important role in the decision making processes of agriculture, trade and industry. The obligation to reduce waste and to control emissions affects decisions on e.g. production planning, logistics, and inventory control. On the other hand, the international nature and the complexity of many environmental problems make it virtually impossible to base policy decisions on intuition and simple methods.

These developments have stimulated us to investigate the possibilities of incorporating environmental issues in 'traditional' Operational Research (OR) applications, and the possibilities of using OR models and techniques in Environmental Management (EM) problems. Two research questions, formulated in Chapter 1, structure the exploration of the integration of Operational Research and Environmental Management.

1. How can Operational Research models and methods be adapted to include environmental issues?

2. To which degree can Operational Research models and methods be used to solve environmental problems?

Section 8.1 introduces the framework for the integration of Operational Research and Environmental Management. This framework defines three types of management to deal with environmental issues in a supply chain, and three types of policy orientation to deal with environmental problems. This typology helps to analyse the research questions more specifically. Section 8.2 summarizes the conclusions of the studies described in Part II, illustrating the three types of management in a supply chain. We discuss the contribution of each study to finding answers for research question 1 and propose avenues for a further development of the incorporation of environmental issues in OR models. Section 8.3 summarizes the conclusions of the studies described in Part III, illustrating the three types of policy orientation in dealing with environmental problems. We discuss the contribution of each study to finding answers for research question 2 and propose avenues for further use of OR models to solve environmental problems. Section 8.4 confronts the general ideas from Part I (i.e. the framework) with the knowledge obtained from the capita selecta in Part II and III and Section 8.5 gives directions for further research.

8.1 Framework for the integration of OR and Environmental Management

Chapter 2 describes the development of a framework to show how environmental issues and economic processes can interact in two ways:

1. *Impact of environmental issues on the supply chain:* Environmental issues play a role in the routine activities of firms. Decisions on e.g. production planning, logistics, and inventory control will change due to legal requirements or consumer pressures to reduce waste and emissions. Therefore, there is a need to adapt OR tools such as production planning algorithms, location models and routing heuristics in order to deal adequately with a new situation requiring 'green supply chain modelling'.

2. *Impact of economic activities on the environmental chain:* The amount of waste and the level of emissions caused by the supply chain can result in a number of serious environmental pollution problems, such as global warming and acid rain. Frequently, these environmental problems are international and complex. The interaction between OR and EM can result in a clear formulation of the headlines of these problems and in new insights in the impacts of alternative policy measures.

The shift from effect-oriented control towards pollution prevention and the increasing acknowledgement of the complexity and international character of environmental problems are open invitations for the increasing interaction between OR and EM. We discuss this shift within the context of both the supply chain and the environmental chain.

The *supply chain* comprises the extraction of raw materials, production, distribution, use of goods and waste collection. In general, changes within the supply chain are necessary to reduce the amount of waste and emissions, and the use of non-renewable resources. We structure the discussion around a hypothetical shift from an end-of-pipe approach (waste management), via recovery management (e.g. recycling) towards a source-oriented approach of pollution prevention.

In the *environmental chain*, emissions and waste are transported and transformed and result in water, air, and soil pollution with damaging effects to the environment. We structure the discussion around a hypothetical shift from local end-of-pipe policies, via a regional orientation towards a global, integral approach to prevent environmental problems.

Figure 8.1 summarizes the interactions between the supply chain and the environmental chain and shows the degrees of the integration of OR and EM with respect to supply chain modelling and environmental chain modelling.

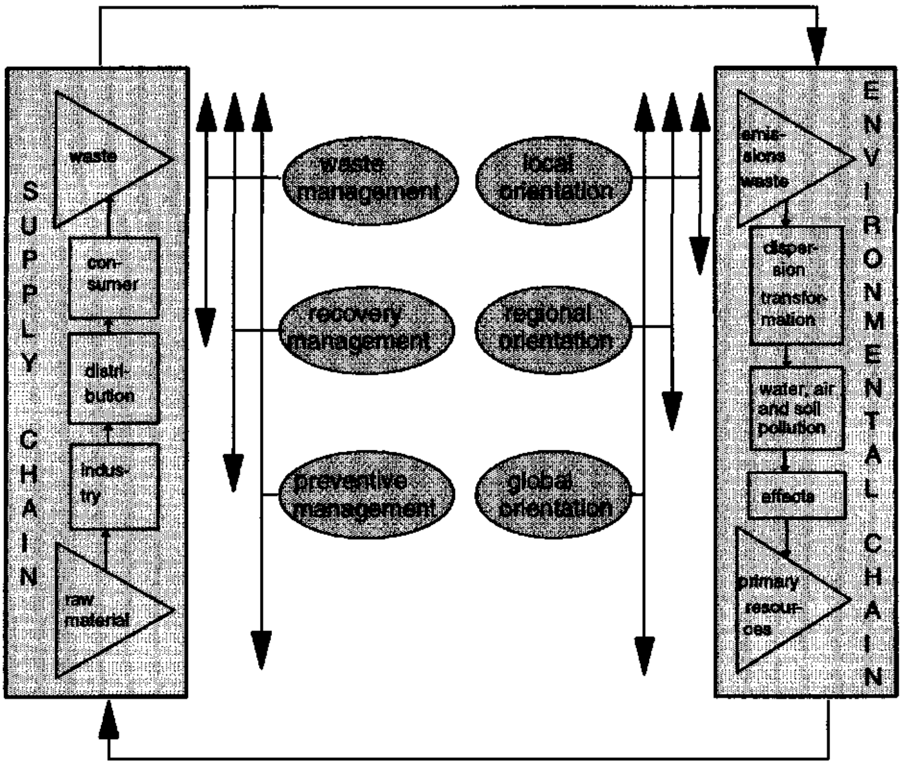


Figure 8.1: Framework for the integration of OR and EM

Impact of environmental issues on the supply chain

Thinking about environmental issues in the supply chain has evolved from end-of-pipe control towards waste prevention at the source. We distinguish three stages in the increasing integration of OR and EM that correspond with the shift from an end-of-pipe approach towards a 'from the cradle to the grave' approach in supply chain modelling.

1. *waste management*
   In the first (hypothetical) degree of integration, environmental issues (waste and emissions) influence only the final processes in the supply chain, i.e. distribution, product use and waste disposal. Economic activities that have to be developed or adapted are e.g. the distribution of hazardous waste and the selection of appropriate locations for disposal sites and incinerators. Emissions to air and water are in most cases reduced through end-of-pipe techniques.

2. *recovery management*
   On the intermediate level of integration, production is also subject to change because

of environmental issues. At this level, end-of-pipe treatment and disposal of waste to reduce environmental damage are no longer sufficient. Recovery management aims at postponing the generation of waste and lengthening the life time of products by means of recycling and reuse. This requires manufacturers to feel responsible for their products after consumer use and to consider ways to increase the use of recycled materials. It requires changes in both process and product design.

3. *preventive management*
   Prevention is the key-issue in the final stage of integration. The objective of pollution prevention is to avoid the use of materials whose acquisition and transformation are environmentally damaging. Environmental burdens associated with a product or process have to be quantified. Evaluation studies of this assessment are in general complex and expensive.

Impact of economic activities on the environmental chain

Environmental policy has shifted from traditional single pollutant/ single effect abatement policies towards the development of sustainable integrated policies that can cope with a.o. multi-pollutant transboundary problems. We distinguish three stages in the integration of OR and EM that correspond with the shift in policy making from end-of-pipe abatement towards integrated assessment.

1. *local orientation*
   At this level, local problems (e.g. soil pollution, smog) can be solved by local solutions (end-of-pipe technologies). Measures to abate emissions reduce environmental effects at the end of pipe without influencing economic activities (flue gas desulfurization, low NO_x burners).

2. *regional orientation*
   Emissions and waste disposal cause effects on ecosystems and human health. These environmental effects depend largely on the geographic distribution and movement of damaging components. Therefore, environmental policy evolves towards an approach that can cope with the effects of emissions on all components of the environment (soil, water and air).

3. *global orientation*
   General indicators of the effects on ecosystems and human beings are developed, rather than focusing on effects of a single pollutant on a single species. An example is the concept of critical loads in acidification policy, i.e. the highest deposition of an acidifying compound that will not lead to long-term harmful effects. The intention of policy makers at this level is to use an integrated approach for global problems.

8.2 Incorporation of environmental issues in Operational Research models

Incorporating environmental issues in OR models can vary from just changing one parameter to complete new problem formulations. We analyse three types of problem settings that show why incorporating environmental issues (and knowledge from Environmental Management) enriches the working area of Operational Research.

The first problem setting deals with the distribution and disposal of waste as an illustrative example of waste management (Section 8.2.1). The second problem setting deals with the reuse of manure as an illustrative example of recovery management (Section 8.2.2). The last problem setting deals with the environmental impacts of raw materials in product blending, as an illustrative example of preventive management (Section 8.2.3).

We use the conclusions from these studies to illustrate important issues with respect to research on the incorporation of environmental issues in OR models and applications.

8.2.1 Product and by-product flows (Chapter 3)

We consider the problem of how to design an efficient (i.e. minimal cost) distribution structure which simultaneously takes into account the location of production sites and waste disposal sites, and the assignment of product flows and waste flows. The problem is an example of *waste management*. It only considers the treatment of waste, not its prevention or postponement.

The location problem of product and by-product flows is an extension of the well-known plant location problem. We use existing solution approaches for the plant location problem to solve this product and by-product flow problem as well as problem-specific solution approaches. The objective of using existing solution approaches from 'traditional' location theory is to investigate the value of a direct implementation of these approaches and to suggest adaptations to make the approaches more successful for the product and by-product flow problem. We develop linear programming relaxations combined with round-off heuristics, Lagrangean relaxations and greedy-like heuristics.

We conclude that linear programming relaxation gives rather tight lower bounds. We compare the product and by-product flow formulation with an equivalent but more general flow path formulation. Computational results indicate that solving the problem-specific linear programming relaxation takes considerably less computation time than the more general linear programming relaxations, although the quality of the bounds is comparable. Valid inequalities on product flows and by-product flows appear to be essential in strengthening the LP lower bounds. The quality of a simple round-off heuristic for obtaining upper bounds depends heavily on the addition of suitable valid inequalities.

The Lagrangean approach exploits the problem characteristics as it decomposes the problem into a location problem for products and a location problem for by-products. The 'Lagrangean' lower bound has a performance similar to the linear programming bound but is, on average, much faster and less dependent on problem dimensions. The sequential facility location heuristic solves the problem as two sequential single-level facility location problems. Solving these problems just once gives rather poor results. However, the multi-pass version, based on the multiplier adjustment principle, gives good results and is very fast. This result indicates that treating product flows and by-product flows as two non-related issues is a dangerous policy in waste management.

Greedy-like heuristics perform extremely well for the simple version of the problem (i.e. without capacity requirements for plants and waste disposal sites), but require too much computation time if these capacity requirements are added to the model. More research is necessary to find quick and good methods to solve the sub-problems in each iteration of the greedy heuristics.

We give the following recommendations for research related to waste management:

- Although incorporation of waste management issues complicates the traditional distribution and location models, waste disposal has to become a part of these models.
- Many problems in waste management appear to have a very close relation to traditional distribution and location models. Although these traditional models cannot always be used directly, it appears that many existing solution approaches can be very helpful in solving (parts of) the waste management problem.
- It is worthwhile to develop problem-specific model formulations and solution approaches. Results from the product and by-product flow problem indicate that these solution methods require less computation time or give better solutions than general approaches.

8.2.2 Manure utilization in farm management (Chapter 4)

The extended farm management problem is an example of recovery modelling. Traditional farm management models determine a profit maximizing combination of farm activities that is feasible with respect to a set of fixed farm constraints. We incorporate the possibility to utilize manure for fertilizing purposes, thereby replacing expensive inorganic fertilizers. However, environmental legislation from the European Union restricts the possibilities for utilization. These environmental conditions make the farm management problem a non-linear problem.

We formulate the extended farm management problem as a generalized bilinear program, i.e. a model formulation in which both the objective function and the constraint set are linear for one set of decision variables (x) when the other set of variables (y) is fixed and vice versa. Also, we analyse different solution methods.

We conclude that optimization algorithms, developed for a more simple class of bilinear programs, can be applied to obtain local optimal solutions to the farm management problem. However, the results appear to be quite disappointing.

The farm management problem has a specific structure that allows to solve the problem sequentially, i.e. given the optimal expression for one set of variables (e.g. y), the optimal solution for the other set of variables (e.g. x) can be found. In general, this iterative process is as complex as finding the optimal solution for both sets of variables at once. Using the specific structure, we develop a branch-and-bound algorithm that branches in a subspace of the feasible area. This algorithm is easier than general branch-and-bound algorithms, but requires the development of new theoretical results.

We give the following recommendations for research relating to product recovery and product reuse:

- Quality conditions for used products or by-products complicate the integration of recovery issues in traditional planning models. From our study, we learn that a linear problem like the farm management problem becomes non-linear and therefore much harder to solve. Other examples (e.g. recycling materials from used products) show that deterministic models like simple production planning models or inventory models change into stochastic models, due to the fact that the quality or the quantity of (recycled) inputs for the production process is unknown in advance. This makes it very hard to obtain optimal strategies for production and inventory management.

- Recovery problems can still be tractable with OR techniques. For some cases, it is possible to develop solution methods that guarantee optimal solutions, based on new theoretical results. More often, recovery management has to be based on local optimal solutions and feasible strategies. Simulation and scenario analysis are valuable tools for finding 'good' solutions.

8.2.3 Environmental impacts of fat blends (Chapter 5)

Life cycle analysis (LCA), as a method to identify the environmental burdens from a product or process, has usually been applied to individual products or processes. In an integrated approach, the environmental burdens of the entire production system are analysed, from acquisition of raw materials to waste disposal after consumption.

We combine LCA with multiple criteria decision making and linear programming to provide a powerful tool for analysing and managing the environmental impacts of all the production processes necessary for the blending of margarines, while still satisfying other requirements such as quality, taste, etc. Linear programming appears to be very useful in the improvement step in a LCA. Using linear programming (or other optimization routines), it is possible to compare cost-friendly products with environmentally-friendly products with respect to costs, environmental impact and quality requirements.

In this particular case study, we do not use multiple objective linear programming to find the best compromise between cost minimization and environmental optimization. However, if both optimizations give rise to completely different solutions, multiple goal optimization is necessary to find non-inferior (or Pareto-optimal) solutions.

We recommend the following for the environmental evaluation and improvement of production systems:

- Systematic modelling, whether by linear programming or by any other approach, requires data on the environmental burdens and resource usages for individual processes and operations that often goes beyond the product-related information usually reported.
- Multi-criteria analysis already proved its value in complex environmental problems (Nijkamp [113]). From this study, it appears that this tool is also very useful when combining the inventory phases of a life cycle analysis with the improvement phase.
- Linear programming can rather easily be combined with life cycle analysis, since the latter is also based on linear relationships between activities and environmental burdens. Linear programming can offer more than static input-output models because it accommodates changes in the production process (flows between processes) itself and describes relationships within a production system instead of just giving an overall relation between inputs and outputs.
- Multiple objective programming allows to combine the environmental performance of a production system with economic preferences, thus giving the best compromise for the overall performance.

8.3 Operational Research models in environmental problem solving

We analyse three types of problem settings that show why the knowledge of OR will be useful in environmental problem solving.

Section 8.3.1 contains the first problem setting, dealing with the Dutch manure problem. This problem was originally treated as a local environmental problem to be solved through end-of-pipe techniques. However, many years of technical solutions did not solve the manure problem. Therefore, policy makers increasingly prefer a regional approach for at least two reasons: *(i)* air pollution due to ammonia emission requires regional legislation because of the transboundary effects of ammonia emission, and *(ii)* technical solutions are not sufficient to solve the problem.

The second problem setting deals with environmental policy making for the European pulp and paper industry as an example of a regional approach to environmental problems (Section 8.3.2). The European pulp and paper industry has environmental impacts associated with the consumption of scarce raw materials, emissions to air and water due to bleaching processes and the generation of waste paper. These impacts contribute to a wide range of environmental problems of local, regional and global significance. Environmental policy has to be developed on a regional level, since actions to reduce environmental impacts in one place may have serious implications for actions that occur elsewhere.

In this thesis, no illustrative example of a global approach to environmental problems is given. The complexity of global environmental problems is such, that this requires a thesis in itself. Section 8.3.3 discusses the value of Operational Research models for global problems, based on a literature review.

8.3.1 The mineral excess problem (Chapter 6)

A large surplus of minerals in soil, water and air has caused serious environmental problems in the Netherlands. Finding a good emission abatement strategy is complex, due to the mutual relations between the many possibilities to reduce emissions. We review the literature with respect to causes of the manure problem, the measures proposed to solve the problem and quantitative optimization and simulation models dealing with parts of the problem.

We conclude that mineral excess abatement is a complex problem because of *(i)* late recognition of the problem, *(ii)* conflicting goals of manure legislation, and *(iii)* the large number of possibilities to combine measures to abate emissions. We suggest a quantitative modelling approach based on chain-analysis to deal with this complexity. We develop a linear programming model that can be used as a tool to evaluate and improve policy scenarios. This model is only a first attempt to an integrated modelling approach for the manure problem. The model allows to find solutions that combine all feasible instruments developed for the mineral cycle.

This research indicates that:

- The single pollutant/single effect approach has to shift to a multiple sources/multiple effects approach if end-of-pipe solutions are not sufficient. This shift implies the use of different OR models. Single pollutant/single effect problems can still be modelled with analytic models. Multiple sources/multiple effects problems require simulation models and systems analysis as necessary attributes for environmental modelling in addition to optimization routines.

- Integral optimization reduces the risk of a sub-optimal strategy for solving local or regional environmental problems. Research in this area has to shift from a compartments oriented approach (air, water, soil) to an issues oriented approach (acidification, euthrophication).

8.3.2 Recycling of waste paper in Europe (Chapter 7)

The European pulp and paper sector can reduce its contribution to environmental damage in different ways, such as paper recycling, energy recovery and cleaner pulping and bleaching. It is not obvious which method is preferable. We show that an explicit evaluation methodology is necessary before consistent environmental policies can be defined. With a network flow model, we derive stable environmental policies that are both defendable and predictable.

Policies are being implemented to promote particular measures, such as mandated recycling of waste paper, even though there is no scientific consensus on their environmental impacts. We combine an environmental life cycle analysis with a network flow optimization model to search for policy measures that are robust and effective in reducing environmental impacts in the short term and the longer term. From our model results, we conclude that promoting a high level of recycling is a good short-term strategy as long as full energy recovery is not available. However, investment in capacity for energy recovery has a larger potential for environmental impact reductions in the longer term, without disturbing international trade relations. The model results also imply that environmental impact reductions through relocation cause many changes in the paper market. Paper production shifts towards regions with a high paper consumption.

This example of using OR models to evaluate and improve environmental policy for regional problems illlustrates that:

- Dealing with regional problems requires an integrated modelling approach using optimization models, economic models, physical models, scenario analysis, etc.

- Environmental policies, based on national interests, can easily result in non-optimal solutions for the economy and for the environment. Combining environmental evaluation tools such as life cycle analysis with optimization tools such as linear programming contributes to a better understanding of preferable policy strategies.

- Operational Research models can be effective for the policy debate on the reduction of environmental pollution. A multiobjective approach (in this example through a weighted sum of the objectives) accomodates dealing with different opinions.

8.3.3 Operational Research models for climate change

Climate models differ from other mathematical programming models for environmental control in that they are highly aggregate and deal with global issues such as the greenhouse effect. Mathematical programming models have made an important contribution to understanding the climate change problem.

Most of the integrated models are welfare economic models that mostly use nonlinear programming techniques. An important source of nonlinearity is the approximation of the differential equations that describe hydraulic and aerodynamic phenomena. Another source is uncertainty. Manne and Richels [102] developed Global 2100, which is an integrated (nonlinear) model of the (macro) economy, electricity generation, non-electric energy supplies, international oil trade, and carbon emissions. The DICE model (Dynamic Integrated Climate-Economy) by Nordhaus [116] uses nonlinear programming to determine a dynamic, economic equilibrium that copes with the threat of global warming. These optimization models are very simplistic descriptions of reality (e.g. they assume that the world economy produces a single product).

More advanced climate change models are integrated assessment models using simulation. IMAGE (Alcamo [7]) simulates the dynamics of the global society-biosphere-climate system. Uncertainty (like changes in population and GNP) is modelled using Monte Carlo sampling. ESCAPE (Hulme et al. [75]) enables the user to generate future scenarios (through an energy-economy model). It is possible to examine the impact of the scenarios on global climate and sea level and to illustrate some of the consequences of global climate change. These models focus more on understanding physical systems, than on optimizing human reactions to an environmental threat (e.g. the models do not contain prices).

Based on different surveys of mathematical models for the climate change problem (a.o. Greenberg [64] and Janssen et al. [79]), we identify the following issues in a global approach to environmental problems:

- Air quality control models are increasingly integrated with energy and economy models. Most of the integrated models use either simulation or non-linear analysis techniques.

- The objective of using optimization models for global environmental problems is not to supply 'the' optimal solution, but to stimulate policy makers from different countries to develop world-wide environmental legislation.

- Environmental control can be ineffective if policy makers are primary concerned with e.g. the environment whereas industry is primary concerned with e.g. profit maximization. Fully integrated models, based on both engineering and economic principles, give the opportunity to improve the necessary cooperation between various parties in order to solve global problems.

8.4 The research questions revisited

In this section, we discuss the research questions 1 (Section 8.4.1) and 2 (Section 8.4.2).

8.4.1 Environmental issues in Operational Research models

In order to incorporate environmental issues in OR models, we recommend to identify the level in which environmental issues affect the supply chain. If environmental issues affect only the distribution of products and waste, the problem can be classified as a waste management problem. Recovery management deals with environmental issues that also affect decision making in production and manufacturing. Finally, preventive management incorporates environmental issues in all echelons of the supply chain, from the cradle to the grave.

Waste management: The waste management approach leads to optimization models closely related to traditional routing and location models. Since waste treatment and disposal do not influence the production process, it is relatively easy to incorporate waste management issues in OR models. It is very likely that the environmental issues give rise to the addition of cost parameters in the objective function or new constraints similar to other constraints in the constraint set. A waste management model looks very similar to traditional models, i.e. either it can be decomposed into traditional models, or solution approaches, optimal for traditional models, appear to be successful heuristics.

Recovery management: Recovery management has a large effect on production planning models and inventory control models. Recovery management models still have parts that can be recognized as traditional production or inventory models, but it is likely that the models as a whole belong to a different 'family' of OR problems, i.e. a recovery farm management model might be non-linear whereas a traditional farm management model is linear, a recovery production model might be stochastic, whereas a traditional production model is deterministic. Quality restrictions on reusable materials often cause these shifts.

Preventive management: Preventive management opens perspectives to a new area of multi-disciplinary research that contains both OR models and techniques and Environmental Management approaches. Up to now, the results from environmental evaluation studies cannot be directly applied in OR decision models. They have to be adapted to provide environmental impacts that can be meaningfully used in OR models. Multiple criteria analysis and multiple goal optimization can help to close the gap between environmental life cycle studies and optimization methods.

8.4.2 Operational Research models to solve environmental problems

In order to use OR models in solving environmental problems, we recommend to identify the suitable policy approach to solve environmental problems. If environmental problems can be solved by technical end-of-pipe solutions without affecting economic activities, we identify this type of orientation as local. If the environmental problem also contains the distribution and movement of polluting components, a regional orientation is suitable. If the environmental problem has world-wide consequences, a global orientation is necessary. This identification gives an impression of *(i)* the degree to which OR models can be used in Environmental Management and *(ii)* the type of OR models to be used.

Local orientation: A local approach to environmental problems often benefits from the use of optimization models. Local environmental problems are characterized by a small number of technical solutions with known effects. This situation allows to use mathematical programming models. The fundamental model is a linear programming model, which extends naturally to mixed integer linear programming models (e.g. location decisions of wells), nonlinear programming models (e.g. optimal design), or dynamic programming (detection).

Regional orientation: Regional problems are much more complex than local problems. Dynamic simulation models can be used to describe the phenomena. It is also possible to combine descriptive simulation models and management optimization models in a hierarchical approach, i.e. decompose a complex problem into smaller, tractable units that can be dealt with, and aggregate results that are essential in a higher level of hierarchy. Formulating, solving and analysing multiple objective models is regarded by leading researchers in this area as an important frontier (Nijkamp et al. [113]).

Global orientation: Global environmental problems like climate changes can only be solved if measures are taken on a world-wide level. These measures will affect economic activities all over the world because this is the only way to obtain changes in a global system (e.g. energy taxes, prohibition of CFCs, birth control). An integrated assessment model is the only way to cover the complex system of pollution sources, emissions, and environmental effects. Optimization is only used as a sub-module of a larger modelling system that also contains economic, physical and environmental models.

8.5 Suggestions for further research

The framework in Figure 8.1 suggests a shift in the integration of environmental issues in OR models using three management types, and a shift in the use of OR models to solve environmental problems using three types of policy orientation. The examples in this thesis illustrate these shifts but do not give a full proof of the completeness and robustness of our framework. We suggest a thorough literature review together with the development of a questionnaire for environmental managers and policy makers to investigate if they recognize the shift in thinking about environmental problems, and the shift in using mathematical models, in particular optimization models, in their decision making.

The framework describes three steps in green supply chain management: waste management, recovery management and preventive management. We have the impression that the waste management approach is quite easy to implement in real-life problem situations. OR practitioners, interested in the field of waste management, will easily find projects to work on. Recovery management deals with frequent occuring environmental problems with a typical structure. In fact, we know too little about efficient solution methods for these problems (e.g. bilinear programs) to cope with real-life problem situations. Since the recovery approach appears to become important in the near future, we suggest the development and implementation of general solution methods that can be adapted to specific circumstances. Preventive management requires joint work between environmental departments and people from acquisition, production and sales departments. We expect an increase in the number of 'cradle to grave' projects and suggest close cooperation between OR and EM practioners both in industry as in academia in the development of integrated modelling approaches.

We distinguish a local, regional and global orientation in the approach to environmental problems. OR tools for local and regional problems have been developed since the first interest in environmental issues (e.g Das and Haimes [45]). Most of the research takes place in Europe or the USA where the economic development has already caused many environmental problems. We suggest further research in new-developing countries such as India and China in order to develop a sustainable economic and environmental situation which prevents the creation of new environmental problems. For global problems, we suggest further research in combining simulation techniques with optimization in order to overcome the drawbacks of using only simulation or optimization.

Finally, it is an interesting question to see if there is any similarity between the management types in the supply chain and the types of policy orientation in the environmental chain. The existence of such similarities intensifies the need for a interdisciplinary approach for problems that originally belonged to either the field of OR or the field of EM. The examples in this thesis give some assistance to investigate possible similarities.

- Both *waste management* and *local orientation* can be characterized by the large contribution of 'traditional' OR models and methods. Models used in waste management might be applicable to local problems in the environmental chain and vice versa. Literature is available in both environmental journals and OR journals. Individual researchers can cross the borders between OR and EM by e.g. reading environmental/mathematical papers and joining environmental/mathemathical sessions at conferences.

- *Recovery management* and *regional orientation* are intermediate steps between end-of-pipe emission control and an integrated approach to solve problems. These intermediate steps are characterized by complex models which sometimes require complex solution methods. Both fields probably describe the actual state-of-the-art of possible interactions between OR and EM. The examples in this thesis show that problems in the intermediate phase are interesting from a theoretical point of view (both for OR and EM) as well as from a practical point of view (both for OR and EM). Integration of OR and EM will be possible by working together as a team of OR specialists and EM specialists. The EM specialists are required for the right understanding of the environmental problems, the OR specialists are required to develop suitable solution methods. Projects in recovery management and the regional orientation to environmental problems will probably be characterized by an iterative process between OR and EM.

- *Preventive management* and *global orientation* require multi-disciplinary research. Operational Research contributes to the validation of model building or the evaluation of policy scenarios. Environmental Management contributes to the understanding of the problem and the development of rational scenarios. Integration of OR and EM is probably still music of the future because of the complexity of the problems and the skills required to solve the problems (physics, social science, economics, etc.) On a simple level, interactions between OR and EM are certainly possible.

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Summary

Integration of operational research and environmental management

The subject of this thesis is the integration of Operational Research and Environmental Management. Operational Research (OR) concerns the decision support (which choice out of a number of alternatives is best, given certain constraints) through mathematical models. Some examples of OR applications are: inventory management (when do I order, what is the size of the order), production planning (when do I make which product and what is the batch size), and distribution planning (how many vehicles do I need and which is the optimal route). Environmental Management (EM) concerns the measures to solve or prevent environmental problems in order to obtain sustainability. Examples of environmental management are: emission reduction, livestock reduction, or management with respect to population growth or cultural development. Both OR and EM can play an important role in the research of environmental issues. Economic growth is frequently considered to be in conflict with sustainable development and environmental quality. More and more, governments, industry and consumers have to search for new paths which are both economically efficient and environmentally sustainable. Therefore, a decision maker needs to know how to deal with environmental issues that come around. This book aims to investigate *(i)* the possibilities of incorporating environmental issues in 'traditional' OR applications when analysing supply chains and *(ii)* the possibilities of using OR models and techniques in environmental research.

The thesis is structured around two research questions:

1. How can Operational Research models and methods be adapted to include environmental issues?
2. To which degree can Operational Research models and methods be used to solve environmental problems?

We search for an answer to these questions in a number of steps. First, we develop a framework to show how environmental issues and economic decision making interact in two ways. Economic activities have large impacts on the environmental chain (emissions, pollutions, disturbance and depletion): the use of CFCs is one of the causes of stratospheric

ozone depletion. The environmental chain has also impacts on the supply chain (purchasing, production, distribution, consumption and waste collection): packaging convenants have to change the behaviour of managers dealing with their waste.

In the framework we consider three stages in the integration of environmental issues in supply chain decision making:

1. *waste management*: managers take account of the environment by disposing hazardous waste or building depots for incineration.
2. *recovery management*: managers bear in mind the environment by searching for ways to recover their products (or materials) by means of recycling or reuse.
3. *preventive management*: managers take account of the environment from the purchasing of raw materials, the design of the products and production process, to the end-use of products.

We also consider three stages in environmental policy development:

1. *local orientation*: local problems (soil pollution, air quality) can be solved by local solutions (end-of-pipe technologies).
2. *regional orientation*: environmental problems on a larger spatial scale like pollution of the Rhine are treated by the relevant countries together.
3. *global orientation*: global problems like ozone depletion and climate change can only be solved by an integrated approach e.g. a world-wide production stop for CFCs or a reduction of the use of fossil fuels.

A literature review shows that there appears to be a relation *(i)* between the management approach towards environmental problems and the possibilities to include environmental issues in existing OR models (research question 1), and *(ii)* between the environmental policy orientation and the degree to which Operational Research can be used to solve environmental problems (research question 2).

Part II and Part III of this thesis deal with a number of examples of the integration of environmental issues in OR models and the use of OR models for the development of environmental policies. Each chapter contains an application of the integration of OR and EM and can be read separately. The purpose of these chapters is also to investigate the relation between the approach towards environmental problems and the answers to the research questions as described above. Part II contains three examples of dealing with environmental issues in OR models and techniques, described in Chapters 3, 4, and

5. Part III contains two examples of using OR models and techniques in environmental management, described in Chapters 6 and 7.

Chapter 3 describes an extension of the classical location problem. The location problem deals with the design of an 'optimal' distribution structure of plants, based on a trade-off between fixed costs of plants and variable costs of the transportation of products between plants and clients. Environmental issues play a role if waste, generated during production, has to be disposed of at waste disposal units. This situation occurs for example in agriculture (transportation of manure), and in nuclear power stations (transportation of nuclear waste). The question is then how to design an efficient distribution structure which simultaneously takes into account the location of plants and waste disposal sites. This is an example of an OR-application in *waste management.*

Chapter 4 describes an extension of the classical farm management problem. In the farm management problem, the farmer has to determine a profit maximizing combination of farm activities on his land. Environmental aspects play a role if manure, normally disposed of at some cost, can be utilized as a fertilizer. The Dutch government restricts the use of manure for fertilizing purposes through the introduction of environmental standards for spreading the manure in the fields to counter environmental problems such as acidification and eutrophication. The farmer has the choice in his farm activities as well as the choice between disposing manure or applying it for fertilizing purposes, replacing inorganic fertilizers. This problem can be considered as an example of an OR-application in *recovery management.*

Chapter 5 describes an extension of the classical blending problem. The blending problem concerns the composition of a raw materials blend such that the costs of the raw materials are minimal and the blend satisfies all quality conditions of the product. Apart from having a good-quality product, it is also important to sell an environmentally friendly product. The environmental quality of e.g. margarine depends on the environmental quality of the raw materials (oils and fats). The environmental quality of refined oils consists of the environmental effects of the growing of the crops, the production of crude oil, refining and processing and transportation. To weigh the environmental quality of raw materials against the costs of raw materials, we develop the environmental index, using life cycle analysis and multiple criteria analysis. The environmental index is a one-dimensional parameter, that can be used to find the optimal blend of an environmentally friendly product. This problem is an example of an OR-application in *preventive management.*

Chapter 6 describes the mineral excess problem in the Netherlands. A *local approach* towards this problem consists of fodder adjustments, emission-poor stables, covered storage, and application measures. Beforehand, it is hard to tell which combination of measures is the most effective and efficient, due to the complexity of the problem. Operational Research can play a role both in structuring the problem and determine strategies for various environmental standards. In this example, linear programming is used to find suitable measures for the different parts of the Netherlands.

In Chapter 7 we discuss the issue of paper recycling in Europe. Recycling of waste paper will reduce the environmental impacts of the pulp and paper industry. Is maximal paper recycling the best policy or should other possibilities such as better pulping technologies and waste paper incineration for energy recovery be considered? To explore this question, we use a combination of life cycle analysis and optimization. A linear network flow model helps to find answers to questions such as: what is the optimal collection rate of waste paper, and what is the optimal share of recycled pulp in paper furnish such that total environmental impact of the paper and pulp industry in Europe is minimized. This is an example of the use of OR models in a *regional orientation.*

Chapter 8 confronts the general ideas from the framework with the knowledge obtained from the chapters in Part II and Part III. We discuss briefly the role of OR models and techniques in solving *global* environmental problems. Finally, we reconsider the research questions and give suggestions for further research.

Samenvatting

Integratie van operationele analyse en milieubeleid

Het onderwerp van dit proefschrift is de integratie van Operational Research (Operationele Analyse) en Environmental Management (milieubeleid). Operational Research (OR) houdt zich bezig met het ondersteunen van beslissingen (wat is de beste keuze uit een aantal alternatieven, gegeven een aantal beperkende voorwaarden) met behulp van wiskundige modellen. Enkele voorbeelden van OR toepassingen zijn: voorraadbeheer (wanneer plaats ik een bestelorder van welke grootte), produktieplanning (wanneer maak ik welk produkt en hoeveel maak ik er van), en distributieplanning (hoeveel vrachtwagens heb ik nodig en welke route moeten zij rijden). Environmental Management (EM) houdt zich bezig met maatregelen die worden uitgevoerd voor het oplossen of voorkomen van milieuproblemen met als doel het streven naar duurzaamheid. Voorbeelden van milieubeleid zijn emissiereductie, volumebeleid (bijvoorbeeld van de veestapel), beleid gericht op bevolkingsgroei of op culturele ontwikkeling. Zowel OR als EM kunnen een belangrijke bijdrage leveren als het gaat om beslissingsproblemen waarbij het milieu een rol speelt. Economische groei gaat niet altijd samen met een duurzaam milieu. Meer en meer moeten overheden, bedrijven en consumenten nieuwe wegen zoeken die economisch verantwoord en duurzaam zijn. Daarom is het van belang dat men weet hoe om te gaan met de milieu-aspecten van economisch handelen. Het doel van dit boek is tweeledig: *(i)* besliskundigen laten zien dat het meenemen van milieu-aspecten in beslissingsmodellen een uitdagend toepassingsgebied is, zowel theoretisch als in concrete toepassingen, en *(ii)* milieukundigen laten zien wat de waarde kan zijn van het gebruik van wiskundige methoden en technieken bij het ontwikkelen van milieubeleid.

Het proefschrift is opgebouwd rond twee onderzoeksvragen:

1. Hoe kunnen OR modellen en methoden worden aangepast zodat milieu-aspecten kunnen worden meegenomen?

2. Tot op welke hoogte kunnen OR modellen en methoden worden gebruikt bij het oplossen van milieuproblemen?

We zoeken een antwoord op deze vragen in een aantal fasen. Allereerst ontwikkelen we een raamwerk waarin de relaties tussen milieu-aspecten en economisch handelen tot uitdrukking komen. Economisch handelen heeft een grote invloed op de milieu-effectketen (emissies, verontreiniging, aantasting en uitputting): het gebruik van CFK's heeft een bijdrage geleverd aan het ozongat. De milieu-effectketen heeft zelf weer invloed op de economische keten (inkoop, produktie, distributie, consumptie en afvalverzameling) via het milieubeleid: verpakkingsconvenanten moeten er bijvoorbeeld voor zorgen dat ondernemers anders met hun afval omgaan.

In het raamwerk beschouwen we drie stadia waarin milieu-aspecten worden meegenomen bij bedrijfsbeleid in de economische keten:

1. *afvalbeleid*: managers houden rekening met het milieu door gevaarlijk afval veilig op te slaan of afvalverbrandingsinstallaties te laten bouwen.
2. *recycling beleid*: managers houden rekening met het milieu door te zoeken naar manieren om hun produkten (of onderdelen) vaker te gebruiken door middel van recycling.
3. *preventief beleid*: managers houden rekening met het milieu vanaf de inkoop van grondstoffen, de inrichting van het produktie-proces, het ontwerp van produkten, tot en met het gebruik van de produkten.

Ook beschouwen we drie stadia in het ontwikkelen van milieubeleid:

1. *lokaal georienteerd*: lokale problemen (bodemverontreiniging, luchtkwaliteit) worden aangepakt via lokale oplossingen (technische aanpassingen, hogere schoorstenen).
2. *regionaal georienteerd*: milieuproblemen die spelen in een groter gebied (waterverontreiniging in de Rijn) worden door verschillende landen tegelijk aangepakt.
3. *globaal georienteerd*: globale milieuproblemen zoals het ozongat en klimaatverandering worden geïntegreerd benaderd via wereldwijde aanpak van de productie van CFK's of het terugdringen van energie-gebruik.

Vervolgens laten we, aan de hand van een literatuuroverzicht, zien dat er een verband lijkt te bestaan *(i)* tussen het type bedrijfsbeleid en de mogelijkheden om milieu-aspecten op te nemen in bestaande OR modellen (onderzoeksvraag 1), en *(ii)* tussen het soort milieubeleid en de mate waarin OR modellen en technieken een rol kunnen spelen bij het oplossen van milieuproblemen (onderzoeksvraag 2).

Deel II en deel III van dit proefschrift behandelen een aantal voorbeelden van het omgaan met milieu-aspecten in OR modellen en het gebruik van OR modellen bij het ontwikkelen van milieubeleid. Ieder hoofdstuk beschrijft een toepassing van Operationele Analyse en milieubeleid en is als losstaand stuk te lezen. Tegelijkertijd dienen deze hoofdstukken om bovenstaand verband tussen de aanpak van milieuproblemen en het antwoord op de gestelde onderzoeksvragen nader te onderzoeken. Deel II bevat drie voorbeelden van het omgaan van milieu-aspecten in OR modellen en technieken, beschreven in Hoofdstuk 3, 4 en 5. Deel III bevat twee voorbeelden van het gebruik van OR modellen en technieken bij het ontwikkelen van milieubeleid, beschreven in Hoofdstuk 6 en 7.

Hoofdstuk 3 beschrijft een uitbreiding van het klassieke lokatieprobleem. Het lokatieprobleem gaat in op de vraag: welke fabriekslokaties moet ik tot mijn beschikking hebben om mijn produkten te maken zodanig dat de kosten van de lokaties en de transportkosten naar de klanten minimaal zijn? Milieu-aspecten gaan hier een rol spelen als het afval, ontstaan tijdens de produktie, vervoerd moet worden naar afvaldepots. Deze situatie doet zich voor bijvoorbeeld in de landbouw (vervoer van varkensmest), of bij kerncentrales (vervoer van nucleair afval). De vraag luidt dan: hoe bepaal ik simultaan de plaatsen van de fabrieken en de afvaldepots zodat de totale kosten minimaal zijn? Dit is een voorbeeld van een OR-toepassing in het *afvalbeleid.*

Hoofdstuk 4 beschrijft een uitbreiding van het klassieke farm management probleem. Het farm management probleem is het probleem van de boer die een stuk land heeft en dit voor verschillende doeleinden kan gebruiken. De vraag is hoe hij zijn land, zijn apparatuur en zijn mensen moet inzetten om tot een zo hoog mogelijke winst te komen. Milieu-aspecten gaan hier een rol spelen als de mest die normaal wordt afgevoerd tegen bepaalde kosten, kan worden gebruikt als een vervanger van kunstmest. De mest bevat echter zoveel mineralen, dat dit niet onbeperkt kan. De overheid heeft limieten gesteld aan de hoeveelheid mineralen in de grond om milieuproblemen als verzuring en vermesting tegen te gaan. De boer moet nu niet alleen kiezen hoeveel dieren hij op zijn land wil, maar ook hoeveel mest hij wil gebruiken als vervanger van kunstmest. Dit probleem kan worden beschouwd als een voorbeeld van OR binnen *recycling beleid.*

Hoofdstuk 5 beschrijft een uitbreiding van het klassieke blending probleem. Het blending (of mengsel) probleem houdt zich bezig met samenstellen van een grondstoffen-mix zodanig dat de kosten van de grondstoffen minimaal zijn en de grondstoffen-mix voldoet aan de kwaliteitseisen van het produkt. Naast een gezond produkt is het ook belangrijk om een milieuvriendelijk produkt te verkopen. De milieukwaliteit van een pakje margarine hangt af van de milieukwaliteit van de grondstoffen (oliën) die in de margarine gaan. De milieukwaliteit van geraffineerde olie wordt bepaald door o.a. de milieu-effecten bij het verbouwen van oliehoudende zaden, de olie-produktie en raffinage, en het transport. Om de milieukwaliteit van een grondstof af te wegen tegen de kosten van een grondstof, wordt de milieu-index ontwikkeld door gebruik te maken van levenscyclusanalyse en multicriteria analyse. De milieu-index is een getal dat kan worden gebruikt bij de optimale samenstelling van een milieuvriendelijk produkt. Dit probleem is een voorbeeld van OR-toepassingen binnen *preventief beleid.*

Hoofdstuk 6 beschrijft het mestoverschot probleem in Nederland. Een *lokale* benadering van dit probleem bestaat uit het nemen van voedingsmaatregelen, de bouw van emissiearme stallen, overdekte mestopslag en uitrijmaatregelen. Welke combinatie van maatregelen het meest effectief en efficiënt is, is moeilijk op voorhand te zeggen door de complexiteit van het probleem. Operationele Analyse kan een rol spelen zowel bij het structureren van het probleem als bij het bepalen van goede strategieën bij verschillende milieunormen. In dit voorbeeld wordt een lineair programmeringsmodel gebruikt om voor de verschillende delen van Nederland de juiste maatregelen te vinden.

In hoofdstuk 7 bekijken we het vraagstuk van papierrecycling in Europa. Recycling van oud papier is beter voor het milieu. Het is echter de vraag of alles en iedereen moet worden ingezet om zoveel mogelijk papier te recyclen. Andere mogelijkheden in de papier- en pulpindustrie zijn bijvoorbeeld het verbeteren van pulptechnieken of het verbranden van papier als energiebron om zo het gebruik van fossiele brandstoffen te verminderen. Om hier meer duidelijkheid in te brengen, gebruiken we een combinatie van levenscyclusanalyse en optimalisatie. Een lineair netwerk stroom model geeft voor verschillende scenario's antwoord op vragen als: hoeveel moet ieder land aan oud papier verzamelen, en hoeveel oud papier moet worden gebruikt bij het maken van papiersoorten, zodanig dat de totale milieuschade als gevolg van papierproduktie in Europa minimaal is. Dit is een voorbeeld van het gebruik van OR modellen in een *regionale orientatie.*

Hoofdstuk 8 tenslotte gaat in op de algemene lessen die geleerd kunnen worden uit de voorafgaande hoofdstukken. Verder wordt kort ingegaan op de rol van OR modellen en technieken bij globale milieuproblemen (*globale orientatie*). Tenslotte worden de onderzoeksvragen opnieuw beschouwd en worden er suggesties gegeven voor verder onderzoek.

About the author

Jacqueline Maria Ruwaard was born May 30th, 1969 in Katwijk aan Zee, the Netherlands. She completed her secondary school education (VWO) at the Pieter Groen College in Katwijk in 1987. The same year she started to study Operational Research and Econometrics at the Erasmus University Rotterdam. From 1989 to 1991 she held a position as teaching-assistant at the Department of Operational Research. In 1991 she wrote a Master's thesis at the European Institute of Business Administration INSEAD, Fontainebleau, France, on 'integrated coordination of product flows and waste flows'. She obtained her masters degree in Economics in 1992 (cum laude) and moved to the Center for Environment and Climate Studies of the Agricultural University of Wageningen to start her Ph.D. research on Operational Research and the environment. The research reported in this thesis was conducted at the Agricultural University of Wageningen (from 1992 until 1996), Unilever, at which the author worked for six months in 1993, and at the European Institute of Business Administration INSEAD, Fontainebleau, France, which the author visited for four months in 1994. The research was partly sponsored by the Rijksinstituut voor Volksgezondheid en Milieuhygiene (RIVM), Unilever and INSEAD.