Sustainable industrial production : an energy perspective

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Sustainable Industrial Production

an energy perspective

W.T.M. Wolters

Sustainable Industrial Production

an energy perspective

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr. J.H. van Lint, voor een commissie aangewezen door het College van Dekanen in het openbaar te verdedigen op

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Contents

Chapter 1: Introduction

Chapter 2: Process Integration aimed at energy conservation

Chapter 3: The identification of production systems

Chapter 4: The evaluation of production systems

Chapter 5: Case study

Chapter 6: Reflections upon the study

Chapter 7: Conclusions

Preface

This doctoral thesis contains the results of the research that I carried out while I was working at the Graduate School of Industrial Engineering and Management Science of Eindhoven University of Technology. Since this thesis could not have been completed without the help and support of others, I would like to thank a number of people for their support, realising that such a list will never be complete.
Jan Claus contributed to the successful completion of this thesis by his minute comments. Furthermore, his calmness guided me and the other members of the section Energy and Environment (Graduate School of Industrial Engineering and Management Science) through turbulent times.
Fred Lambert and I worked together very closely. We stimulated and criticized each other, which had a positive influence on the quality of our work. Moreover, we had numerous interesting discussions on a wide range of subjects.
Maarten Splinter contributed to my research project by providing me with essential literature. His contribution was vital in the transformation of a physicist into an industrial engineer.
Jean-Pierre Brans and Bertrand Mareschal stimulated me by their constructive comment on my research. We also worked together very pleasantly on a joint research project. Furthermore, we tested and compared the culinary abilities of Dutch and Belgian restaurants.
In the case study that was performed in the framework of the study described in this thesis, I worked together with a lot of people from the Netherlands Organisation for Applied Scientific Research (TNO). Although all of them contributed to the success of the project, I would like to thank Bert Melman and Jac Lemmen for the pleasant way in which we cooperated.
Elaine Lambert gave many useful suggestions with respect to the use of English.

Last but not least, I would like to thank my parents for their continuing support and patience.

Wim T.M. Wolters
Nuenen, March 1994

Chapter 1

Introduction

1.1 Introduction

Industrial energy conservation will be indispensable for a sustainable development of world economy. A change in applied technology will be required to realise the targets that have been indicated, and that have partly already been set by national governments. To achieve those targets will be one of the main challenges to industry in the near future. The study presented in this thesis is aimed at developing a tool that may support decision makers in the strategic process of identifying and evaluating energy efficient production systems.

In section 1.2, the historical background of the subject treated in this thesis, and the managerial and social motives for this study are discussed briefly. Subsequently, its objective is presented in section 1.3. Finally, the structure of the study and the contents of this book are described.

1.2 Background

Before the 1970's, energy and especially fossil fuels, were considered as cheap and amply available. In 1972 however, the report "The Limits to Growth" was published, stressing the limited resources of, among others, fossil energy carriers, and discussing the limits this would impose on future economic growth (Meadows, 1972). Shortly after this publication, the first energy-crisis occurred, presenting the world economy with shortages and rapidly increasing fuel prices. This lead to an economic crisis since the energy intensive industries, which were very important to western economy, were hit very hard by this sudden increase in price of one of their raw materials. As a result of this, there was a growing awareness of the sensitivity of the oil-dependant western economies to disturbances in the availability and price of fossil energy carriers (EZ, 1990). Consequently, the concern about the supply-side of the energy system began to dominate the way energy was applied by the end-users. Because of this concern, from the 1970's on, the availability and, connected to it, the fuel price have been principal inducements for the formulation of energy policies. The objective of these policies was to reduce the dependency of the economy on the availability of oil and thus to decrease its sensitivity to sudden drastic fluctuations in its price (EZ, 1990). This was to be achieved by diversifying the fuel-mix, decreasing the consumption of fossil fuels, enhancing the effectiveness of energy conversion and promoting the use of renewable energy sources.

In recent times it was recognised that not only the supply-side of the energy system, but also its discharges to the environment will impose constraints on energy consumption (IEA, 1991; IPCC, 1990; RIVM, 1990, 1991; WCED, 1987; VROM, 1989, 1990; EZ, 1990). It is even expected that these discharges will become the principal constraints on energy consumption, since nature cannot cope with a further increase of them. Especially some gaseous emissions are considered as a threat because of their contribution to global environmental problems like acid rain (SO_2 and NO_x) and the increase of the greenhouse effect (CO_2). Although this increase was recognised long ago (Arrhenius, 1895), political and public awareness of this problem has been growing probably ever since the first World Climate Conference in 1979 and the publication of the first IPCC-report in 1984 (IPCC, 1984; CEC, 1991). Since the CO_2-emission connected to the use of fossil fuels for energy generation contributes for about 55% to the increase of the greenhouse effect (IPCC, 1990), this is becoming the most important driving force towards rigorous measures to decrease fossil fuel consumption (CEC, 1990). Although a lot of studies have been performed to estimate the consequences of the greenhouse effect (Chartier, 1992; Enting, 1991; Flohn, 1980; IPCC, 1990; Okken *et al.*, 1991; Leggett, 1990), and to indicate what measures will be required to make fossil fuel consumption compatible with a sustainable development (Brady and Maass, 1992; Nakićenović and John, 1991; Okken and Ybema, 1992; RIVM, 1990, 1991), results are still very uncertain and only rough estimates can be made. Although rough, these estimates indicate that drastic measures will be required to decrease the emissions to a more sustainable level (e.g. an 80% decrease of the CO_2-emission by the year 2030 (RIVM, 1990,1991)). This is certainly the case if a world-wide sustainable development is to be achieved with a more equal global distribution of economic welfare.

In spite of the uncertainties in the results of the studies mentioned above, the CO_2 related greenhouse effect is already becoming very important in energy policies (IEA, 1991; VROM, 1989, 1990; EZ, 1990). The environmental problems connected to fossil fuel consumption make that environmental and energy policies become interrelated. This is reflected in for instance the Dutch National Environmental Plan (VROM, 1989), in which target values for the emissions connected to the consumption of fossil fuels for energy generation are presented. These target values are shown in table 1.1. Similar targets have been formulated or will be in near future, by governments of other countries (NDCC, 1989).

Table 1.1: The target values for the emissions connected to fossil fuel consumption for energy generation (VROM, 1989).

	Reference year	Emission [kton/yr]	Target emission by 2000 [kton/yr]
CO_2	1989	183000	183000
SO_2	1985	276	105
NO_x	1985	544	268

In the "Memorandum on Energy Conservation" (EZ, 1990) prepared by the Dutch government, a target of 20% energy efficiency improvement with respect to 1990 is set out by the year 2000. This target inevitably raises the question in what way, and at what sacrifices such a decrease may be established, meanwhile preserving or improving the relative independence from a specific type of fossil energy carrier. For this purpose, the following policy-instruments are applied in the member-countries of the International Energy Agency (IEA, 1991):

- Information programmes and energy management services
- Regulations and efficiency standards
- Pricing and fiscal policies
- Subsidies and financing facilities
- Demand-Side Management
- R&D-programmes
- The exemplary role of governments

Furthermore, the following tools are being considered:

- Energy concessions
- Energy (CO_2) tax

At this moment the Dutch government is also applying the instrument of the so-called "covenant", in which industrial branches or firms commit themselves to achieve a certain energy efficiency improvement within a certain period of time.
All these tools are aimed at improving energy efficiency, and depend strongly on the development, availability, and introduction of (new) energy efficient technologies (IEA, 1991; Bruggink *et al.*, 1992).

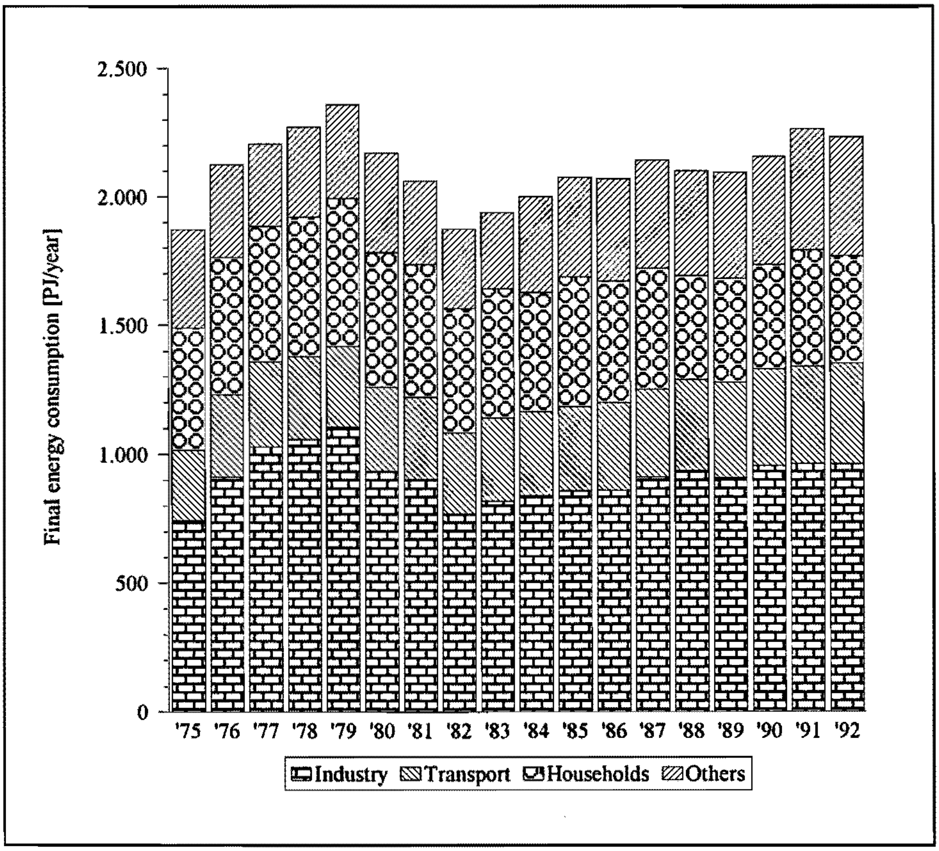

Figure 1.1: The development in time of the final energy consumption by Dutch end-users (CBS, 1976...1993).

Fossil fuel consumption is in principle brought about by the needs of society on:

- Comfort
- Commodities
- Transport of persons and commodities
- Information

These needs are reflected in the final energy consumption by Dutch end-users. Its development in time is presented in figure 1.1. From this figure it can be seen that final industrial energy consumption, which is directly related to the production of commodities, represents a substantial part of the total final energy consumption. Therefore, a considerable part of the target of 20% efficiency improvement has to be achieved by industry (EZ, 1990). Recent studies have shown that a certain potential exists for this (IEA, 1991; Melman *et al.*, 1990), although some obstacles will have to be overcome. In the coming years, the challenge to industry will be to bring down the final industrial energy consumption. This challenge results from energy/environmental policies, and from a changing market where customers are increasingly demanding "green" products. The work presented in this thesis is triggered by this challenge.

1.3 Objective of the study

The measures which are available to decrease the final industrial energy consumption, can be divided into four categories (Melman *et al.*, 1990):

- Good housekeeping
- Replacement of energy inefficient equipment
- Addition of energy saving equipment
- Application of novel processes and process-integration

The policy instruments mentioned in the previous section are, as far as they can be applied to industry, all aimed at these four measures. This inevitably raises the question of whether it will be possible to achieve the necessary decrease in final industrial energy consumption by stimulating such measures. To gain insight into the answer of this question, one should have a look at the intended development in time of the energy intensity of a specific commodity. In figure 1.2, an idealised example of this is presented.
Two years are indicated in this figure: 1985 and 1994. Curve 1-2 represents the idealised development of the energy intensity of a specific commodity between 1985 and 1994. Due to continuous innovations caused by better housekeeping, gradual replacement of energy inefficient equipment and addition of energy saving equipment, a gradual decrease of energy intensity has occurred. It is expected that this decrease will continue until point of time T1 has been reached. At this point, it will no longer be feasible (technically, economically etc.) to decrease the energy intensity by continuous innovations. Only by a discontinuous innovation like the application of novel processes and extensive process-integration may a discontinuous step in energy intensity be made. This step is represented by point 3 and point 4 at time T1. After this step has been taken, the energy intensity will gradually decrease due to continuous innovations. At time T2 the energy intensity may be decreased again only by a discontinuous innovation, as is represented by points 5 and 6. After this innovation, energy intensity will gradually decrease again, etc. In theory this can continue until the theoretical minimum energy intensity (indicated by point 8 in figure 1.2) which is determined by the laws of thermodynamics, has been reached.

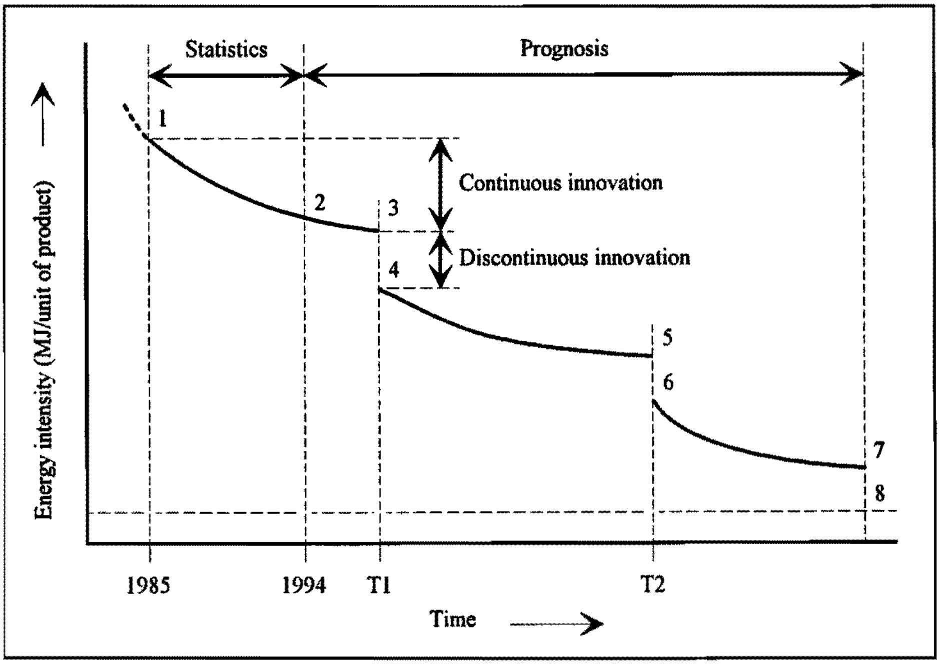

Figure 1.2: The idealised development of the energy intensity of a specific commodity (Melman *et al.*, 1990).

Referring to the question asked at the beginning of this section, one may conclude from figure 1.2 that it is most likely that other, more energy efficient production systems will have to be applied in order to achieve the necessary decrease in final industrial energy consumption. These discontinuous innovations will have to be achieved at the aggregation level of individual firms. Therefore, the first part of the tool described in this thesis is focused on identifying alternative, more energy efficient production systems.

From experiences with discontinuous innovations in other sectors than energy/environment related ones, it is widely known that there is a rather long time between the development of a novel process and its large scale application in practice (CLTM, 1990). Furthermore, experience has shown that a number of unwanted or unexpected effects may occur besides the expected benefits of novel processes. For example, the application of composite materials in cars has reduced their energy consumption. However, the possibilities to recycle them have also been reduced (CLTM, 1990). Thus a positive effect on the environment, a reduction of air pollution, is accompanied by a negative one in the waste treatment. It is expected that similar effects may occur in more energy efficient production systems. Such interacting effects should be studied and weighed against each other before the actual introduction of a novel process. Therefore, the second part of the tool described in this thesis is focused on such an evaluation.

The objective of this study is to develop a tool that may support decision makers in the strategic process of identifying and evaluating the energy efficient (process-integrated) production systems which will be indispensable for a sustainable development of industrial production.

1.4 Structure of the study

In chapter 1 of this thesis, the background and the objective of this study have been presented.

Chapter 2 gives an extensive literature review of currently applied methods for industrial energy conservation. There is a focus on the most important process integration methods for energy conservation (by means of heat recovery), rather than on specific (energy conserving) technologies. Given the objective of this study, a number of gaps in the literature are identified at the end of this chapter. From these gaps a number of research questions are deduced.

The part of the tool that may support decision makers in the process of identifying more energy efficient production systems is presented in chapter 3. After the system boundary has been defined, three subsystems are distinguished: the *transformation subsystem*, the *utility subsystem* and the *heat recovery subsystem*. The elements of these subsystems are put forward for debate in this study. To identify the most energy efficient production system (i.e. the optimum combination of elements), a mathematical programming approach is presented. This approach also enables one to study the influence of sequential decision making on the specific energy consumption of a production system.

The evaluation of a set of production systems as identified in chapter 3, is studied in chapter 4. It is argued that within the framework of this study, a multiple criteria decision aid method has to be applied. By means of two experiments it is demonstrated that the proposed method may support the decision maker in selecting one of the alternatives, and in studying the interactions between the applied criteria. Furthermore, an extension to the proposed methods is presented.

To demonstrate the methods described in chapter 3 and 4, a case study has been conducted in the framework of the project "Sustainable Industrial Production". This project has been performed by TNO (Netherlands Organisation for Applied Scientific Research) in cooperation with Eindhoven University of Technology, on behalf of the Dutch Ministry of Economic Affairs. The results of the case study are presented in chapter 5.

In chapter 6 there is a reflection upon this study. The importance of the results is discussed from the point of view of an integral chain approach. Furthermore, the role which the presented methods may play in the decision making process and in the policy formulating process is described. At the end of this chapter, a number of recommendations for further research are presented.

The principal conclusions of this study are presented in chapter 7.

Chapter 2

Process integration aimed at energy conservation

2.1 Introduction

In industry, energy conservation via heat recovery is applied on a large scale. Some principal methods developed for this type of process integration are reviewed in this chapter. Two categories of methods are distinguished: heuristic methods and mathematical programming ones. Both may be applied to stationary (flow processes) and non-stationary energy flows (batch processes).
At the end of this chapter, a number of gaps in the literature (from the point of view of this study) are presented. Subsequently it is indicated which of these gaps can be filled by the tool described in this thesis.

2.2 Process integration

Process integration is defined as bringing together a number of production stages into one system by establishing relations between the mass, energy or information flows through these production stages. The objective of process integration is to improve the performance of the total system. In the case of process integration with thermal energy flows, the objective is to minimise the demand for hot and cold utility (required for heating respectively cooling purposes) of the total system.
In most production systems, so-called hot and cold streams are present, which have to be cooled respectively heated from a certain temperature to a target temperature. In cooling, a thermal power ΔH_h [kW] is transferred from the hot streams to the cold utility. Heating involves the transfer of a thermal power ΔH_c [kW] from the hot utility to the cold streams. ΔH_h and ΔH_c are defined by relation 2.1, respectively relation 2.2.

$$\Delta H_h = \sum_i Cp_i \, \Delta T_i \tag{2.1}$$

$$\Delta H_c = \sum_j Cp_j \, \Delta T_j \tag{2.2}$$

The indices i and j indicate the hot and cold streams respectively; Cp_i and Cp_j are the heat flow rates [kW/°C] of the hot respectively the cold stream; ΔT_i and ΔT_j represent the temperature difference [°C] over the temperature trajectory of the hot and cold streams.

In the case of no process integration, the energy balance of the hot and cold streams is given by relation 2.3 and 2.4.

$$Q_c = \Delta H_h \tag{2.3}$$

$$Q_h = \Delta H_c \tag{2.4}$$

where Q_c and Q_h are the required external cooling respectively heating [kW]. If process integration is applied, meaning that heat is transferred from the hot to the cold flows, Q_h and Q_c become related since in that case:

$$Q_c = \Delta H_h - \Delta Q_{transf} \tag{2.5}$$

$$Q_h = \Delta H_c - \Delta Q_{transf} \tag{2.6}$$

where ΔQ_{transf} is the thermal power [kW] transferred from the hot to the cold streams. Relations 2.3 and 2.4 and also 2.5 and 2.6 can be rewritten to give:

$$Q_h + \Delta H_h = Q_c + \Delta H_c \tag{2.7}$$

Since ΔH_h and ΔH_c are constant, relation 2.7 implies that striving for minimum external heating (Q_h) is equivalent to striving for minimum external cooling (Q_c). The objective of process integration with thermal energy flows is to reduce Q_h.

2.3 Process integration with stationary thermal energy flows

2.3.1 The pinch method

Continuous operation of a production system implies stationary energy flows in the system. In this situation, the principal heuristic method for process-integration is the *pinch method* (Linnhoff and Flower, 1978; Linnhoff *et al.*, 1982; Linnhoff and Hindmarsh, 1983). This method is based on the fact that in many industrial processes hot and cold streams are present. For each stream the following characteristics are determined:

- type: hot or cold (to be cooled and heated respectively)
- initial and target temperature
- the heat flow rate (product of flow rate and specific heat)

The objective of the pinch method is to analyze the hot and cold streams in a production system and subsequently to optimise the heat recovery within the system. The latter is aimed at minimising the required external energy, i.e. the energy required by the production system for heating and cooling purposes. For this a target value is set called *Minimal Energy Requirement* (MER). In determining the MER the presence of a driving force in the heat exchangers is taken into account by defining a minimum temperature difference ΔT_{min}.

To determine the MER, the pinch method uses the concepts of the so-called *Hot Composite Curve*, *Cold Composite Curve*, *Composite Curve* and *Grand Composite Curve*. The Hot Composite Curve and Cold Composite Curve show how much heat is supplied respectively is required at specific temperature levels. This information is combined in the Composite Curve. The Grand Composite Curve is a graph showing the heat that has to be supplied or extracted at specific temperature levels after heat recovery. The use of these curves is illustrated by a demonstration problem which is introduced in table 2.1.

Table 2.1: The data of the demonstration problem (Eastop and Croft, 1990)

	Stream no.	Initial temperature [°C]	Final temperature [°C]	Heat flow rate [kW/°C]
Hot streams	1	200	60	2.0
	2	170	70	4.0
Cold streams	3	40	175	3.0
	4	100	150	4.5

Analyzing this problem leads to the Composite Curve presented in figure 2.1. Note that the Hot Composite Curve and Cold Composite Curve have been shifted horizontally towards each other until the minimum vertical distance between the two curves equals the applied $\Delta T_{min} = 20\ °C$. The point where the minimum vertical distance appears is called *pinch*, provided that above and below this point external heating respectively cooling is required. It should be noted that the pinch is not always present.

From figure 2.1 it follows immediately that at least 90 kW external heating and 140 kW external cooling is required. Note that above the pinch there is a deficit of heat, while below the pinch there is a surplus of heat.

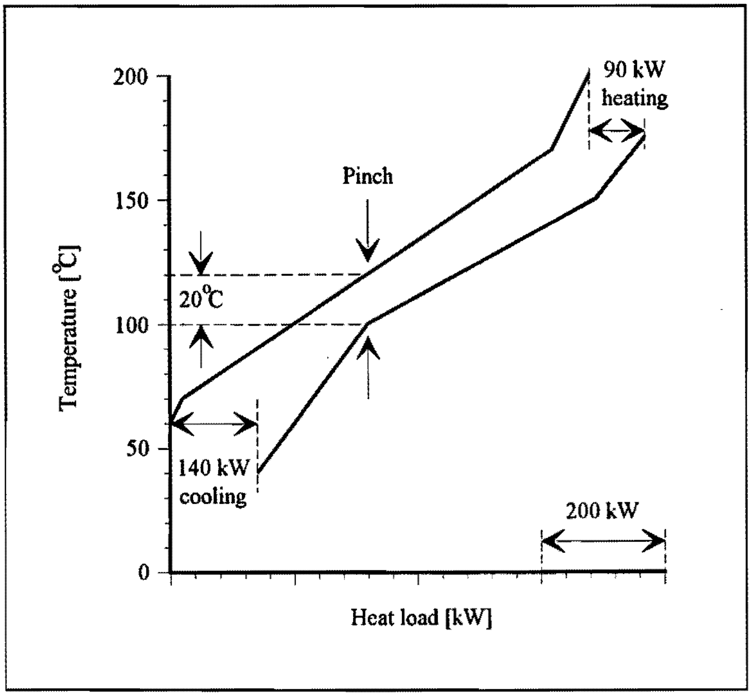

Figure 2.1: The Composite Curve of the demonstration problem (Eastop and Croft, 1990).

If some of the heat available above the pinch is transferred to the external cooling, an extra amount of external heating and cooling is required. This leads to the three rules which must be kept in mind in the design of optimum heat exchanger networks (Linnhoff *et al.*, 1982):

- no heat transfer across the pinch
- no external cooling above the pinch
- no external heating below the pinch

The design of an optimum heat exchanger network is based on these three rules and the knowledge of the stream temperatures at the pinch. This is illustrated by constructing a heat exchanger network for the problem presented in table 2.1.

The first step is to construct a design chart as shown in figure 2.2. This figure shows the streams as horizontal lines between their respective temperature limits and broken by vertical lines representing the pinch. Basically the design process of a heat exchanger network consists of linking the hot streams to the cold streams by heat exchangers. The second rule presented above requires that above the pinch all

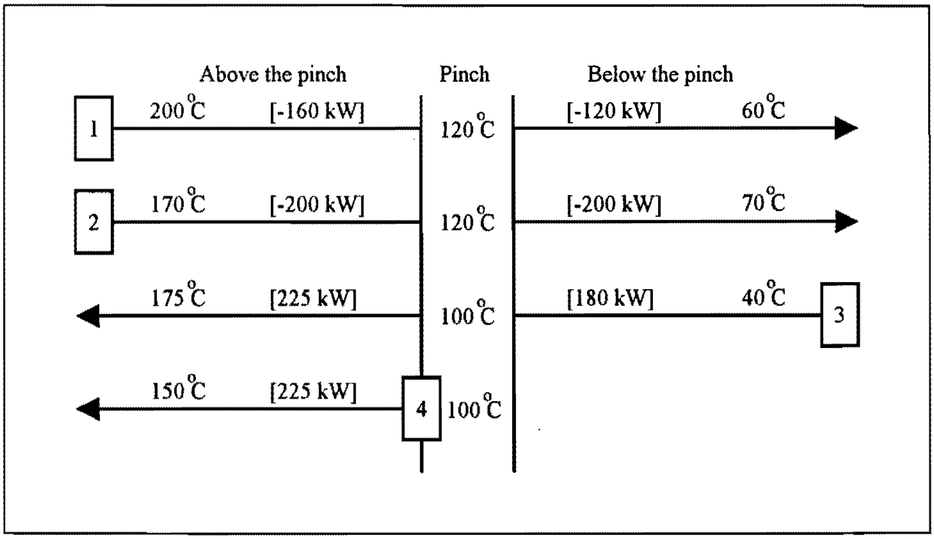

Figure 2.2: The design chart of the demonstration problem (Eastop and Croft, 1990).

hot streams are cooled only by heat exchange with the cold streams. Similarly, the third rule requires that below the pinch the cold streams are heated only by heat exchange with the hot streams. The combination of the three rules implies that the problem of designing a heat exchanger network can be divided into two separate ones: one above and one below the pinch.

To link the hot streams to the cold ones, the influence of a heat exchanger on the temperature profile of the streams near the pinch should be studied first. This influence is shown in figure 2.3. From this figure it becomes clear that if the total heat flow rate of the hot streams (C_h) is less than that of the cold streams (C_c), the minimum temperature difference will occur at the point where the hot streams leave the heat exchanger and the cold streams enter. The opposite is the case if $C_h \geq C_c$. If $C_h = C_c$ then the temperature profiles are two parallel lines. It follows that if the hot and cold streams are to be linked, the following rules should be obeyed:

- $C_h \leq C_c$ above the pinch
- $C_h \geq C_c$ below the pinch

These rules should be applied to each heat exchanger whose inlet or outlet equals the pinch temperature.

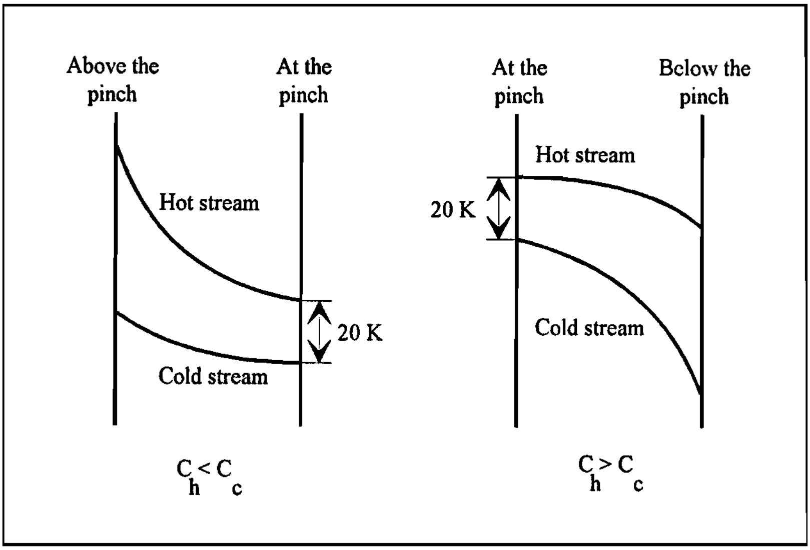

Figure 2.3: The influence of a heat exchanger on the temperature profiles of the streams near the pinch (Eastop and Croft, 1990).

Before the hot and cold streams can be linked to each other, the number of heat exchangers that can be applied to meet the MER condition, has to be determined. In practice one usually wants to minimise this number. The minimum number of units (heat exchangers, heaters, coolers) required to construct a network that meets the MER condition equals S-1, where S is the number of streams (Hohmann, 1971). This relation holds above and below the pinch. Consequently, the heat exchanger network for the demonstration problem should consist of 4 units above the pinch and 3 below. A feasible heat exchanger network for the demonstration problem, which obeys all the rules and limitations imposed by the values of C_h and C_c, is presented in figure 2.4.

It should be noted that the pinch method described above, does not necessarily result in a heat exchanger network that is optimum from an economic point of view. Furthermore, the application of the rules and guidelines described in this section does not always give a feasible result. Occasionally it appears to be impossible to link streams because one or more of the design criteria cannot be satisfied. Usually the splitting of some streams copes with this problem.

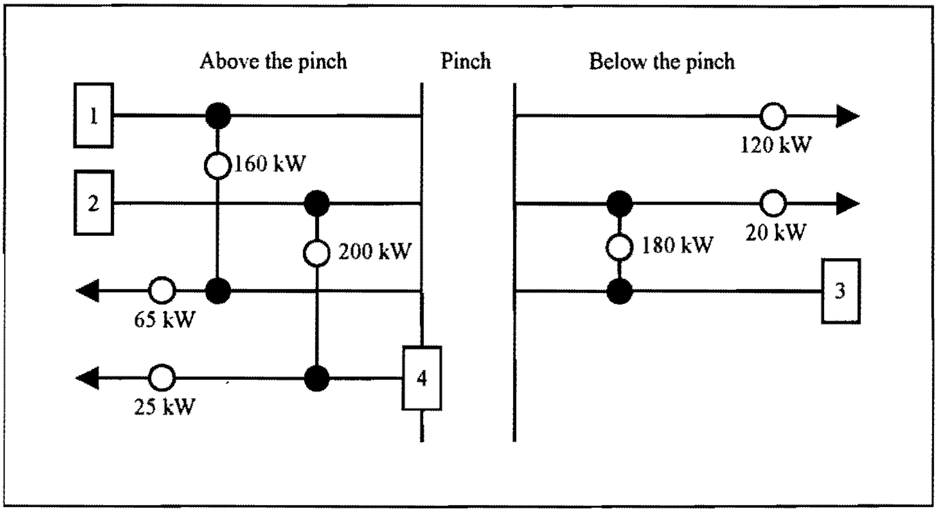

Figure 2.4: A heat exchanger network for the demonstration problem.

So far the external heating and cooling systems have been considered as heat loads of a certain magnitude. The Grand Composite Curve, which is shown in figure 2.5, makes it possible to study the applicability of different types of heating and cooling systems. In the Grand Composite Curve the surplus energy is plotted against the adjusted temperature (thus taking into account the value of ΔT_{min}); at the pinch the surplus is zero.

Several alternative systems are available for external heating and cooling: direct heating or cooling (by means of steam generated by a boiler or by cooling water), heating (and cooling) by means of heat pumps and heating by means of a cogeneration unit. The pinch method gives the following guidelines for the positioning of these systems with respect to the temperature trajectory: direct heating and cooling systems should be placed above respectively below the pinch, taking into account the practical limitations of such systems (e.g. steam available at a specific temperature); heat pumps should be placed across the pinch; heat engines should be placed below the pinch; cogeneration units should be placed above the pinch.

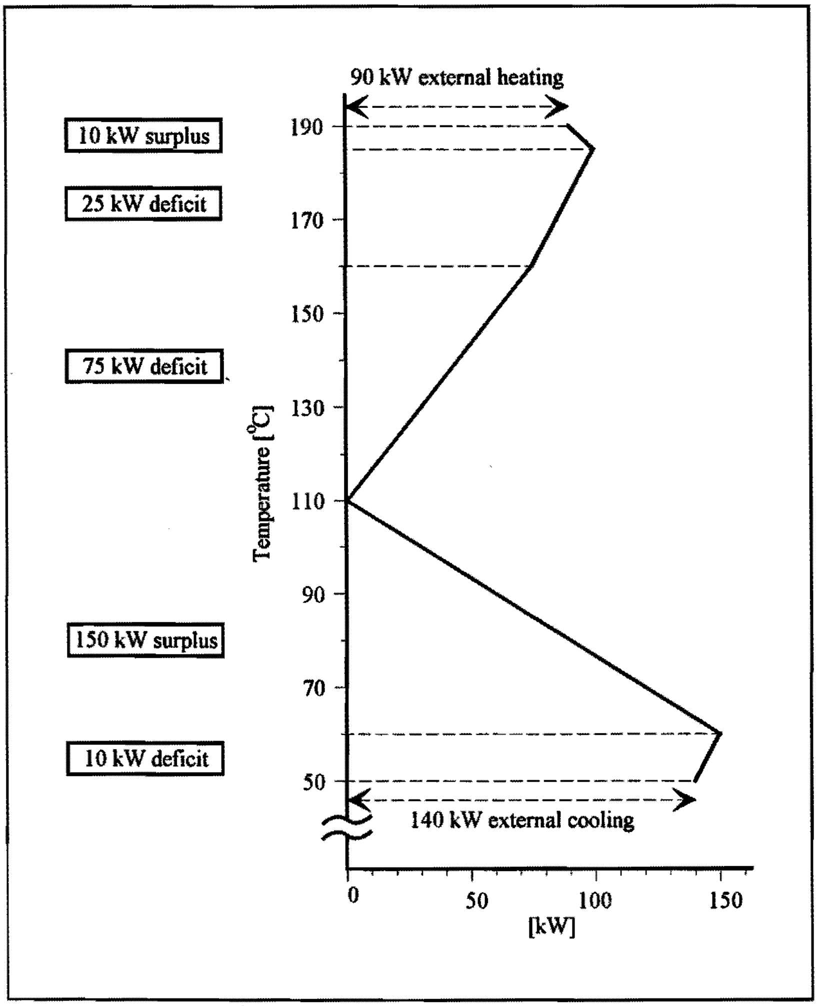

Figure 2.5: The Grand Composite Curve for the demonstration problem.

2.3.2 Mathematical programming methods

Complementary to the pinch method, which is based on physical insights, mathematical programming methods have been developed for the synthesis of heat exchanger networks. The reason for this was that these methods make it possible to automatize the search among the many design alternatives, while explicitly accounting for trade-off between investment and costs (Grossmann, 1992). In this subsection a brief overview is given of the mathematical models that have been developed for this purpose.

The synthesis of heat exchanger networks using mathematical models, commonly relies on the following assumptions (Grossmann, 1992):

- Constant heat flow rates
- Fixed inlet and outlet temperatures
- Constant heat transfer coefficients
- Single-pass countercurrent heat exchangers
- Pressure drops are neglected
- Operating cost is given in terms of the heat duties of the utilities
- Fixed value of ΔT_{min} for all matches

All methods are based on the thermodynamic description of the problem, which is presented in section 2.2. Furthermore, in all methods the heat load Q [kW] of a heat exchanger is calculated using relation 2.8.

$$Q = U A \frac{(T_i - t_j) - (t_i - T_j)}{\ln\left[\dfrac{T_i - t_j}{t_i - T_j}\right]} \tag{2.8}$$

U is the heat transfer coefficient of the heat exchanger [kW/m^2] and A is the effective area of the heat exchanger [m^2]. T_i and t_i are the inlet and outlet temperatures [K] of the hot streams. T_j and t_j are the inlet and outlet temperatures [K] of the cold streams. The cost of a heat exchanger with area A is approximated by relations like 2.9.

$$C = C_f + \alpha A^{\beta} \tag{2.9}$$

C is the cost of the heat exchanger [\$] and C_f is the fixed cost connected to installing the heat exchanger [\$]. The cost-function is characterised by the coefficients α and β ($0 < \beta < 1$). These coefficients have different values for several types of heat exchangers (Hall *et al.*, 1990).

In one of the first publications on the use of mathematical programming for the synthesis of heat exchanger networks (Hwa, 1965), a so-called superstructure is specified which results from combining several alternative network structures. This is illustrated in figure 2.6.

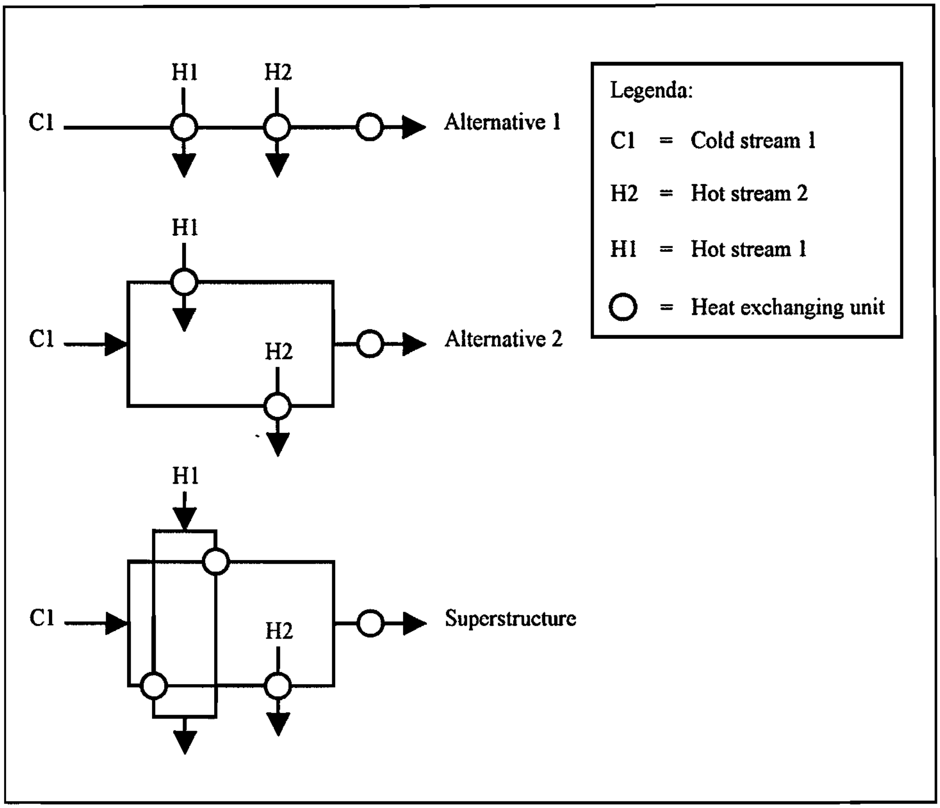

Figure 2.6: The generation of a superstructure (Hwa, 1965).

The superstructure is modelled as a nonlinear programming problem with an objective function based on relation 2.9. By solving the nonlinear programming (NLP) problem, the cost optimum structure is achieved. The major disadvantage of this approach is that it is often trapped into local optimum solutions. Furthermore a number of numerical difficulties are encountered as the areas of the heat exchangers approach zero. Another major problem is how to construct the superstructure so as to guarantee that the optimum design is not excluded.

The synthesis problem can also be formulated as a linear programming (LP) problem (Kesler and Parker, 1969). In this approach the heat content of each stream is subdivided into small chunks. Each match from a hot chunk to a cold chunk is modelled with a heat flow variable. To account for the cost of the required heat exchangers, cost coefficients are assigned to each variable. These cost coefficients are inversely proportional to the heat transfer coefficient and the temperature difference. The disadvantage of this method is that the resulting heat exchanger networks contain a large number of heat exchange units.

The results of the research described above stresses the need for procedures that can explicitly handle discrete decisions. Such a method is the so-called branch and bound optimization procedure. This procedure has also been applied to the synthesis problem (Lee *et al.*, 1970; Rathore and Powers, 1975; Grossmann and Sargent, 1977). The major difficulty with this approach is that heuristic decisions have to be made on how much heat to exchange at each match. Furthermore, stream splitting is disallowed.

The results of the work described in the previous subsection (Linnhoff and Flower, 1978; Umeda *et al.*, 1978) offer the opportunity to include targets for minimum utility consumption into the mathematical approaches. As discussed in subsection 2.3.1, the pinch based methodologies predict target values for the minimum utility consumption, the fewest number of units and the minimum total area. To provide more accurate estimates of these targets, other mathematical methods have been developed. The first method is the LP transportation model (Cerda and Westerberg, 1983; Cerda *et al.*, 1983), which allows the treatment of multiple utilities and forbidden matches. In this approach, the hot and cold streams are modelled as heat sources respectively as heat sinks at different temperature levels. These levels are defined in the same way as in the pinch method (Linnhoff and Flower, 1978). Linear variables are assigned to each thermodynamically feasible match between sources and sinks, and an objective function is defined that expresses the (hot) utility consumption. Minimization of the objective function yields the value of the MER. The significance of this method is that it makes it possible to calculate the MER, taking into account some practical restrictions (forbidden matches, multiple utilities).

Another mathematical targeting method is the so-called LP transshipment model (Papoulias and Grossmann, 1983). In this method, the heat flows supplied by the hot streams are summed for each temperature interval. These intervals are determined in the same way as in the pinch method, albeit that only potential pinch points are considered as interval boundaries. Thus the number of required intervals and consequently, variables is reduced by a factor two (Cerda and Westerberg, 1983). The cold streams are treated in the same way as the hot ones. Similar to the LP transportation model (Cerda and Westerberg, 1983; Cerda *et al.*, 1983) hot and cold streams are treated respectively as sources and sinks. By doing this, heat flow can be treated as a commodity that is transferred through "warehouses" (which physically correspond to the temperature intervals) from the sources to the sinks. Linear variables are assigned to the heat flows between the warehouses. The objective function is defined similar to the one in the transportation model. Optimization again yields the value of the MER. The major advantage of the transshipment model over the transportation model is that the number of variables is reduced drastically.

To predict the fewest number of units, both the LP transportation model and the LP transshipment model can be extended by assigning 0-1 variables for every pair of streams. This results in a mixed integer linear programming (MILP) model. The transshipment model is more suited for this because of its smaller size. The MILP model predicts the fewest number of units, but also which streams are involved in each match and their corresponding heat loads. In practice the prediction of the fewest number of units by the MILP model turns out to be more exact than the prediction by the targeting equation used in the pinch method (Hohmann, 1971).

As discussed at the beginning of this subsection, one of the major incentives for the development of mathematical programming methods for heat exchanger network synthesis was that such methods make it possible to automatize the search for "optimum" solutions. Based on the targeting methods described above, the following procedure was proposed to perform the synthesis of a network (Floudas *et al.*, 1986):

1 Prediction of the minimum utility (cost) using the LP transshipment model.
2 Prediction of the fewest number of units and matches with the MILP transshipment model, subject to the result of step 1.
3 Automatic derivation of the network structure, subject to the results of step 1 and 2, using a NLP model.

The third step is the novel aspect of this procedure. By defining a superstructure and an objective function, optimum network structures are derived. The superstructure includes all possible interconnections for the matches predicted in step 2. In figure 2.7, an example of a superstructure is presented.
The objective function expresses the investment cost of the heat exchanger network, and is based on relations like 2.9. Optimization of this objective function results in a network that satisfies the MER and has the fewest number of units. The most important disadvantages of this approach are that the MILP problem in step 2 may have multiple solutions and that NLP problem may get trapped in local optima. Although some attempts have been made to circumvent some of these difficulties (Floudas and Ciric, 1989; Gundersen and Grossmann, 1990), the real cause could not be eliminated because these approaches also involved sequential optimization.
To solve the problems caused by sequential optimization, three simultaneous design approaches have been proposed. One approach uses simulated annealing (Aarts and

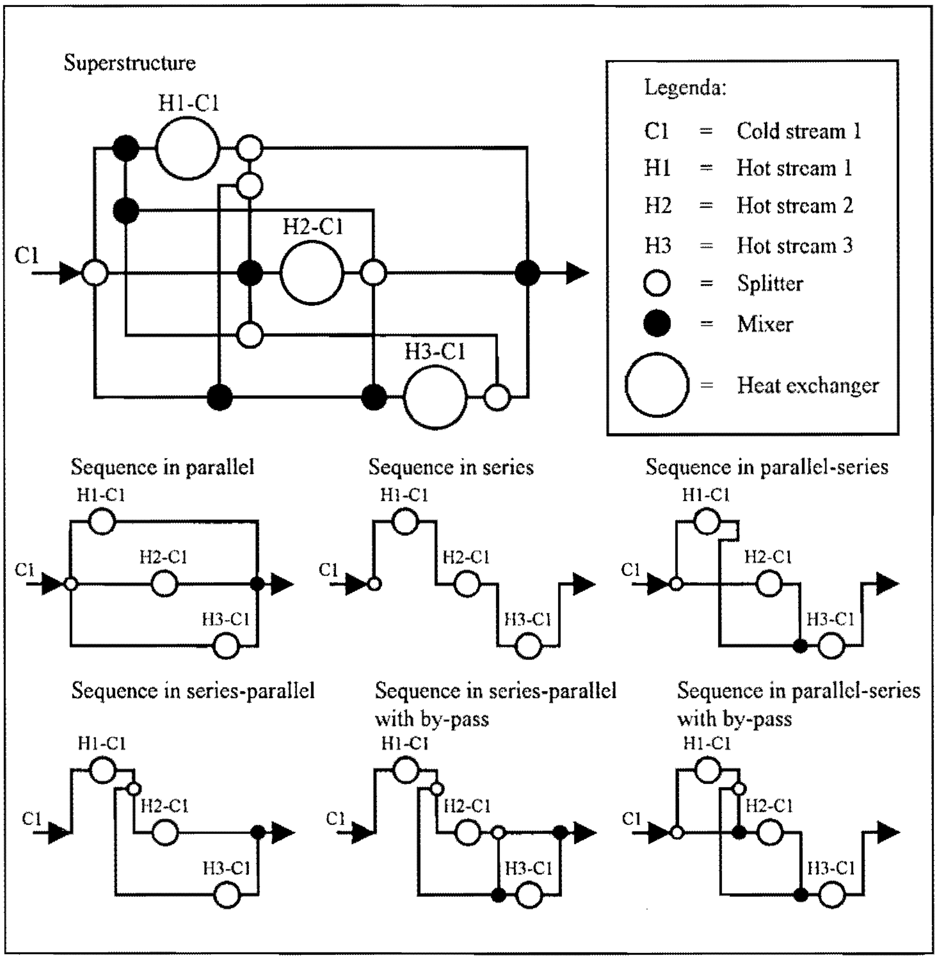

Figure 2.7: The superstructure for 3 matches and some alternative configurations (Floudas *et al.*, 1986).

van Laarhoven, 1985) to optimize the selection of the matches, area and heat recovery simultaneously (Dolan *et al.*, 1989). The major disadvantage of this method is that it is computationally very intensive.

A second approach (Floudas and Ciric, 1989) involves the expansion of the superstructure in order to integrate step 2 and step 3. This leads to a MINLP problem in which 0-1 variables are used to denote the possible existence of units. Despite of the integration of step 2 and 3, part of the sequential character of the synthesis procedure is maintained (step 1).

The third approach (Yee and Grossmann, 1990a, 1990b) optimizes the selection of matches, areas and heat recovery simultaneously, using newly developed MINLP optimization algorithms (outer-approximation methods) and codes (Duran and Grossmann, 1986; Viswanathan and Grossmann, 1990). The basic idea behind this approach is to consider a superstructure in which, in a number of stages, hot and cold flows are successively split and remixed. The main disadvantage of this approach is that not all possible options for steam splitting are embedded in the superstructure and, as for all three approaches discussed above, that no global optimum solutions can be guaranteed.

Besides the well documented methods for heat exchanger network synthesis, another targeting method, the exergy optimization method, has been proposed (Groscurth, 1987; Kümmel *et al.*, 1987; Gool v. *et al.*, 1988; Groscurth *et al.*, 1989). By means of this method, which is basically similar to the LP transshipment model (Papoulias and Grossmann, 1983), a target value for the minimum primary energy consumption of a production system can be calculated, taking into account the possibilities of heat recovery by a heat exchanger network (similar to the transshipment and transportation model) and heat pumps, heat generation by a boiler, heat and electricity generation by a cogeneration unit and electricity generation by a public utility. In this approach temperature intervals are determined in the same way as in the transshipment model. To each interval a so-called quality level is assigned (Gool v., 1987). By means of these quality levels the temperature intervals are implicitly embedded in the optimisation model. Hot and cold streams are, again similar to the transshipment model, modelled as heat sources and sinks. A linear objective function is defined that expresses the primary energy consumption of the production system. This objective function can be optimised by standard LP codes. As stated before, this method calculates a target value for the minimum primary energy consumption of a production system taking into account a wider range of process integration opportunities than the pinch method and the mathematical approaches discussed in the previous two subsections. The latter methods however, are not only aimed at predicting a target value, but are also aimed at the synthesis of a heat exchanger network. This is a major disadvantage of the exergy optimization approach. Although it predicts a target value, it does not indicate how this target should be realized in practice.

2.4 Process integration with non-stationary thermal energy flows

2.4.1 Introduction

In the case of batch processes, process integration is complicated, because (Kemp and Macdonald, 1987):

- not all streams coexist simultaneously
- the possibility of rescheduling can be considered
- batch plants are often multi-product, so several different flowsheets may have to be considered
- process integration may reduce flexibility

Process integration in batch processing and the resulting consequences for the scheduling of the production system, is much less studied than the equivalent problem in the continuous case. Similar to the methods described in the previous section, heuristic and mathematical programming methods can be distinguished.

2.4.2 Heuristic methods

The principal heuristic method for process integration with non-stationary energy flows is based on the pinch method (see section 2.3.1). In fact two approaches have been presented (Obeng and Ashton, 1988): The *Overall Plant Bottleneck* approach (Linnhoff *et al.*, 1988) and the *Time Temperature Cascade* approach (Kemp and MacDonald, 1987, 1988).

Overall Plant Bottlenecks (OPB) are defined as bottlenecks which prevent a plant reaching its achievable performance. Any plant is likely to have several OPB's related to e.g. throughput, yield, effluent flow, labour requirements and energy. In the case of an energy OPB, an analysis can be carried out using the *time average model* and the *time slice model.* In the time average model, time is ignored as constraint, and the energy sources and sinks are averaged over a chosen period. This makes it possible to treat this problem in the same way as in the case of continuous processes.

The time slice model takes account of time as a limiting constraint by "slicing" it into periods during which energy flows are constant. In each period, the flows can be analyzed using techniques eventually developed for continuous plants.

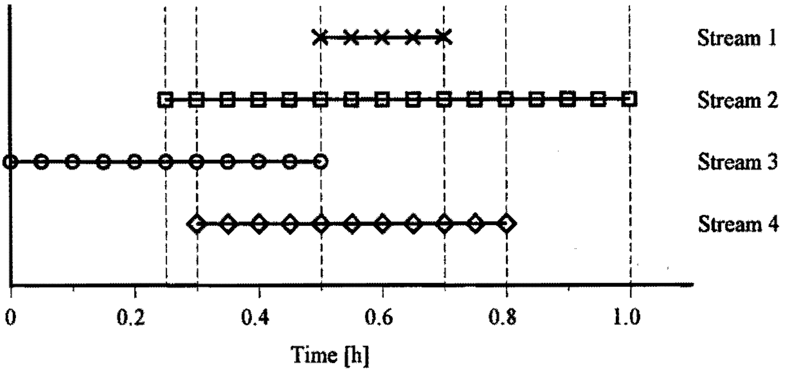

Figure 2.8: The time slices for the demonstration problem (Obeng and Ashton, 1988).

The analysis of an OPB using the time averaged model and the time slice model is illustrated by means of a demonstration problem. The data of this demonstration problem are presented in table 2.2.

Table 2.2: The data of the demonstration problem (Obeng and Ashton, 1988).

Stream no./type	Supply temp. [°C]	Target temp. [°C]	Start time [h]	Finish time [h]	Cp [kW/°C]
1 Cold	20	135	0.5	0.7	10
2 Hot	170	60	0.25	1	4
3 Cold	80	140	0	0.5	8
4 Hot	150	30	0.3	0.8	3

Analyzing this problem with the time average model reveals that a hot utility target of 20 kWh could be obtained. The time slice model subdivides the total period of operation into slices, as is illustrated in figure 2.8.

Clearly six time slices are present in the demonstration problem. For each of them the possibilities for heat recovery can be studied using the methods developed for the continuous case. Summing the utility targets for all time slices gives a total hot utility target of 198 kWh. This target can be reduced by considering changes to the initial scheduling. These changes should be aimed at obtaining more coincidence between the streams. This can be achieved either by starting earlier or later, or (if

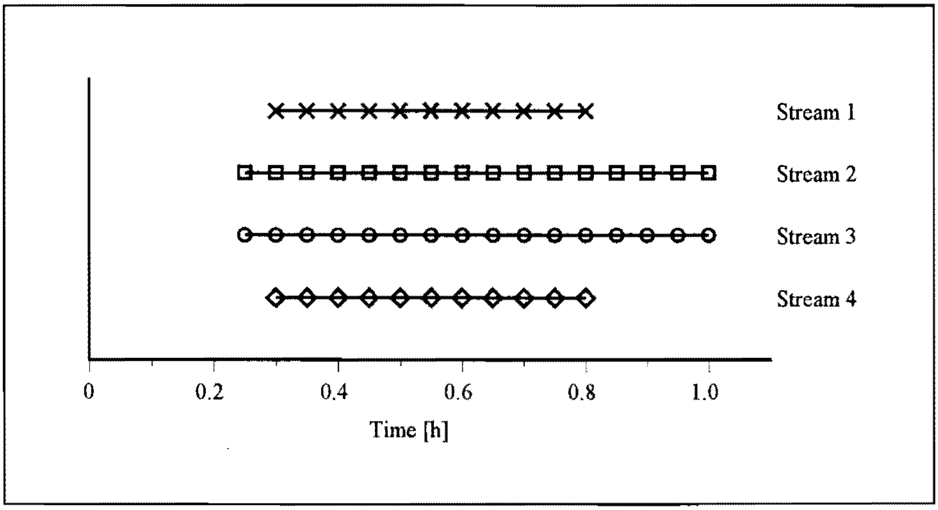

Figure 2.9: The revised schedule for the demonstration problem (Obeng and Ashton, 1988).

possible) by the speeding up or slowing down of streams. If all opportunities for rescheduling can be used, the time slice method yields the same target values as the time average method. In figure 2.9 an example is presented of a revised schedule.

The Time Temperature Cascade (TTC) approach is more or less similar to the OPB approach combined with the time slice model. Similar to this model, the problem is divided into time intervals. The TTC approach is aimed at studying the possibilities for heat recovery by transferring heat from one time interval to another by means of storage. In fact, the TTC approach allows heat flows to be time cascaded and temperature cascaded. This means that besides the temperature pinch, which can be identified for each time interval, also a time pinch can be determined. Before the time pinch net heat must be added to the process, after the time pinch net heat must be subtracted. The two assumptions underlying the TTC approach are that the process schedule is fixed, and that direct heat recovery is always preferable to energy storage.

Application of the TTC approach yields a target hot utility consumption of 134 kWh and a value of 64 kWh for the minimum heat storage required to achieve this target. In the case of repeated batches, the TTC approach yields a hot utility target of 20 kWh. This is identical to the results of the time average model.

It should be noted that adding heat storage devices to a process may prove to be very difficult, depending on the process itself (instability of materials to be stored), plant safety aspects (accumulation of hazardous materials) and process economics (Espuña *et al.*, 1990).

Both the OPB and the TTC approach can be applied to calculate an energy target for a specific situation. Neither of these approaches is able to indicate how these targets can be realised in practice.

Besides the pinch based approaches described above, another method has been developed (Vaselenak *et al.*, 1986) which is in fact a mixture of heuristic rules and mathematical programming. This method focuses on heat transfer between the fluids in batch tanks. Two types of heat exchange are investigated, which are similar to the usual cocurrent and countercurrent continuous case. The cocurrent case corresponds to the situation where the fluids in both the hot and cold tank are withdrawn for heat exchange and then returned to the source tank. The countercurrent case corresponds to the situation where the fluids are transferred to separate tanks after heat transfer. For the cocurrent case a heuristic is given to determine the processing order of exchanges when multiple hot and/or cold batches are present. For cases in which the desired final temperatures limit some of the exchanges (i.e. the ΔT_{min} constraint becomes active before the desired temperature has been reached), a MILP formulation is proposed. The objective in this formulation is to maximise the sum of the heat exchanged in each match. In both the heuristic and MILP approach it is assumed that a batch cannot be split, meaning that only one-to-one matches are allowed. Furthermore it is assumed that the exchange of heat can be carried out at any moment, thus neglecting the intermittent character of the batch steams which is caused by the scheduling of the batch operations.

2.4.3 Mathematical programming approaches

Process integration of batch processes by means of mathematical programming has been studied only recently (Reklaitis, 1989; Lee and Reklaitis, 1990; Papageorgaki and Reklaitis, 1991). A mixed integer linear programming formulation has been proposed (Lee and Reklaitis, 1990; Papageorgaki and Reklaitis, 1991) to determine the operating schedule for maximum heat integration between the batch streams in a single product production system. This problem is studied for the case where intermediate storage of heat is not applicable. It is assumed that only the starting time of batches can be changed, thus neglecting the possibility of speeding up or slowing down certain batches. Furthermore it is assumed that each stream can be matched only once during each cycle. This approach makes it possible to take the subsequent character of batch production into account (batch i must precede batch $i+1$, etc.), as well as restrictions with respect to the holding time of every specific batch. The proposed formulation attempts to identify an optimal heat integration pattern for a sequence of N batches, where the value of N can be calculated with respect to the number of stages (tasks) M in the production system and the operating

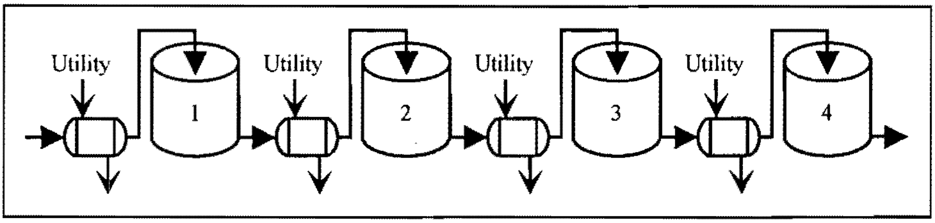

Figure 2.10: A simplified batch process consisting of four batch units (Lee and Reklaitis, 1990).

mode of the processing units (in and out of phase).

The applicability of the proposed formulation is illustrated by the following demonstration problem (Lee and Reklaitis, 1990; Papageorgaki and Reklaitis, 1991). Consider the simplified batch process presented in figure 2.10. The data on the thermodynamic properties of the input stream and the processing time of each batch unit are presented in table 2.3.

Table 2.3: The data on the thermodynamic properties of the input stream and the processing time of each batch unit (Lee and Reklaitis, 1990).

Unit. no.	Heat flow rate [kW/°C]	Initial temperature [°C]	Desired temperature [°C]	Status hot/cold	Processing time [h]
1	1.8	202	90	hot	2
2	1.0	138	250	cold	4
3	2.1	128	240	cold	1
4	1.6	208	80	hot	3

If the production of only three batches is considered, the input stream of batch unit 3 (cold) during the first charge, can be matched to the input stream of batch unit 1 (hot) during the third charge by scheduling their transfers to occur simultaneously. Given the minimum approach temperature ΔT_{min} = 10°C, 115.2 kW of heat can be exchanged in this match. The input stream of the first batch with batch unit 4 (hot) and the input stream of the third batch with batch unit 2 (cold) can be matched. 60 kW of heat can be exchanged in this match. In order to satisfy this second match, the no intermediate storage with holding time transfer rule is assumed to apply. Since heat losses are neglected, 175.2 kW of heat is transferred in the two matches. The resulting schedule for this demonstration problem is presented in figure 2.11.

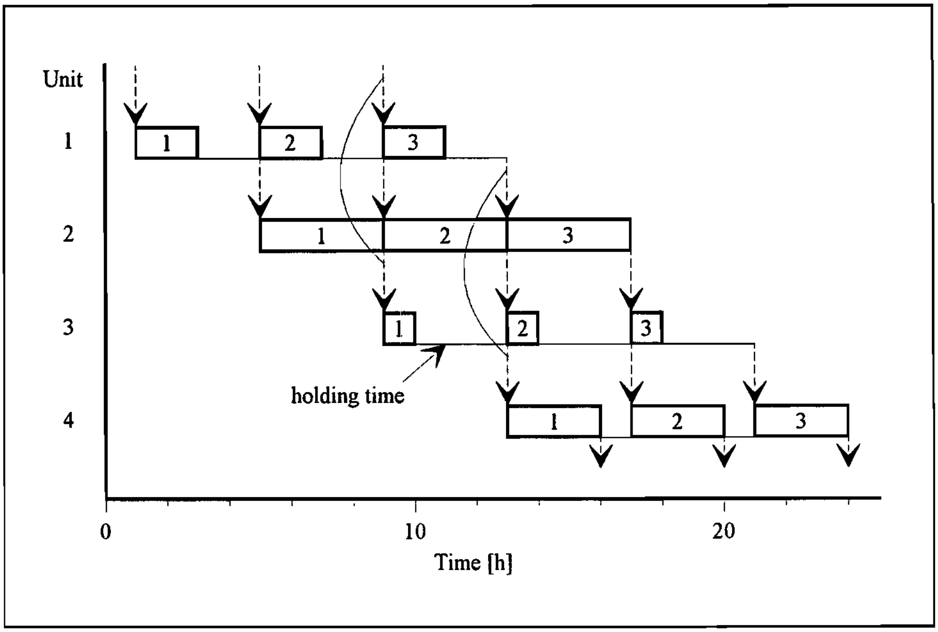

Figure 2.11: The schedule for the demonstration problem (Lee and Reklaitis, 1990; Papageorgaki and Reklaitis, 1991).

2.5 Gaps in the literature

In chapter 1 it is mentioned that this study is aimed at giving decision support in identifying and evaluating novel, more energy efficient production systems. These activities take place during the design process of such production systems. Analysis of general design methodologies reveals that the design process contains five phases (Cross, 1984, 1989; Ray, 1985; Suh, 1990; Svensson, 1976):

- Recognition of societal need
- Specification of functional requirements and constraints
- Mapping of the functional requirements on a physical domain, i.e. identification of alternatives
- Evaluation of the alternatives
- Selection of an alternative

In the first phase decision makers recognise that a new production system is required that is more able to cope with the needs from society. In the second phase it is specified what this production system should be able to do (e.g. production of a specific commodity from a set of raw materials) and which constraints are imposed on this (e.g. production of a certain amount of a commodity within a certain time-span using a minimum amount of energy). The third phase involves a creative process during which it is determined how the functional requirements and constraints can be satisfied, i.e. in this phase alternative production systems are identified. In the evaluation phase all alternatives are evaluated with respect to a number of criteria. This should provide sufficient information to select one of the alternatives (fifth phase). The five phases described above can be traversed in a serial or serial-parallel way, depending on the design methodology that is chosen by the decision makers. Feedback-loops may also be present.

This study is focused on the development of a tool that may support those decision makers in the third and fourth phase of the design process. With respect to the third phase, the following gaps in the literature can be discerned (given the problem formulation of this study and the review in the previous sections):

- No decision support in the identification of novel processes is given.
- The process integration techniques discussed in the previous sections are applicable only in existing production systems. They are not able to take the application of alternative processes into consideration.
- The influence of sequential decision making on the design of a total production system and, consequently, on its specific energy consumption, has not been studied.
- The influence of the periphery on the design of a production system and, consequently, on its specific energy consumption has not been studied.

The part of the tool that is described in chapter 3 of this thesis is aimed at filling these gaps. It provides a systematic framework by means of which decision makers can be guided through the creative process that is required for the third phase. Firstly, a systematic approach is described by means of which the specified functional requirements can be mapped on a physical domain. Thus the decision maker can identify alternatives for "parts" of his production system. Since multiple alternatives may be available for each task, the question arises which combination of alternatives is the best from an energy point of view. In determining this combination, the energy conservation potential of process integration has to be taken into account. Another question that arises is whether it is sufficient to select optimum alternatives and to apply process integration afterwards. Yet another interesting question is how the periphery of a production system influences the structure of that system and, consequently, its specific energy consumption. To answer these questions, a mathematical programming method is presented. This part of the tool is strongly linked to the process integration methods described in the previous sections. Since the exergy optimization approach is the only approach that is able to take several process integration options into account simultaneously, this approach has been adapted and extended.

With respect to the fourth phase, the following gap in literature can be discerned (given the problem formulation of this study and the review in the previous sections):

- The evaluation of alternatives is mostly based on a single cost related criterion. Other criteria like technical and managerial ones are not taken into account.

The selection of a new production system is of high strategic importance to a company, since it determines to a large extent its long term profitability. A fundamental problem that arises in making such a selection, is that the future is uncertain to a large extent. Due to this, the selection of an alternative on the basis of an evaluation with respect to a single cost related criterion is at the least doubtful, certainly if this evaluation is performed using cost estimates (e.g. by means of cost-functions). To take a more deliberate decision, other criteria like technical and managerial ones have to be taken into account as well (Suh, 1990). This raises the question of how the selection of energy efficient production systems is influenced by other than energy or cost related criteria. To answer this question and to fill the gap mentioned above, a multiple criteria evaluation method is adapted and extended in chapter 4 of this thesis.

Chapter 3

The identification of production systems

3.1 Introduction

In this chapter a tool is presented that may support decision making in the *identification* of a set of *production systems*. Each system has to be able to perform its task, i.e. has to be able to produce a certain amount of a commodity within a certain time-span). The tool is focused on the identification of that production system which uses a minimum amount of (fossil) fuel per unit of product.
In section 3.2, the framework underlying the tool is introduced. The system boundary of the production system, its subsystems and their elements are identified and modelled. Subsequently, a qualitative approach towards the identification of alternative production systems is introduced in section 3.3. To identify the most energy efficient production system, building blocks for a mathematical formulation are derived and presented in section 3.4. By applying six so-called design strategies, which are introduced in section 3.5, the energy conservation potential can be estimated, taking into account the effect of sequential decision making. Subsequently, some extensions of the mathematical formulation are presented in section 3.6. In section 3.7, some interactions between the production system and its periphery are discussed. The tool presented in this chapter is illustrated by a demonstration problem which is treated in section 3.8.

3.2 A general production system

3.2.1 The structure of a general production system

In this study, a *production system* is defined to be the set of unit operations and their mutual relations, which are present at a specific location and which are directly or indirectly involved in the transformation of a specific set of raw materials into a commodity (or family of commodities). In practice, a production system as defined above, corresponds to a plant. This implies that the *system boundary* of a production system is defined to be at plant-level. Within this system boundary, *subsystems* are identified. The decomposition of the production system into subsystems is based on the different processes acting upon the energy flows passing through the system. In the case of flow processes (stationary energy flows), three different kinds of processes can be discerned, resulting in a division into three subsystems. The

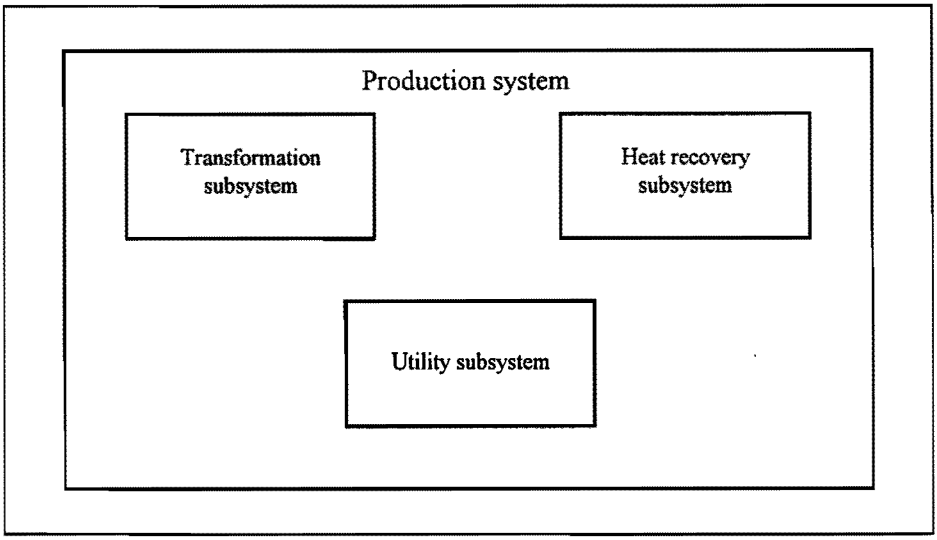

Figure 3.1: The production system and its subsystems.

transformation subsystem transforms the raw materials into the desired commodity by using energy. The *utility subsystem* makes energy available to the other subsystems in the right quality and quantity. In the *heat recovery subsystem*, residual heat is recovered. The three subsystems are shown in figure 3.1.

Each subsystem can be divided into elements. In this study, the elements of the transformation subsystem are the *production unit operations*. Each production unit operation performs a specific task in transforming the raw materials into the commodity. This is illustrated in figure 3.2.

Thermal and electrical energy flows are dominant in most production systems. Therefore, *boilers* and *combined heat and power (CHP)-units* are important elements of the utility subsystem. In this thesis, they are considered to be the only elements of this subsystem, although other devices (e.g. fuse box, transformer unit, gas pressure control system) may be present. However, compared to a boiler or a CHP-unit, such devices generally have a negligible contribution to an energy conservation potential. In this study they are therefore not considered to be elements of the utility subsystem.

In a boiler (fossil) fuel is burned to generate heat at specific temperature levels. A CHP-unit generates both heat and electricity, again by burning (fossil) fuel.

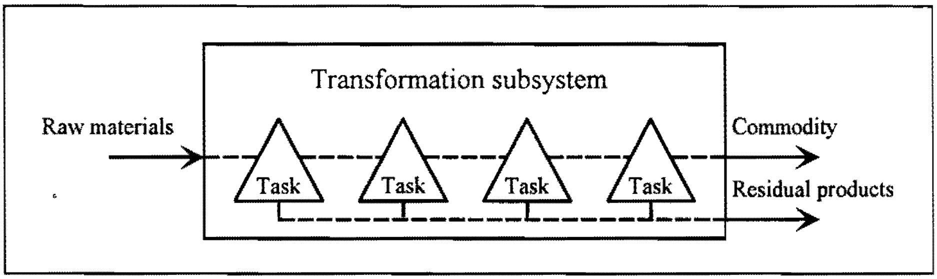

Figure 3.2: The transformation of the raw materials into the desired commodity.

The heat recovery subsystem recovers leaving energy flows by means of *heat exchangers* (passive elements) and *heat pumps* (active elements). An active element needs input of external energy to operate, a passive one does not. In this study only electrically driven heat pumps are taken into account.

To design an optimum production system from an energy point of view, the choice of the production unit operations has to be attuned to each other, and to the possibilities of designing the other two subsystems. From systems theory (Mesarović *et al.*, 1970) it follows that an optimum system generally contains non-optimum subsystems and elements. This complicates the problem of designing "optimum" production systems, since it implies that it is insufficient to sequentially select optimum elements for each subsystem. The tool presented in this chapter facilitates a study of the influence of sequential decision making on the design (choice of unit operations) and, consequently, on the specific energy consumption of a production system.

The structure of a production system as presented in this subsection applies to virtually all production systems. In the case of batch processes, a fourth subsystem will be present: the *control subsystem*. This subsystem controls the starting and ending times of the different batches.

3.2.2 The modelling of a general production system

The production system, its subsystems and their elements are modelled, using the black box approach. Since this study is focused on industrial energy conservation, the models incorporate the mass and energy flows involved in the production of commodities. Furthermore, only available energy (exergy) flows (Gool v., 1987; Hedman, 1981; Moore, 1981; Szargut *et al.*, 1988; Wall, 1986) are incorporated in the models. It should be noted that mass and energy flows, although treated separately, may be physically combined in practice. To illustrate the applied modelling approach, the model of a general production system is shown in figure

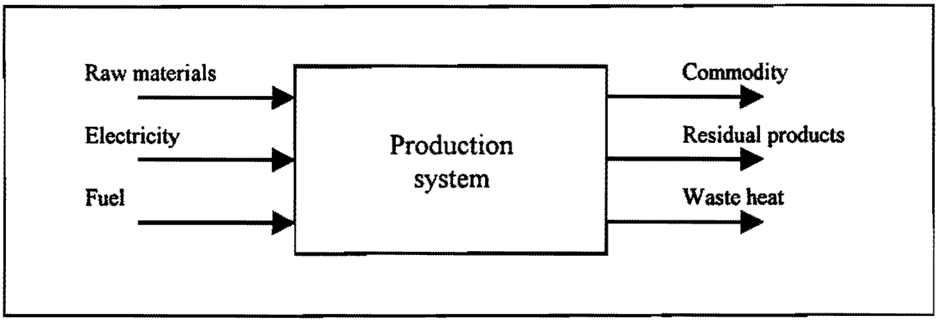

Figure 3.3: The model of a general production system.

3.3. According to the first law of thermodynamics, the energy entering a production system (in the shape of fuel, electricity or heat) is conserved. However, according to the second law of thermodynamics, the leaving energy (in the shape of residual heat and/or surplus electricity) has been degraded with respect to the entering one (Moore, 1981).

The modelling approach described in this subsection is validated by the results of other studies (Hedman, 1981; Boustead and Hancock, 1979; Brown *et al.*, 1985).
The models of the subsystems described in this subsection, can be integrated into a so-called plant-overview model which is presented in figure 3.4. This model includes the relations generally present between the mass and energy flows entering and leaving the three subsystems. The model enables the study of the mass and energy flows in production systems on a high level of aggregation. It visualizes the function of the three subsystems, and the ways in which they are related to the inputs and outputs of a general production system.

3.2.3 The determination of the energy characteristics

Consider the data of the energy flows of a production unit operation, shown in table 3.1. The energy content H of the heat flows (referenced to the ambient temperature T_0), can be calculated using relation 3.1.

$$\begin{aligned} H &= \dot{m} c_p (T - T_0) \\ &= C_p \Delta T \end{aligned} \tag{3.1}$$

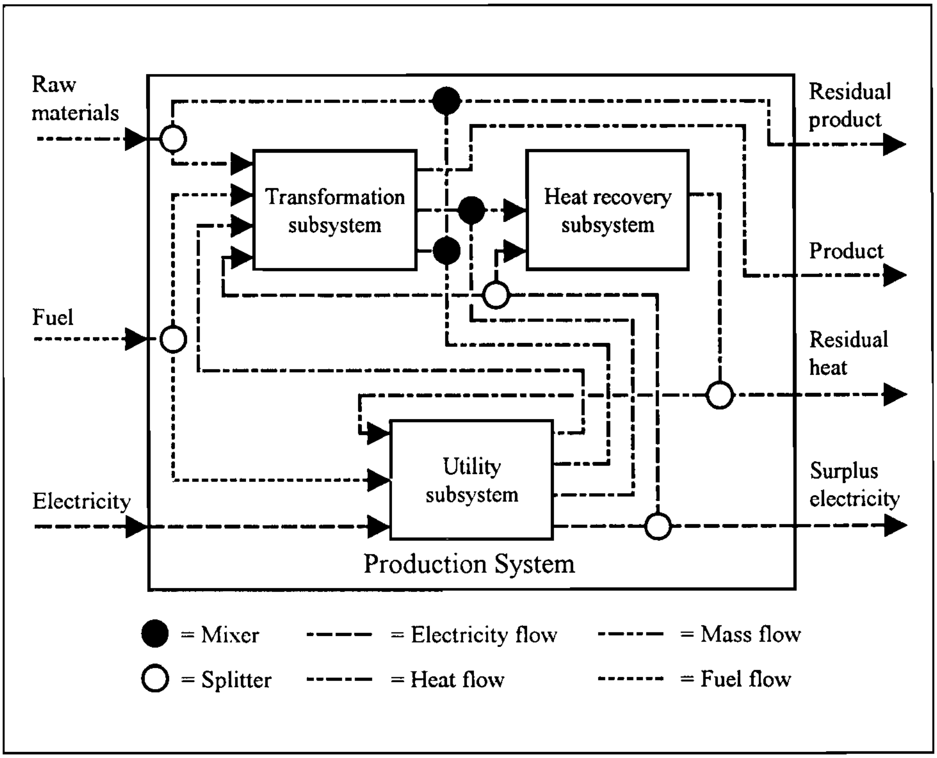

Figure 3.4: The overview model of a general production system.

In relation 3.1, $\dot{m}$ is the mass flow of the energy carrier [kg/s], c_p is its specific heat [kJ/kgK], T and T_0 are respectively the temperature of the flow and the reference temperature [K], $C_p = \dot{m}c_p$ is the heat flow rate [kW/K], and $\Delta T = T\text{-}T_0$ is the temperature difference [K]. The energy content of the different flows is shown in table 3.1.

Table 3.1: The data of the energy flows of the example unit operation

	Cp [kW/K]	T [K]	H [kW]	Electrical power [kW]
heat1-in	3	450	480	-
heat2-in	2	350	120	-
heat1-out	3	380	270	-
heat2-out	2	330	80	-
heat3-out	1	340	50	-
El. power in	-	-	-	100

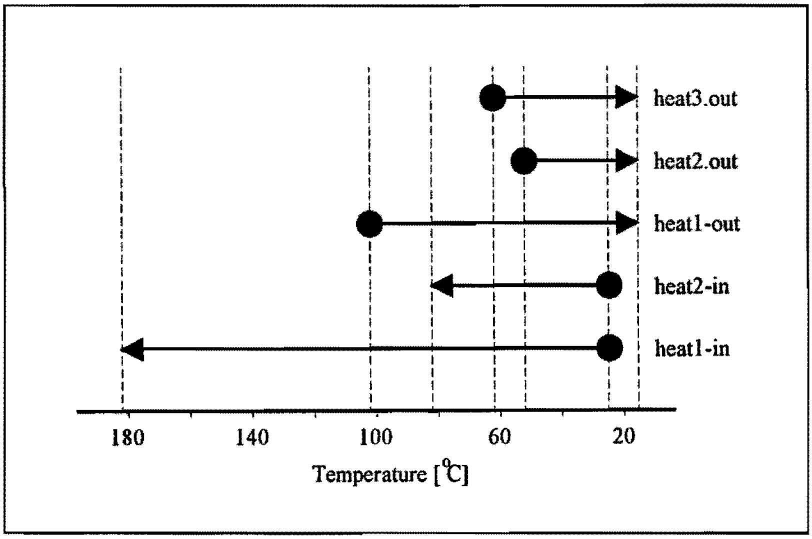

Figure 3.5: The arrow diagram for the example production unit operation.

In figure 3.5, a so-called arrow diagram (Lambert, 1991), the heat flows entering and leaving the production unit operation are represented as arrows from the right to the left, respectively from the left to the right. It is assumed that in principle each entering/leaving heat flow is heated/cooled from/to the ambient temperature T_0. The length of the arrows corresponds to the temperature interval that has to be covered.

A heat flow leaving a production unit operation can be cooled to its target temperature by exchanging heat either to the entering heat flows or to a cold utility (e.g. cooling water); an entering heat flow can be heated to its target temperature by exchanging heat either from leaving heat flows or from a hot utility (e.g. steam). To exchange heat from a leaving heat flow to an entering one, heat exchangers can be applied if the temperature of the leaving flow is higher than the temperature of the entering one. In the opposite case, heat pumps are applicable. In practice, heat flows are sometimes transferred directly from one production unit operation into the other; i.e. no external heating or cooling is required. This situation is treated as a heating/cooling process with a heat exchanger with a heat exchanging area of zero square meter.
To ensure the presence of a driving force in the devices exchanging heat between entering and leaving heat flows, a minimum temperature difference has to be taken into account (Linnhoff *et al.*, 1982; Linnhoff and Hindmarsh, 1983). For this purpose, the entering and leaving heat flows are shifted up and down respectively,

on the temperature scale. In practice, values of +5 K and -5 K are often chosen because of economical reasons. These values are also chosen in this study.

A shortcoming of the arrow diagram is that the demanded electrical power cannot be incorporated. This means that it cannot represent the complete information on the energy characteristics. To cope with this problem, the concept of *quality of an energy carrier* is introduced. Since exergy is that part of an enthalpy flow that can be transferred into useful work (Moore, 1981; Gool v., 1987; Szargut, 1988), a quality level q can be defined by relation 3.2:

$$q = \frac{\text{exergy flow}}{\text{enthalpy flow}} \tag{3.2}$$

In the case of heat supplied or demanded in a temperature interval, this can be elaborated to yield (Moore, 1981):

$$\begin{aligned} q &= \frac{1}{T_h - T_l} \int_{T_l}^{T_h} (1 - \frac{T_0}{T}) dT \\ &= 1 - \frac{T_0}{T_h - T_l} \ln \left[\frac{T_h}{T_l} \right] \end{aligned} \tag{3.3}$$

T_h and T_l are the highest and the lowest temperature in the interval under consideration. T_0 is the reference temperature. If the heat is supplied or demanded at a constant temperature (e.g. in the case of infinite heat sources and sinks), q is equal to the Carnot efficiency. For heat $0 < q < 1$, for electrical and mechanical energy $q = 1$ and for (fossil) fuels $q \approx 1$ (Gool v., 1987).

The definition of the quality level offers the possibility of representing the heat characteristics and the electricity characteristic on two diagrams: The extended *Hdq* and *Hsq* diagram (enthalpy *H* *d*emanded respectively *s*upplied at quality level *q*). The former shows the energy characteristics of the entering energy flows, the latter the ones of the leaving flows. The two diagrams are constructed in the same way. To each temperature interval from figure 3.5 a quality level q is assigned using relation 3.3. The energy flows entering/leaving the production unit operation at each quality level are shown in the extended *Hdq/Hsq* diagram as accumulated bars. The total length of each bar represents the total energy flow demanded/supplied on that quality level. Each bar is subdivided in parts, representing each individual flow.

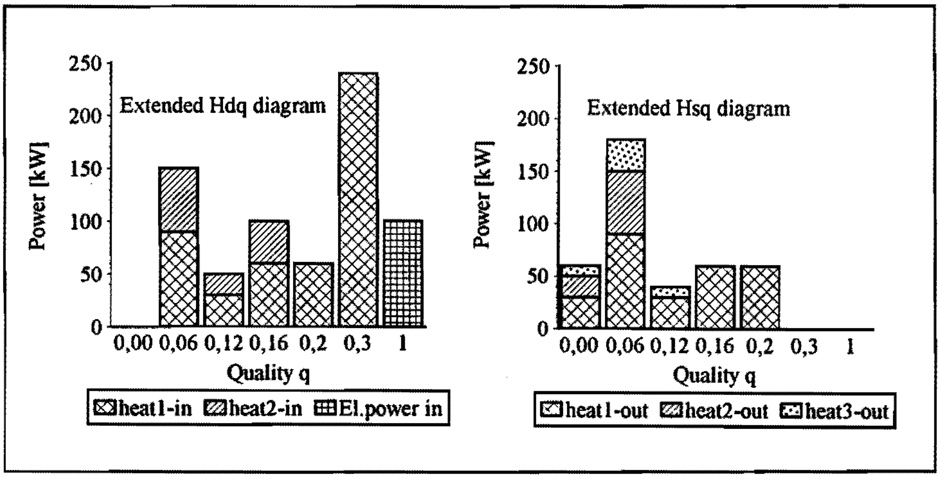

Figure 3.6: The energy characteristics of the production unit operation.

The extended *Hdq* and *Hsq* diagram for the example production unit operation are shown in figure 3.6. They are an analysis instrument for the energy characteristics of a production unit operation (or a set of production unit operations). The information in figure 3.6 is complementary to that in figure 3.5: Only after figure 3.5 has been constructed and the temperature intervals have been determined, can the extended diagrams be obtained.

3.3 The identification of alternative production systems

3.3.1 Introduction

Whenever a (new) production system is (re-)designed, decision makers are faced with problems concerning the identification of alternative production unit operations. These may be based on alternative technological concepts which are also applicable in the system (Cross, 1984, 1989; Jones, 1973; Suh, 1990). This problem is particularly emphatic if a shift in applied technology, such as indicated in figure 1.2, has to be realised. In that case the real problem is to identify the different technological concepts that can be applied. To simplify this identification, the use of a list of so-called elementary tasks is described in this section. Each elementary task represents the essentials of the transformation performed by a production unit operation. By analyzing a production system into elementary tasks, the function (within the total system) of the currently applied production unit operations can be aggregated. Subsequently, the search for novel, innovative production unit operations begins. This results in a stock-taking of alternative production unit operations for each elementary task.

Each production unit operation may be characterised by several characteristic numbers such as throughput, yield, energy consumption, reliability etc. By imposing constraints on such characteristic numbers, the decision maker can make a pre-selection from the (combinations of) production unit operations. Thus, infeasibility of production systems containing specific (combinations of) production unit operations is avoided beforehand.

3.3.2 Elementary tasks

A possible list of elementary tasks is presented in appendix 3. Each elementary task represents the essentials the transformation performed on the mass flows by a certain production unit operation. The list is meant to be a decision support tool in aggregating the function of currently used production unit operations. Although it is quite comprehensive, it is not claimed that the list is complete.

In this thesis *transformation* is defined as a change in the state variables of a mass flow (Ayres, 1978). Within this definition a distinction can be made between transformations of extrinsic and intrinsic state variables. Transformation of extrinsic state variables involves transformations in place and time of mass flows, i.e. logistical activities (transport, storage). The tasks involving transformations of extrinsic state variables are subdivided into two task-categories:

- transformation in place
- transformation in time

In appendix 3 a number of technological concepts that can be used to perform these tasks are listed.

The tasks involving transformations of intrinsic state variables of the mass flows are subdivided into five task-categories:

- mixing
- separation
- transformation in shape
- transformation of chemical properties
- transformation of physical properties

Mixing and separation do not change the chemical or physical properties of the involved partial mass flows. Only the spatial distribution of the involved substances

is changed. In the case of mixing the distribution becomes more homogeneous, while in the case of separating it becomes more heterogeneous.
Transformation in shape involves a change in the spatial dimensions of a mass flow. For tasks involving transformations of chemical and physical properties separate task-categories are defined. All five task-categories of transformations of intrinsic parameters are divided into sub-categories. These are presented in appendix 3 together with a number of technological concepts that might be applicable to perform these tasks.

3.3.3 The use of the list

In order to achieve reasonable results the following 6 steps have to be taken sequentially:

Step 1	Determine upon which technological concepts the production unit operations in a current production system are based.
Step 2	Aggregate the results of the first step to elementary tasks.
Step 3	Search for alternative technological concepts by segregating the elementary tasks.
Step 4	Search for alternative production unit operations based on the technological concepts found in the third step.
Step 5	Eliminate those (combinations of) production unit operations which are not applicable in the specific case under consideration.
Step 6	Generate alternative production systems by combining the feasible production unit operations.

The purpose of the first and second step is to stimulate decision makers to reflect on the function of currently applied production unit operations in the total production system. The elimination of (combinations of) production unit operations (the fifth step) requires a rather high technological knowledge and intensive involvement of the decision maker.

3.3.4 Demonstration problem

Consider a production system transporting a certain amount of a commodity over a certain distance within a certain time-span. Initially this is carried out by means of trucks. Assuming that these have to be replaced, the main question is: what alternative production systems (means of transport) would be suited to transport the commodity. To answer this question, the five steps from the previous subsection are applied.

The first step is to determine upon which technological concept the current production system (application of trucks) is based. According to the list in appendix 3, a truck is "a self-propelled vehicle with its motor carried in transport". The second step reveals that using trucks is a motorised transformation in place. Segregating (the third step) shows that production unit operations based on the following technological concepts might be applicable to transport the commodity:

- motorized vehicles with their motor carried in transport (truck, goods-train, freight-airplane, tractor, ship)
- motorized vehicles with their motor not carried in transport (cable car, conveyor belt)
- non-motorized means of transport (pipeline, gravity flow, bicycle, horse)

Examples of production unit operations are presented between brackets (fourth step). Which of these production unit operations is actually applicable depends on the specific situation. For example, if the commodity is a fluid (e.g. petrol), probably only trucks, goods-trains, ships and pipelines are applicable. Therefore the other production unit operations have to be eliminated (fifth step).
Although the example discussed in this section comprises a production system with only one elementary task, the method is also valid in the case of two or more tasks. Problems of this type can be handled by repeating the procedure for each single task. Alternative production systems may then be generated by considering all (feasible) combinations of production unit operations.

3.4 The mathematical formulation: an idealized approach

In this section a mathematical formulation is presented that may support decision making in designing a production system which is optimum from an energy point of view. The formulation is based on the exergy optimisation method (Gool v. *et al.*, 1988; Groscurth *et al.*, 1989; Kümmel *et al.*, 1987). It is assumed that the yield of all alternative production unit operations available for a task equals the desired yield for that task. Furthermore, it is assumed that the material efficiency is equal for each production unit operation available for each single task. Based on these assumptions, mathematical building blocks are derived for all elements of the three subsystems, which can be used to define an objective function (see next section).

A *The transformation subsystem*

The transformation subsystem demands mainly thermal and electrical energy. For each task within the transformation subsystem several production unit operations may be available. Under the assumptions described above, one production unit operation has to be selected for each task. The combination of the selected production unit operations defines the transformation subsystem.

Consider the case where I tasks have to be performed, for each of which J_i (i is task index) production unit operations are available. The primary energy Fd [kW] demanded by any combination of production unit operations is expressed by relation 3.4, which is subject to relations 3.5 and 3.6.

$$Fd = \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij}\left[\frac{Hd_{ij}}{\eta_h} + \frac{Ed_{ij}}{\eta_e}\right] \tag{3.4}$$

$$x_{ij} \in \{ 0, 1 \} \tag{3.5}$$

$$\sum_{j=1}^{J_i} x_{ij} = 1 , \qquad \forall\, i \in \{ 1, 2, \ldots, I \} \tag{3.6}$$

Hd_{ij} and Ed_{ij} are respectively the thermal and electrical power [kW] demanded by production unit operation with index j for task i. η_h and η_e are the efficiencies with which the heat and electricity are generated from fossil fuels. The integer variables x_{ij} indicate which production unit operations are selected, and thus define the transformation subsystem. Relations 3.5 and 3.6 ensure that just one production unit operation is selected for each task.

B *The heat recovery subsystem*

In section 3.2 it is discussed that energy leaving a (combination of) production unit operation(s) can be recovered by the heat recovery subsystem which, in this study, contains heat exchangers and (electrically driven) heat pumps. Before such elements can be introduced, temperature interval and quality levels have to be determined as discussed in section 3.2.

By means of a heat exchanger network, residual heat can only be transferred to the same or a lower quality level. Consequently, before a combination of production unit operations has been selected, the energy conservation potential (expressed in primary energy [kW]) resulting from the application of a heat exchanger network can be expressed as:

$$Fex = \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij} \sum_{t=1}^{T} \sum_{t^*=t}^{T} \frac{1}{\eta_h}\, \eta_{ex}\, u_{t^*t}\, Hs_{ijt^*} \tag{3.7}$$

subject to relation 3.5 and 3.6, and relations 3.8 to 3.10.

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij} \sum_{t^*=t}^{T} \eta_{ex}\, u_{t^*t}\, Hs_{ijt^*} \leq \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij}\, Hd_{ijt} \tag{3.8}$$

$$u_{t^*t} \geq 0 \tag{3.9}$$

$$\sum_{t=1}^{t^*} u_{t^*t} \leq 1 \tag{3.10}$$

Fex is the energy conservation potential. t and t^* are the indices of the temperature intervals ($t = 1$ corresponds to the interval with the lowest quality level). η_{ex} is the efficiency with which the thermal power is transferred, and u_{t*t} is the fraction of the available thermal power that is transferred from interval t^* to t. Hs_{ijt*} and Hd_{ijt} are respectively the thermal power supplied and demanded by production unit operation ij at temperature interval t^* and t.
Relation 3.8 ensures that the thermal power transferred from temperature interval t^* does not exceed the demand in interval t. Relations 3.9 expresses that thermal power can only be transferred from the leaving heat flows. By relation 3.10 it is expressed that no more thermal power than supplied at temperature interval t^*, can be transferred.

Heat pumps can transfer residual heat from a lower to a higher quality level. The net energy conservation potential resulting from the application of (electrically driven) heat pumps can, before a specific combination of production unit operations has been selected, be expressed as:

$$Fhp = \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij} \sum_{t=1}^{T} \sum_{t^*=0}^{t-1} \frac{v_{t^*t}\, Hs_{ijt^*}}{COP_{t^*t} - \eta_p} \left[\frac{COP_{t^*t}}{\eta_h} - \frac{1}{\eta_e} \right] \tag{3.11}$$

subject to relation 3.5, 3.6 and 3.12 to 3.15.

$$COP_{t^*t} = \frac{q_{t^*} - 1}{q_{t^*} - q_t} \tag{3.12}$$

$$v_{t^*t} \geq 0 \tag{3.13}$$

$$\sum_{t=t^*+1}^{T} v_{t^*t} \leq 1 \tag{3.14}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij} \sum_{t^*=0}^{t-1} \frac{COP_{t^*t}}{COP_{t^*t} - \eta_p} v_{t^*t}\, Hs_{ijt^*} \leq \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij}\, Hd_{ijt} \tag{3.15}$$

Fhp is the energy conservation potential resulting from the application of heat pumps; the higher *Fhp*, the more energy can be conserved. The first term in relation 3.11 corresponds to the primary energy (required for heating purposes) that can be conserved by applying heat pumps; the second term corresponds to the primary energy used for the generation of the electrical power required to drive the heat pumps. v_{t^*t} is the fraction of the thermal power that is transferred from temperature interval t^* to t. η_p is the fraction of the driving energy that is not lost in operating the heat pump. COP_{t^*t} is the coefficient of performance of the heat pump (Moser and Schnitzer, 1985). It expresses the effectiveness of the heat pump, and is defined as the quotient of the heat supplied at temperature interval t and the driving energy. In the framework of this study, the definition of COP_{t^*t} is expressed by relation 3.12 (Gool v. *et al.*, 1988).

Relations 3.13 expresses that heat can only be transferred from temperature interval t^*. By relation 3.14 it is expressed that no more heat than is supplied at interval t^*, can be transferred. Relation 3.15 expresses that no more heat can be transferred to temperature level t than is demanded at this level.

It is also possible to design a heat recovery subsystem with both heat exchangers and heat pumps. The primary energy that can be conserved in this way, is expressed by summing relation 3.7 and 3.11, subject to relation 3.5 and 3.6, the combination of 3.8 and 3.15 (thus expressing that the thermal power supplied by the heat exchangers and heat pumps does not exceed the demand in a specific temperature interval), 3.9, the combination of 3.10 and 3.14 (thus expressing that no more thermal power than available at a specific temperature can be transferred by heat exchangers and heat pumps), 3.12 and 3.13.

In relation 3.11 and further, it is assumed that heat pumps can be applied at any temperature or temperature interval. Furthermore it is assumed that heat pumps can lift the temperature of a flow over any temperature difference. As the result of technical limitations, these assumptions might not hold true in practice. Such practical limitations can be taken into account in the mathematical formulation. If the available heat pumps cannot be operated above a certain temperature, or equivalently above a certain quality level, the variable v_{t^*t} can be set to zero for $t > t_h$, where t_h is the temperature interval index corresponding to the highest quality level where heat pumps are applicable. If the heat pumps can lift the temperature of a flow only over a limited temperature difference or, equivalently a limited quality difference, the variable v_{t^*t} can be set to zero for $t^* < t_l^*$, where t_l^* is the temperature interval index corresponding to the lowest quality level from which heat can be pumped up. Note that in general t_l^* depends on t, i.e. on the quality level where the heat is pumped to. By including the restrictions on the value of v_{t^*t} as additional constraints in the mathematical formulation, the decision maker can take the technical limitations of the heat pumps into account.

C *The utility subsystem*

So far it has been implicitly assumed that all heat is generated by a boiler (characterised by its efficiency η_h), and that all electricity is purchased externally and generated by a power station (characterised by its efficiency η_e). As an alternative, the application of a CHP-unit is studied. A CHP-unit produces heat and electricity in a certain ratio from fossil fuel. The heat can be produced at several quality levels. The net energy conservation potential (expressed in primary energy) resulting from the application of a CHP-unit can be expressed by relation 3.16.

$$Fc = \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij} \sum_{t=1}^{T} \left[\frac{\eta_{ch}}{\eta_{ce}}\frac{Ec_t}{\eta_h} + \frac{Ec_t}{\eta_e} - \frac{Ec_t}{\eta_{ce}} \right] \qquad (3.16)$$

This relation is subject to relation 3.5 and 3.6, and also to relation 3.17 to 3.19.

$$Ec_t \geq 0 \qquad (3.17)$$

$$\frac{\eta_{ch}}{\eta_{ce}} Ec_t \leq \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij}\, Hd_{ijt}\,, \qquad \forall\, t \in \{\, 1, 2, \ldots, T \,\} \qquad (3.18)$$

$$\sum_{t=1}^{T} Ec_t \;\leq\; \sum_{i=1}^{I}\sum_{j=1}^{J_i} x_{ij}\left[Ed_{ij} + \sum_{t=1}^{T}\sum_{t^*=0}^{t-1} \frac{v_{t^*t}\, Hs_{ijt^*}}{COP_{t^*t} - \eta_p} \right] \tag{3.19}$$

Fc is the net energy conservation potential; the higher *Fc*, the more energy can be conserved. The first and second term in relation 3.16 express the primary energy (required for heat respectively electricity generation) that can be conserved by the application of a CHP-unit; the third term expresses the primary energy required by the CHP-unit. η_{ch} and η_{ce} are the efficiencies with which respectively heat and electricity ($\Sigma_t\ Ec_t$) are produced. The quotient of η_{ch} and η_{ce} defines the heat to power ratio. Ec_t is the amount of electricity cogenerated with the heat that is supplied at temperature level t.

Because heat is supplied from the CHP-unit, Ec_t is a positive variable (relation 3.17). Relations 3.18 and 3.19 express that the CHP-unit cannot produce more heat respectively electricity than is demanded by the system (if present, including the electrical power required by the heat pumps).

3.5 The design strategies

During the process of designing a production system, decisions on the design of the three subsystems can be made in different sequences. Each sequence is called a *design strategy*. Since the three subsystems interact, the specific energy consumption of the total production system depends on the design strategy that is used. Because the transformation subsystem actually transforms the raw materials into the desired commodity, this is the core part of the production system. Consequently, this subsystem is always incorporated in the first optimisation decision (e.g. with respect to energy intensity of the commodity) that is taken. Considering this, six different design strategies (DS1, ..., DS6) are possible. In table 3.2 it is indicated in which of the optimisation decisions (first, second or third) each of the three subsystems is involved, according to the six design strategies. The first decision does not necessarily have to be optimal from an energy point of view. Thus retrofit and rebuild situation are incorporated in the design strategies. For example, in the case of a retrofit, DS1, DS2 and DS3 represent situations where the utility subsystem and heat recovery subsystem are optimized (sequentially or simultaneously); DS4 and DS5 represent the situations where only the heat recovery respectively the utility subsystem are optimized; DS6 represents the situation where nothing is changed. Note that in the case of a rebuild, DS6 represents an integral design approach.

Table 3.2: The six design strategies.

	DS1	DS2	DS3	DS4	DS5	DS6
Transformation subsystem	1st	1st	1st	1st	1st	1st
Utility subsystem	2nd	3rd	2nd	1st	2nd	1st
Heat recovery subsystem	3rd	2nd	2nd	2nd	1st	1st

The design strategies can be used to define an objective function based on the building blocks derived in the previous section. Since this proceeds basically in a similar way for each design strategy, only the application of DS1 (rebuild situation) is illustrated. According to this design strategy, the first optimisation decision has to be taken on the design of the transformation subsystem. To find the optimum combination of production unit operations, relation 3.4 has to be minimized using relations 3.5 and 3.6 as constraints, i.e. at this stage the objective function is:

$$\begin{aligned} Min \quad F1 &= Fd \\ &= \sum_{i=1}^{I} \sum_{j=1}^{J_i} x_{ij} \left[\frac{Hd_{ij}}{\eta_h} + \frac{Ed_{ij}}{\eta_e} \right] \end{aligned} \tag{3.20}$$

The only variables in the objective function are the integer variables x_{ij}, which means that a simple combinatorial problem has to be solved. By adding extra conditional constraints the decision maker can indicate that a certain combination of production unit operations is infeasible, and thus cannot be selected. An example of this is:

IF $x_{ab} = 1$, THEN $x_{cd} = 0$; $a,c \in \{1,\ldots,I\}$, $b,d \in \{1,\ldots,J_i\}$, $a \neq c$, $b \neq d$

The result of this optimization is always that those production unit operations are selected so that, when considered apart, a minimum amount of primary energy per unit of time is demanded. The minimization fixes the variables x_{ij}, i.e.:

$$x_{iJ} = 1 \, , \quad x_{ij} = 0 \, , \quad j \neq J \, , \quad \forall \, i \in \{ 1, 2, \ldots, I \} \tag{3.21}$$

J is the index of the production unit operation that has been selected for task i. Note that in a retrofit situation the choice of the production unit operation (i.e. the fixation of the x_{ij}) can already have been made according to an objective function other than 3.20.

The second subsystem that has to be designed according to DS1, is the utility subsystem. In relation 3.20 it is implicitly assumed that all heat and electricity are generated in a boiler respectively in a power station. As an alternative the application of a CHP-unit is studied. This is done by combining the result of the optimization of the transformation subsystem (*f1*) and relation 3.16. This results in the objective function expressed by relation 3.22.

$$\begin{aligned} Min\ \ F2 &= f1 - Fc \\ &= \sum_{i=1}^{I} x_{iJ} \left[\frac{1}{\eta_h} \sum_{t=1}^{T} (Hd_{iJt} - \frac{\eta_{ch}}{\eta_{ce}} Ec_t \right. \\ &\quad \left. + \frac{1}{\eta_e} (Ed_{iJ} - \sum_{t=1}^{T} Ec_t) + \sum_{t=1}^{T} \frac{Ec_t}{\eta_{ce}} \right] \end{aligned} \tag{3.22}$$

In this objective function the variable is Ec_t. The objective function can be optimized by standard Linear Programming (LP) codes, using relations 3.17 to 3.19 as constraints (note that at this stage no heat pumps are present). The minimization fixes the variables on a value EC_t. Before the optimization can take place, a reasonable value has to be chosen for the heat to power ratio and, consequently, for η_{ch} and η_{ce} (to be called η_{Ch} and η_{Ce}) of the CHP-unit. The influence of this choice can be studied by means of sensitivity analysis, i.e. choosing another value for the heat to power ratio and repeating the optimization. If the thermal power delivered by the CHP-unit is the limiting factor to its capacity, the sensitivity analysis may lead to a change of the value of EC_t found in the first optimization.

In section 3.7 it is argued that under some conditions constraints 3.18 and 3.19 can be relaxed. If this is the case, the demanded external thermal and/or electrical power has to be included in the objective function.

The third subsystem that has to be designed according to DS1, is the heat recovery subsystem where heat exchangers and heat pumps are applied. Assuming that both devices are applied simultaneously, the objective function is defined by the results of the optimization at the previous two steps (*f2*) and by relation 3.7 and 3.11. This results in the objective function expressed by relation 3.23. This objective function has to be minimized.

$$\begin{aligned} Min\ F3 &= f2 - Fex - Fhp \\ &= \sum_{i=1}^{I} x_{iJ} \left[\frac{1}{\eta_h} \sum_{t=1}^{T} (Hd_{iJt} - \frac{\eta_{Ch}}{\eta_{Ce}} EC_t - \sum_{t^*=t}^{T} \eta_{ex}\, u_{t^*t}\, Hs_{iJt^*} \right. \\ &\quad - \sum_{t^*=0}^{t-1} \frac{COP_{t^*t}}{COP_{t^*t} - \eta_p}\, v_{t^*t}\, Hs_{iJt^*}) + \frac{1}{\eta_e} (Ed_{iJ} - \sum_{t=1}^{T} EC_t \\ &\quad \left. + \sum_{t=1}^{T} \sum_{t^*=0}^{t-1} \frac{1}{COP_{t^*t} - \eta_p}\, v_{t^*t}\, Hs_{iJt^*}) + \sum_{t=1}^{T} \frac{EC_t}{\eta_{Ce}} \right] \end{aligned} \tag{3.23}$$

$$\sum_{t=1}^{T}\left(u_{t^*t}+v_{t^*t}\right) \leq 1\,, \qquad \forall\, t^* \in \{\,1,\,2,\,\ldots,\,T\,\} \tag{3.24}$$

$$\sum_{i=1}^{I} x_{iJ}\, Hd_{iJt} - \frac{\eta_{Ch}}{\eta_{Ce}}\, EC_t \;\geq\; \sum_{i=1}^{I} x_{iJ} \left[\sum_{t^*=t}^{T} \eta_{ex}\, u_{t^*t}\, Hs_{iJt^*} + \sum_{t^*=0}^{t-1} \frac{COP_{t^*t}}{COP_{t^*t}-\eta_p}\, v_{t^*t}\, Hs_{iJt^*} \right] \tag{3.25}$$

Relation 3.23 is a linear objective function with u_{t^*t} and v_{t^*t} as variables. It can be minimized by LP with relations 3.9, 3.12 and 3.13 as constraints. Furthermore, the combination of relation 3.10 with 3.14 and 3.8 with 3.15 (and considering that the demand for heat has already been reduced by the decision in the previous stage) leads respectively to relations 3.24 and 3.25. These have also to be added as constraints to the LP problem.
Minimization of the objective function fixes the values of u_{t^*t} and v_{t^*t}. Consequently all degrees of freedom in the three subsystems have been fixed, meaning that within the framework of this approach no more energy conservation options exist.

In the foregoing, the application of the six different design strategies has been illustrated. Summarized it can be said that each optimization decision fixes a part of the variables. By these fixations the possibilities for energy conservation at a later stage may be diminished. Therefore, only a design strategy that represents a fully integrated design of the three subsystems of the total production system (DS6) leads to an optimum result.

3.6 The mathematical formulation: some generalisations

In section 3.4 a mathematical formulation is derived which is applicable in very ideal cases. In this section some generalisations to the idealised approach of section 3.4 are discussed.

A *Production unit operations with differing yield*

The mathematical formulation of section 3.4 is derived for the case where all production unit operations available for a task have the same yield and material efficiency. However, in practice production unit operations generally have differing yields and material efficiencies. This complicates the problem of selecting production unit operations for a task, since in such cases not only a single production unit operation may have to be selected for a task, but also combinations of production unit operations.

In case the production unit operations that are available for a task have differing yields, application of the design strategies and the mathematical formulation may lead to a decrease of the utilization level of all production unit operations (assuming that the production unit operations are operated at the desired yield). To bypass this problem, the objective functions resulting from the application of the design strategies have, for a specific combination of production unit operations, to be divided by the yield (for a specific task) which is closest to (but higher than or equal to) the desired yield. If the utilization level of the production system is increased until it becomes 100% for a specific task, the energy intensity of the produced commodity is at a minimum. If the yield of the total production system is higher than the desired one, campaign lengths must be reduced.

Besides dividing the objective functions, the constraints expressed by relations 3.5 and 3.6 have to be adjusted in such a way that multiple production unit operations can be selected for a task ($x_{ij} \in \{0, 1, 2, ...\}$) respectively so that the yield of the production unit operations selected for a task is higher than or equal to the desired yield for that task ($\Sigma_j \, m_{ij} \, x_{ij} \geq M_i, \ \forall \ i \in \{1, 2, ..., I\}$; m_{ij} is the yield of production unit operation ij, M_i is the desired yield for task i).

B *Production unit operations with differing material efficiencies*

In the mathematical formulation presented so far, only direct energy is taken into account (IFIAS, 1974; Boustead and Hancock, 1979). This can lead to a production system which produces a product with the lowest direct energy intensity, at the expense of relatively large amounts of raw materials (with an amount of energy sequestered in them). To take this into account, a correction factor may be added to the objective function. If, as is assumed here, the material efficiency of the alternative production unit operations is constant for each single task, the energy intensity of the produced commodity can be corrected by adding the energy intensity of the required raw materials (a constant) to the objective function.

In case the production unit operations available for a task have differing material efficiencies, the amount of raw materials required to produce one unit of commodity will vary with the choice of the production unit operations. This implies that the correction term described in the previous paragraph is no longer a constant. This problem can be dealt with by replacing the constant by the product of the specific energy intensity of the raw materials (e.g. [J/kg]) and the quotient of M_I and the product of the material efficiencies of the selected unit operations ($\Pi_i\, x_{ij}\, \eta_{ij}$; η_{ij} is the material efficiency of production unit operation *ij*).

C *Energy sequestered in the required capital goods*

Sometimes the energy sequestered in the required capital goods (third and fourth level of energy analysis method) can have a significant contribution to the energy intensity of a commodity. This is especially apparent in case the capital goods are operated very little during their lifetime. To take this into account, the sequestered energy can be approximated by a linear term which can be added to the objective function. This term is the quotient of the amount of energy sequestered in all capital goods (production unit operations, heat exchangers, heat pumps, boilers, CHP-units) and the total amount of commodity that is produced during the lifetime of the production system.

3.7 The influence of the periphery

The performance of a system is determined by the elements and structure of the system itself and by the interactions with its periphery (Mesarovic *et al.*, 1970). Therefore, if a production system is pursued that is optimum from an energy point of view, these interactions have to be studied carefully. In this section some aspects of the periphery in which the production system is embedded and that affect its specific energy consumption, are discussed.

A *Reference state for exergy calculation*

To calculate the exergy content of a system, a reference state has to be defined (Gool v., 1987; Szargut, 1988). For thermal energy flows a reference temperature T_0 has already been defined: $T_0 = 293{,}15$ K ($\equiv$ 20 °C). It is stressed that this reference temperature is considered to be constant. It is an average value, meaning that sudden or seasonal climatic influences are neglected. Note that if a full exergy analysis of a system has to be performed, the characteristics of the reference state have to be completed by a number of additional reference parameters such as ambient pressure etc. (Szargut, 1988).

B *Juridical restrictions*

In some countries (or regions) juridical restrictions exist for companies intending to deliver their surplus electricity to the grid. These restrictions result from the fact that the controller of the grid puts forward demands with respect to reliability of supply, quality (voltage, frequency), etc.

Furthermore, selling heat and/or electricity to a (another) company is sometimes prohibited. This imposes limitations to e.g. the application of joint CHP-units. Upperbounds on the produced amount of heat and electricity are already included in the mathematical formulation. By relaxing these upperbounds, the possibility of selling heat or electricity can be taken into account.

C *The environmental occupation space*

The scope of the work presented in this thesis is to investigate the possibilities of industrial energy conservation by minimizing the energy directly used in the production of a commodity. In chapter 1 it is argued that this is inevitable for a sustainable development of world economy. Considering the mix of energy carriers that can be applied at a specific location, the question arises what is more sustainable: using fossil (oil, coal, lignite, natural gas), nuclear or renewable (wind, geothermal, solar, biomass) fuels. The answer to this question is strongly related to the *environmental occupation space* that is available to each environmental aspect related to the extraction, conversion and use of a specific type of energy carrier. The environmental occupation space indicates the maximum environmental impact that nature can cope with at a specific location, given the area that is affected by each impact.

Each type of fuel has its weaker and stronger environmental aspects. Two categories of aspects can be distinguished: intrinsic and extrinsic ones. Intrinsic aspects are inevitably connected to the extraction, conversion and use of a specific type of fuel (e.g. all emissions to the environment, resource depletion). All other environmental aspects are extrinsic. Examples of these aspects are skyline pollution and noise. To answer the question posed above, it is proposed to define the concept of *non-sustainable energy* E_{ns}. This is done by relation 3.26 to 3.29.

$$E_{ns} = \sum_{r=1}^{R} \sum_{i} w_i \int_{0}^{E_r} U_i(E_1,\dots,E_r,\dots,E_R)\, dE_r \tag{3.26}$$

$$\sum_{i} w_i = 1 \tag{3.27}$$

$$w_i \leq 1 , \qquad \forall\, i \tag{3.28}$$

$$0 \le U_i(E_1,\ldots,E_r,\ldots,E_R) \le 1 , \qquad \forall\, i \qquad (3.29)$$

E_r is the power [kW] of fuel type r that is applied, w_i is a subjective parameter representing the relative importance of environmental aspect i. U_i is a function expressing which percentage of dE_r is considered to be non-sustainable on this environmental aspect, taking into account the application of the other energy carriers. E_{ns} as defined by relations 3.26 to 3.30, is that part of $\Sigma_r E_r$ which is considered to be non-sustainable. In principle the concept of E_{ns} defined above can be included in the objective function by replacing the included efficiencies by functions similar to relations 3.26. However, this would make the objective function non-linear, making the optimisation problem less easy to solve. To cope with this, so-called *Coefficients of Sustainability* (COS_h, COS_{el}, COS_{ch}, COS_{ce}) are defined as the quotient of the useful (thermal or electrical) power obtained from the conversion of $\Sigma_r E_r$ and E_{ns}. This conversion can be done in a boiler (COS_h), in a CHP-unit (COS_{ce}, COS_{ch}) and in a power station (COS_e). The coefficients of sustainability can be used analogous to the efficiencies. By performing a sensitivity analysis with respect to the coefficients of sustainability, the influence of the sustainability of the applied energy carriers can be studied. Since $0 \le E_{ns} \le \Sigma_r E_r$, the coefficients of sustainability are always positive. The higher their value, the more sustainable the application of $\Sigma_r E_r$.

Generally, U_i is a step-function. The point where U_i reaches the value 1, is determined by the environmental occupation space on environmental aspect i that is available to the production system under consideration (see figure 3.7). If $E_r = 0$, there is no environmental impact on aspect i. Any increase dE_r generally reduces the environmental occupation space, until at a certain point there is no more space left. Before that point, any increase of E_r may be considered as sustainable since it is an impact that nature can still cope with; after that point, any increase is non-sustainable since it is an impact that nature cannot cope with.
The environmental occupation space depends on the characteristics of the (surroundings of the) locations where fuel type r is extracted, converted and used. Especially, environmental pollution from other sources (either inside or outside the system boundary) than the one under consideration has to be taken into account. For instance, if a large emission of p is present in the surrounding of a system which also emits p, the environmental occupation space will be smaller than in the situation where the former emission source is not present.

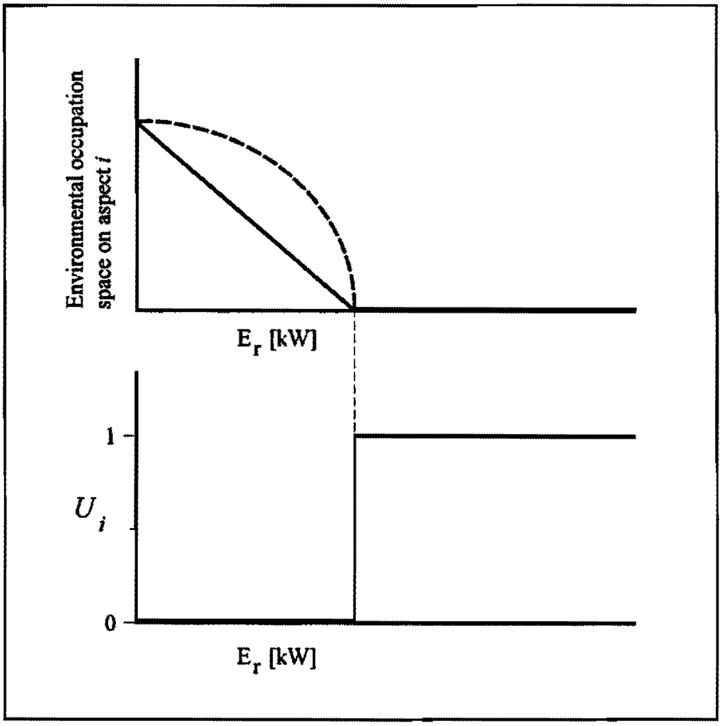

Figure 3.7: An example of the shape of U_i.

The values assigned to the parameters representing the relative importance of the intrinsic and extrinsic aspects will also depend on the surroundings of the location under study. For example, consider two aspects with equal values of the utility function. One of these aspects may be considered to be more important than the other, for sustainability reasons or other short term ones (e.g. safety).

It is outside the scope of this work to elaborate on the procedures that are needed to establish all parameters required to calculate E_{ns}. In the rest of this thesis it is therefore assumed that all energy is obtained from fossil energy carriers. However, to illustrate the importance of the topic discussed in this section, the mix of energy carriers used for electricity production within the countries of the European Community, is presented in table 3.3. In this table the ratio of electricity production and consumption is given. This ratio indicates how much electricity is imported or exported by a specific country.

Table 3.3: The energy carriers used for electricity production in the countries of the European Community in 1990 (CEC, 1990).

	Nuclear	Renewable	Fossil	Total [TWh]	Ratio prod./cons.
Belgium	58%	2%	40%	64.2	1.04
Denmark	0%	2%	98%	30.4	0.98
Germany	38%	5%	57%	424.5	0.99
Greece	0%	10%	90%	32.5	0.99
Spain	34%	24%	42%	140.6	1.05
France	74%	18%	8%	395.0	1.10
Ireland	0%	8%	92%	13.6	1.04
Italy	0%	23%	77%	214.5	0.91
Luxembourg	0%	50%	50%	1.2	0.25
Netherlands	5%	1%	94%	67.1	0.89
Portugal	0%	45%	55%	24.1	0.90
United Kingdom	20%	2%	78%	309.3	0.97
Europe 12	35%	12%	53%	1716.9	1.00

3.8 Demonstration problem

3.8.1 Retrofit situation

Consider a production system producing a commodity *C* from a set of raw materials. To transform the raw materials into *C*, two tasks have to be performed in the transformation subsystem. Currently these tasks are carried out by two production unit operations. The data on the energy flows entering and leaving these unit operations are presented in table 3.4.

Let us study the situation where the decision makers managing the production system are considering an energy conservation project (e.g. as a reaction on the policy instruments mentioned in chapter 1). To take a deliberate decision on energy conservation, the decision makers need insight into the energy conservation potential of the production system. To estimate this potential, the decision makers define the values of the constants needed for the calculation. The results are presented in table 3.5. To study the influence of variations in the defined values on the results of the optimisation, sensitivity analyses have to be performed.

Table 3.4: Data on the energy flows of the currently applied production unit operations.

	Type	Energy flow	Cp [kW/°C]	Temperature [°C]	Electrical power [kW]
Production unit operation 11	in:	Ed_{11}	-	-	400
	out:	Hs_{11}	2.0	150	-
Production unit operation 21	in:	Ed_{21}	-	-	350
		Hd_{21}	1.0	40	-
	out:	Hs_{21}	5.0	70	-

Table 3.5: The estimated values of the constants.

	η_h	η_e	η_{ex}	η_p	η_{ch}	η_{ce}
Value	0.80	0.40	1.00	0.75	0.55	0.25

Subsequently, the decision makers have to indicate which degrees of freedom within the production system can be used to realise an eventual energy conservation potential. Initially the decision makers are not intending to replace the total production system. Instead they prefer a retrofit, thereby keeping the transformation subsystem and the utility subsystem unimpaired. This means that, within the framework of this study, energy conservation can only be realised by introducing a heat recovery subsystem. This situation is represented by DS4 (retrofit situation; see table 3.2), i.e. the energy conservation potential is determined by the heat recovery potential.

To estimate the energy conservation potential, the energy characteristics of the two production unit operations are determined. The results are presented in figure 3.8. Calculations, using the constants from table 3.5, reveal that in this case the heat recovery potential (resulting from the possible application of heat exchangers and heat pumps) is equal to 25 kW. This may lead the decision makers to the conclusion that there is only a relatively small energy conservation potential within this production system.

After they have completed a project in which the 25 kW energy conservation potential has been realised, the decision makers decide to investigate the energy conservation potential of the production system combined with a neighbouring one. In this neighbouring production system a set of raw materials is transformed into a commodity *D* by one production unit operation. The data on the energy flows of this production unit operation are not known by the people managing the former production system. All they know is that this production system requires 2000 kW of heat which is currently generated by a boiler. Since it is not known at which

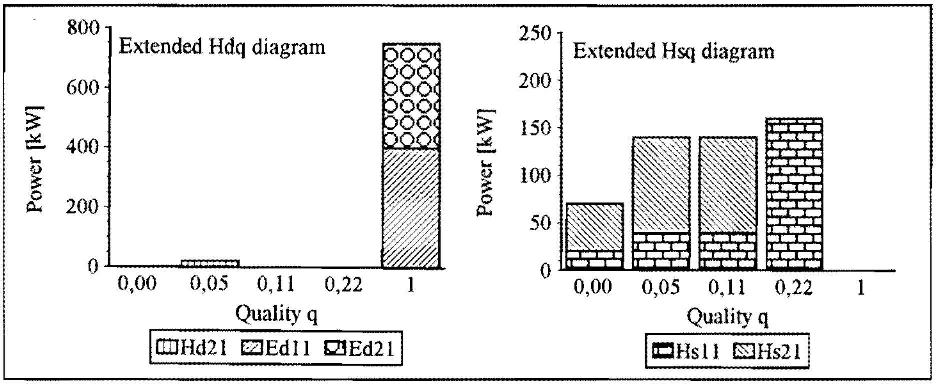

Figure 3.8: The energy characteristics of the two production unit operations.

temperature level this heat is required, a heat recovery subsystem between the two production systems is out of the question. This situation is represented by design strategy DS5 (retrofit situation). The energy conservation potential results from the eventual application of a joint CHP-unit.

Using the mathematical formulation presented in section 3.4 an objective function is derived. The results of the optimisation for several heat to power ratios and constant demand for heat and electricity, are presented in figure 3.9. This figure illustrates that, using the constants from table 3.5, a minimum is reached where the produced electrical power becomes the active constraint in the optimisation. However, it also becomes clear that this minimum is not represented by a single point, but covers a trajectory. Since the results depend on the efficiencies η_h and η_e, a sensitivity analysis with respect to these parameters is useful. The results of these analyses are also presented in figure 3.9. It becomes clear that if η_h is lower than $\eta_{ch}+\eta_{ce}$, a minimum is reached for that heat to power ratio at which the CHP-unit covers both the demand for heat and electricity. If η_h is higher than $\eta_{ch}+\eta_{ce}$, the minimum is reached at the lowest possible heat to power ratio. Note that η_h does not have any influence at those heat to power ratios at which the amount of heat is the limiting constraint to the application of a CHP-unit. At these ratios only η_{el} has an influence.

Some consequences of the introduction of a CHP-unit are a decrease of the occupation level of the boiler and of the electricity purchased from outside the two production systems. These consequences are presented in figure 3.10 as a function of the heat to power ratio of the CHP-unit (assuming that the boiler has a maximum capacity of 2000 kW). Whether or not a joint CHP-unit can be applied, depends on the periphery of the two production systems. It is clear that if it is prohibited, a distinct energy conservation potential is destroyed.

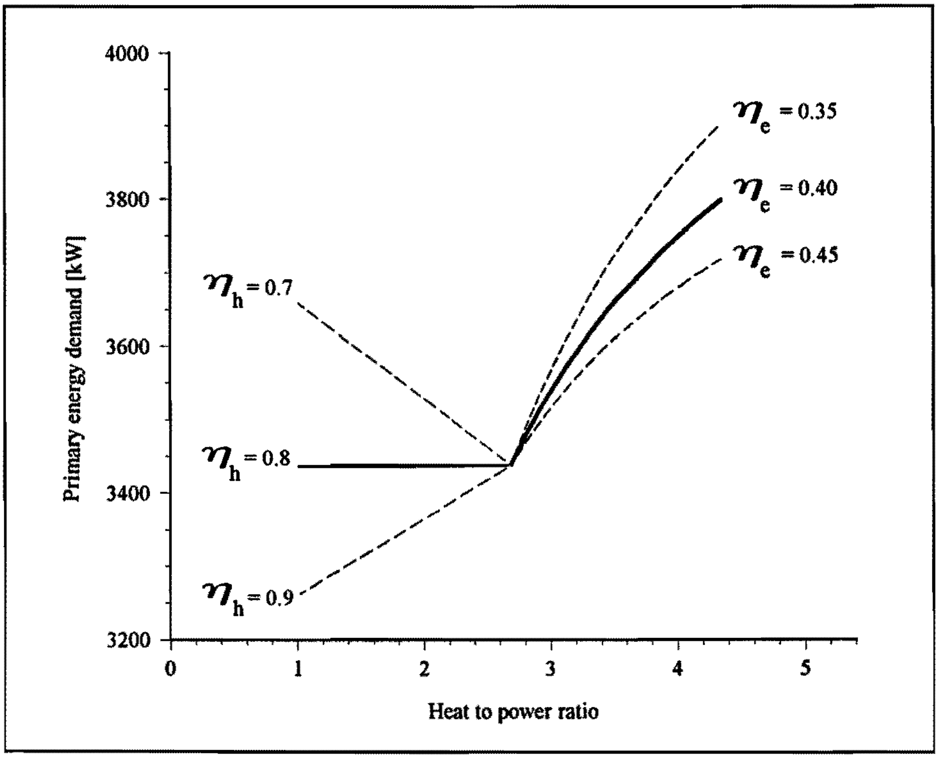

Figure 3.9: The results of the optimisation.

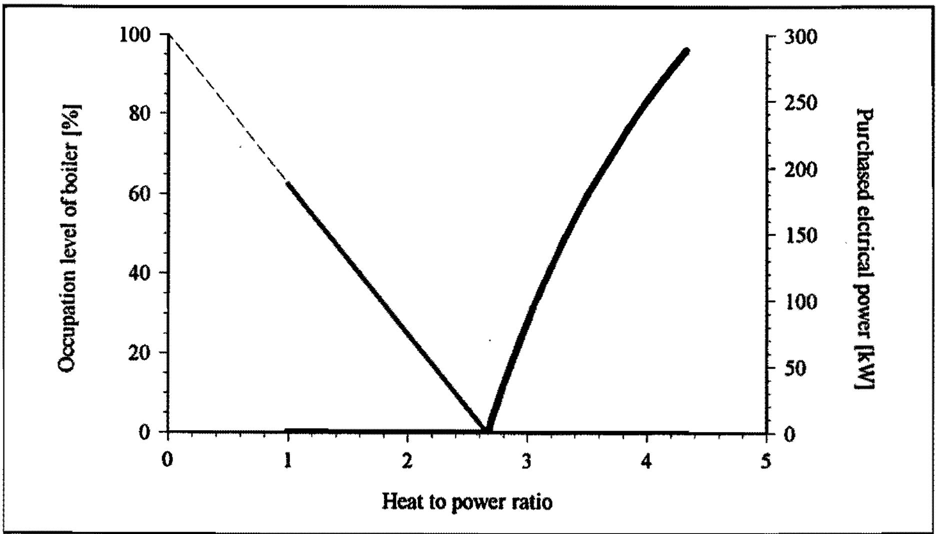

Figure 3.10: Some consequences of the introduction of a CHP-unit.

3.8.2 Rebuild situation

Not being satisfied with the results of the previous subsection, the decision makers decide to investigate the energy conservation potential of a complete rebuild of their production system. For this purpose they apply the method described in section 3.3. Besides the two production unit operations that are currently applied, this results in the identification of an alternative production unit operation which is also able to perform the second task. The data on the energy flows of this alternative production unit operation are presented in table 3.6. The management of the production system is now faced with the question of whether the introduction of the alternative production unit operation results in energy conservation. To solve this problem they can apply each of the six design strategies.

Table 3.6: The data on the energy flows of the alternative production unit operation.

	Type	Energy flow	Cp [kW/°C]	Temperature [°C]	Electrical power [kW]
Production unit operation 22	in:	Hd_{22}	5	180	-
	out:	Hs_{22}	10	60	-

After the energy characteristics are determined, the optimisation according to design strategy DS1 to DS3 reveals that the two originally applied production unit operations have to be preferred. However, application of DS4 to DS6 reveals that the alternative production unit operation has to be chosen to perform the second task. The results of the optimisation according to each of the design strategies are presented in table 3.7. From this table it follows that, in general, each design strategy leads to a different design of the three subsystems and, consequently, to another design of the production system. Note that the "optimum" production system contains those two production unit operations that, when considered apart, require the most energy. Also note that the production system resulting from DS6 has the best overall performance.

The differences in the results for each design strategy can be explained as follows: In DS1 to DS3, the possibilities for energy conservation have been limited by the early selection of the production unit operations. According to DS1 and DS4, a CHP-unit is installed before heat recovery is considered. Although this reduces the amount of purchased electricity, it also diminishes the energy conservation potential of an eventual heat recovery subsystem. In the specific example treated in this subsection, there is no difference between the results of DS2 and DS3. This is caused by the fact that no (electrically) driven heat pumps have to be applied to realise the energy conservation potential of the heat recovery subsystem. The influence of heat pumps is illustrated by the results of DS5 and DS6.

Table 3.7: The results of the optimisation according to the six design strategies. (* = selected; - = not selected).

	DS1	DS2	DS3	DS4	DS5	DS6
Task 1						
production unit operation 11	*	*	*	*	*	*
Task 2						
production unit operation 21	*	*	*	-	-	-
production unit operation 22	-	-	-	*	*	*
Boiler [kW]	0	0	0	0	0	0
CHP-unit [kWe]	9.1	0	0	363.60	35.75	90.91
η_{ch}/η_{ce}	2.2	-	-	2.2	2.2	2.2
Transferred thermal power [kW]	0.0	20.0	20.0	0.0	721.3	600.0
Purchased electrical power [kWe]	740.1	750.0	750.0	36.4	446.0	351.8
Primary energy demand *Ff* [kW]	1889	1875	1875	1545	1258	1243

Since the result of the optimisation depends on the values of the chosen constants, a sensitivity analysis with respect to these parameters is performed. The results of such analyses with respect to η_{ex} and η_p are presented in figure 3.11 and 3.12 respectively. From these figures it becomes clear that varying these parameters within reasonable boundaries has little influence on the results.

In figure 3.13 the results of the sensitivity analysis with respect to COS_{ce} are presented for the case of constant heat to power ratio. Clearly, the specific energy consumption of the production system resulting from DS6 increases with increasing COS_{ce}, while the one resulting from DS3 is just slightly influenced. The results of the sensitivity analysis for DS6 and DS3 show an asymptote at F_s = 90.9 kW respectively at 1852.3 kW. In figure 3.14 and 3.15 the influence of COS_{ce} on the capacity of the CHP-unit respectively on the thermal power transferred by heat exchangers and heat pumps, is shown for DS6. It follows that the capacity of the CHP-unit increases stepwise with increasing COS_{ce} while the transferred thermal power decreases stepwise.

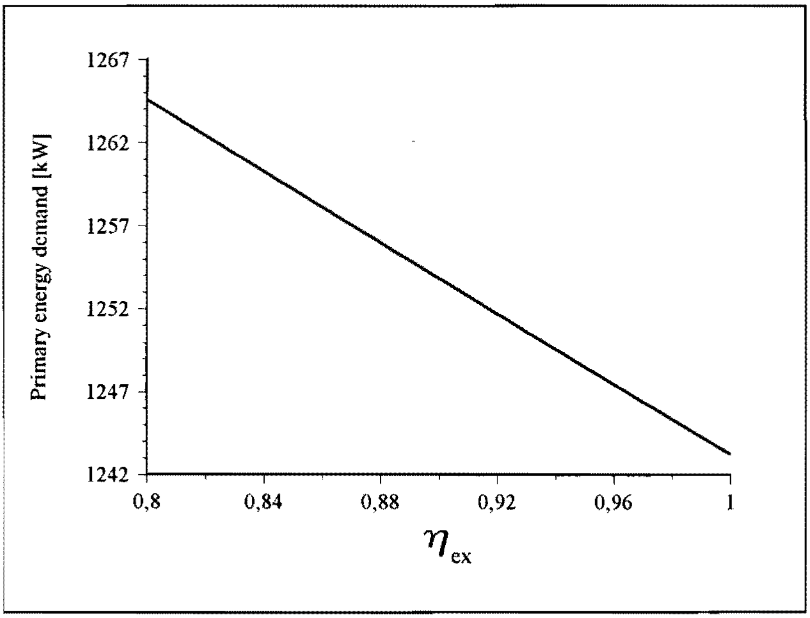

Figure 3.11: The influence of η_{ex} on the primary energy demand of the production system resulting from DS6.

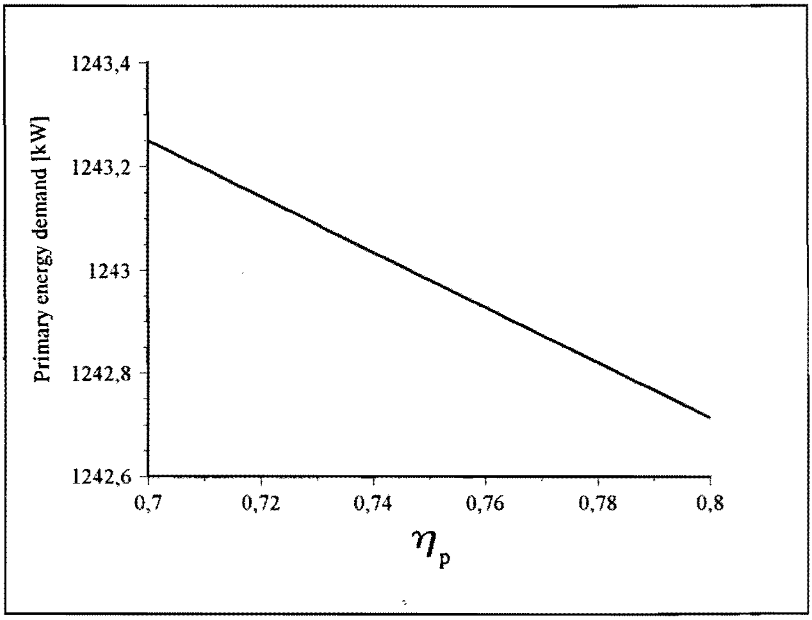

Figure 3.12: The influence of η_p on the primary energy demand of the production systems resulting from DS6.

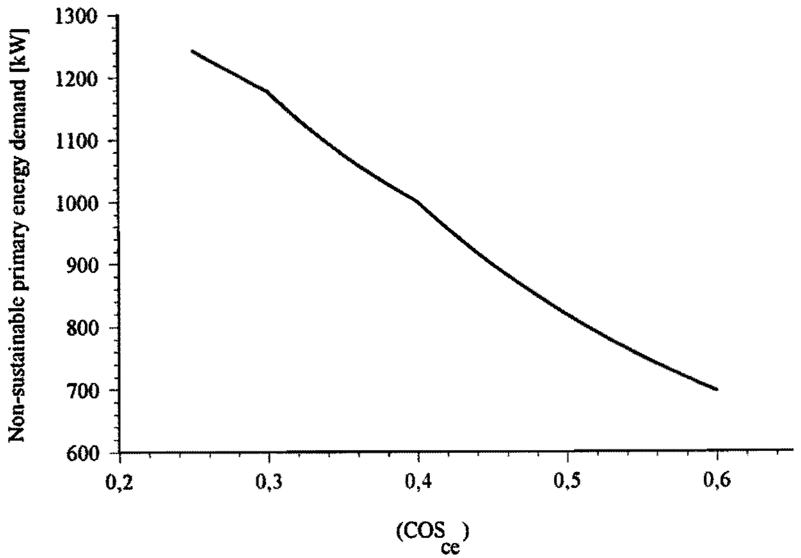

Figure 3.13: The influence of COS_{ce} on the non-sustainable primary energy demand of the production system resulting from DS6.

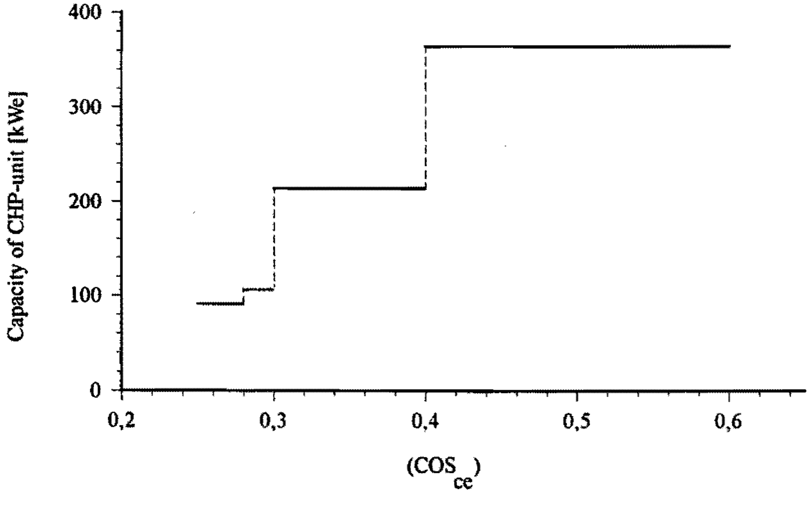

Figure 3.14: The influence of COS_{ce} on the capacity of the CHP-unit of the production system resulting from DS6.

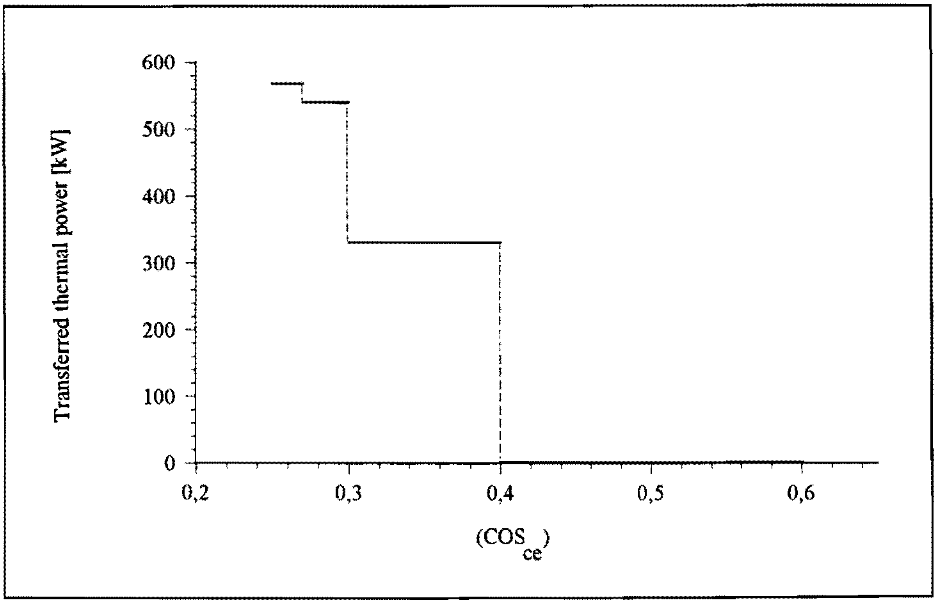

Figure 3.15: The influence of COS_{ce} on the transferred thermal power in the production system resulting from DS6.

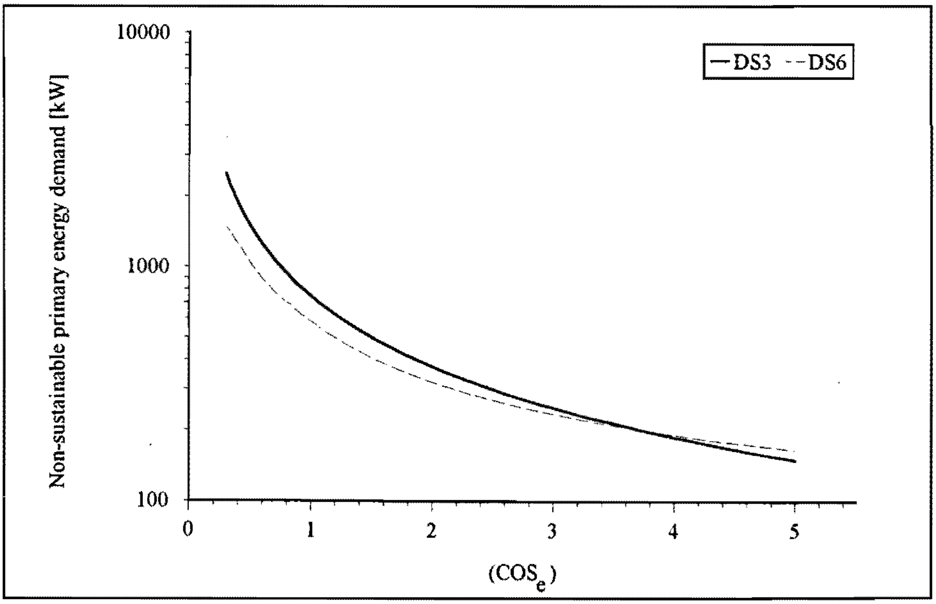

Figure 3.16: The influence of COS_e on the non-sustainable primary energy demand of the production systems resulting from DS3 and DS6.

The results of the sensitivity analysis with respect to COS_e are presented in figure 3.16. From this figure it is concluded that in situations where it is more sustainable to use electricity than heat, production unit operations consuming more electricity may be preferred from the point of view of sustainability. Similar to figures 3.14 and 3.15, the influence of COS_e on the size of the CHP-unit and the transferred thermal power can be studied. The results show characteristics opposite to the ones presented in figure 3.14 and 3.15: The size of the CHP-unit decreases stepwise with increasing COS_e while the transferred thermal power increases.

3.9 Discussion and conclusions

In this chapter, the research questions that were posed with respect to the third phase in the design process (see chapter 2), have been answered. For this purpose, the modelling approach used with this study has been introduced in section 3.2. In that section it is demonstrated that a general production system can be divided into subsystems, which in their turn can be divided into elements. It is argued that in general three subsystems can be distinguished: the *transformation subsystem* the elements of which are the production unit operations; the *utility subsystem* with as elements a boiler and a CHP-unit; the *heat recovery subsystem* containing heat exchangers and heat pumps. The production system, each subsystem and all elements are modelled using the black box approach. The models of the production unit operations are used to determine the so-called energy characteristics of a production system.

To identify alternative production unit operations, a qualitative method has been presented. By analyzing, aggregating and subsequently segregating, alternative technological concepts can be identified. Production unit operations based on these concepts may be (technically) feasible alternatives for a specific task in the transformation system of a production system. All feasible combinations of production unit operations, define a set of production systems.
Mathematical building blocks have been defined for the elements of each subsystem, to identify the production system that is optimum from an energy point of view. These building blocks can be used to define an objective function which can be optimised. To study the influence of sequential decision making, six design strategies are defined. Each represents another sequence of optimisation decisions on the design of a subsystem or on combinations of subsystems. It is illustrated that each step of a design strategy defines a different objective function. This is because these functions are derived from the respective building blocks. Consequently, each step fixes only these degrees of freedom that are connected to the elements under

consideration. It is argued that by this sequential optimisation, the energy conservation potential at a certain stage may have been reduced by a previous decision. This is demonstrated by the experiments presented in section 3.8. The application of the proposed approach in retrofit situations, is demonstrated in subsection 3.8.1. From the experiment presented in subsection 3.8.2, it is concluded that simply selecting those production unit operations with minimum energy use, may result in a production system that is sub-optimum from an energy point of view. Furthermore it is concluded that by means of the proposed approach it is possible to select that combination of production unit operations that combined with each other and the design of the utility and heat recovery subsystem, lead to a production system that is optimum from an energy point of view.

Some aspects of the influence of the periphery on the specific energy consumption of a production system have been discussed in section 3.7. In subsection 3.8.1, it is shown that the prohibition of a joint utility subsystem may drastically reduce the energy conservation potential.

The influence of the sustainability of the applied energy carriers is studied in the experiment presented in section 3.8.2. It is demonstrated that this may have a significant influence on the design of a production system and consequently on its specific energy consumption. If the sustainability of the applied energy carriers is taken into account, this may lead to the selection of a system that consumes more energy but in a more sustainable way.

Chapter 4

The evaluation of production systems

4.1 Introduction

To fill the fourth gap identified in chapter 2, the evaluation of a set of alternative production systems is treated in this chapter. In section 4.2, the general purpose of evaluation methods is discussed, and two categories of such methods are distinguished. At the end of that section, it is discussed which methods are best suited within the framework of the study that is presented in this thesis. To illustrate these methods, viz. the Promethee methods, a demonstration problem is formulated in section 4.3, and (partially) treated as a simulation experiment in section 4.4. The practical applicability of the Promethee methods is illustrated by the experiment described in section 4.5. Subsequently, in section 4.6 a novel type of sensitivity analysis is presented, which enhances the insight into the "decision space".

4.2 The evaluation method

In this thesis *evaluation* is defined as the assessment of a set of alternatives through a number of criteria, including the collecting of the needed data, and the providing of insights into the results. Defined like this, this is an evaluation ex ante; i.e. the evaluation is performed beforehand. Several methods have been developed for this. A review of these is presented elsewhere (MF, 1986; Korhonen *et al.*, 1992).
The general purpose of an evaluation ex ante is to support decision makers in the process of selecting alternatives. This is done by structuring the information on the alternatives and/or by ranking them, and by providing such information that the decision maker understands the results of the evaluation and becomes aware of the pro's and con's of a certain choice. All this should lead to an enhancement of the insight into the selection problem and a decrease of the number of valid alternatives. Thus the selection process is facilitated.

Evaluation methods for cases where the number of alternatives is bounded, can be divided into two categories: monetary methods and non-monetary methods. Monetary methods are especially suited in cases where all or most of the effects caused by the alternatives can be expressed unambiguously in financial terms. If this is not the case, one of the non-monetary methods has to be applied.

In this work, each alternative is a system for the production of a specific commodity. Decisions on such systems generally involve a number of conflicting objectives (Goodwin and Wright, 1991; Suh, 1990), which implies that each alternative has its own advantages and disadvantages. It is indispensable to weigh these advantages and disadvantages carefully, taking into account the preferences of the decision-maker(s), the considerable economic uncertainties in the periphery of production systems (e.g. market development, costs of raw materials, future environmental policy instruments etc.), and their increasing complexity. For this purpose, the bounded number of alternative production systems have to be evaluated through a bounded number of, for instance technical, environmental, economical and managerial criteria.

Since the criteria as mentioned above cannot be measured unambiguously in financial terms, a non-monetary method has to be applied. In cases with a bounded number of alternatives and a bounded number of conflicting criteria, multi-criteria decision aid methods are best suited (MF, 1986; Korhonen *et al.*, 1992). The applicability of such methods has been demonstrated elsewhere (Anandalingam, 1987; Bard, 1990; Brauers, 1990; Delhaye *et al.*, 1991; Keeney and Nair, 1975; Kuula and Stam, 1989; Lootsma *et al.*, 1988, 1990; Mareschal and Brans, 1991; Mladineo and Margeta, 1987; Ray and Sahu, 1990; Stam and Kuula, 1989; Tabucanon, 1988; Vuk *et al.*, 1991; Wu and Tabucanon, 1990). Multi criteria decision aid methods may roughly be divided into a so-called French school and an American school (Lootsma, 1990). The former school is represented by the Electre method (Roy and Hugonnard, 1968) and the Promethee methods (Brans *et al.*, 1984, 1986; Brans and Mareschal, 1985; Mareschal, 1986, 1989). The American school is mostly based on multi-attribute utility theory (Keeney and Nair, 1975; Keeney and Raiffa, 1976; Goodwin and Wright, 1991). A popular method from this school is the Analytic Hierarchy Process (Saaty, 1980, 1986). The methods from both schools are able to take into account subjective human judgements, but the mathematical processing of the data differs. The results of the methods from both schools are identical, apart from some minor differences (Goicoechea and Fu, 1992). The main difference between the French and American school lies in their area of application. Methods from the American school are more applicable in cases where most of the criteria are measured on qualitative scales, whereas the methods from the French school are more applicable in cases where most of the criteria are measured on quantitative scales (Lootsma, 1990). In this thesis most of the criteria can be measured on a quantitative scale. Therefore, a method from the French school is more appropriate. Because of its flexibility and advanced sensitivity analysis, which enables the decision maker to gain insight into the problem, the Promethee methods (Brans *et al.*, 1984, 1986; Brans and Mareschal, 1985) are chosen. A review of these methods is given in appendix 1.

4.3 The demonstration problem

4.3.1 Introduction

The demonstration problem presented in this section deals with an existing production system for which a heat recovery subsystem has to be designed. This corresponds to design strategy DS4 in the retrofit situation (see section 3.5). It is assumed that only heat exchangers are available.

Generally, the methods reviewed in chapter 2, do not result in a single optimal heat exchanger network, but in a family of feasible near-optimal networks that can be constructed for different values of the assumed minimum temperature difference. Moreover, numerous non-optimal feasible solutions exist (for instance solutions with less heat exchangers at the cost of more energy use).

Most of the methods presented in the literature, have in common that the heat exchanger networks are designed by sequential optimization according to a small number of criteria such as energy requirement, number of active matches and costs. This often involves time consuming, complex and untransparent mathematical calculations. As a result of this, the resulting solutions may not meet all the requirements imposed by practice, because:

- The preferences of a decision maker in a specific practical situation are not taken into account.
- Generally, the "optimal" solution is derived for the case where the future economic circumstances under which a heat exchanger network has to operate, are stable. This is an over-simplification in practice.
- Important criteria such as complexity and flexibility are neglected.

The first reason means that in the methods presented in the literature, the final solution cannot be influenced by indicating preferences on the criteria (i.e. stating that a criterion is X times as important than all other criteria). Furthermore, it is not possible to indicate what "value" is added to deviations from the "optimum solution" that can be achieved in theory. For instance, a solution may be preferred which slightly violates the MER condition but has a much simpler structure than all solutions meeting this condition. In that case, a certain degree of indifference with respect to the criterion "energy requirement" has to be taken into account.

The second reason refers to the fact that in practice the economic circumstances under which a heat exchanger network has to operate (at present and in future), seldom are as stable as is assumed in the literature. In fact, a lot of uncertainties arise in practice, ranging from unstable prices of (fossil) fuels and the possible introduction of environmental taxes, to an uncertain development of the market for the product that is produced. Therefore, if an investment in a heat exchanger network is considered, assumptions about possible future developments in the circumstances under which it has to operate, should be incorporated in the final decision for strategic (energy) management purposes. This can be done by defining a set of scenarios. In each scenario, certain assumptions about future developments of e.g. the cost of hot and cold utilities can be made. Thus, part of the practical uncertainties can be taken into account.

The third reason indicates that a number of (managerial) criteria (e.g. complexity, flexibility, operability, safety, net present value etc.) are neglected by the methods presented in literature. In order to obtain a satisfying practical solution, such criteria should also be taken into account.

4.3.2 Outline of the problem

Consider an existing production system producing a specific commodity. In this system the demand for hot and cold utility by the thermal energy flows has to be decreased by the introduction of a heat exchanger network. The production system can be characterised by the following parameters:

Technical characteristics: The data on the heat flows are presented in table 4.1. The heat transfer coefficients of all matches equal 0.1 kW/m^2°C. The hot flows (h1, h2) have to be cooled from the initial to the final temperatures; the cold ones (c1, c2) have to be heated. The ranges for the initial temperature and the heat flow rate, indicate which variations are *possible*, those for the final temperatures indicate which variations are *allowed*. The initial temperatures and the heat flow rates are randomly distributed over the intervals shown in table 4.1. All data in this table are averages taken over an interval of 10 minutes.

Table 4.1: The data on the heat flows in the production system (extended version of the TC3 problem (Linnhoff and Hindmarsch, 1983)).

Flow type	Initial temperature [°C]	Final temperature [°C]	Heat flow rate [kW/°C]
Hot flows h1	150 ± 5	60 ± 5	2 ± 0.1
h2	90 ± 10	60 ± 5	8 ± 0.4
Cold flows c1	20 ± 2	125 ± 2	2.5 ± 0.125
c2	25 ± 5	100 ± 5	3 ± 0.15
Hot utility	180	180	-
Cold utility	10	15	-

Operating characteristics: Currently, no heat exchangers are present and each flow is heated or cooled by its own external utility, i.e its own heater or cooler respectively. However, if a heat exchanger network is introduced, not necessarily all flows exchange heat to/from their cooler/heater (passive matching). In that case, the corresponding heater/cooler is on stand-by for eventualities, and a certain delay time has to be accounted for if this utility has to be activated to cover the variations in the supply of heat. This delay time is not present when a flow is already actively matched with an external utility. With no heat exchanger network present, breakdown of a flow occurs when the average heat flow rate (in an interval of 10 minutes) of that specific flow exceeds the boundaries indicated in table 4.1. If a heat exchanger network is present, breakdown of a flow also occurs if its final temperature exceeds the specified boundaries.
The operating characteristics of production system in the present situation are:

- Operating time: 24 hours a day, 365 days a year
- Chance of breakdown: P_{br}= 0.5% for each flow, in each interval of 10 minutes
- Starting time after breakdown: 30 minutes for each flow
- Cost of breakdown: \$ 1000 each time a flow breaks down

Safety aspects: If heat exchangers are present, flows are brought into close contact with each other. This is an extra source of risk because contamination of flows, and even dangerous situations may result when leakages occur. Moreover, the mixture of two heat exchanging flows can cause damage to other equipment and/or result in a loss of production. The matches between the flows of the problem in question, which are preferred from a safety point of view, are presented in table 4.2. Note that no match is strictly prohibited.

Table 4.2: The preferences of all possible matches:
- = preferred; * = not preferred

	c1	c2
h1	*	-
h2	*	-

Economic uncertainty: The uncertainty in the economic circumstances under which the production system operates, is supposed to be mainly due to the following three facts: First of all, only rough estimates can be made on the boundaries between which parameters such as the cost of hot and cold utilities will vary. Secondly, the development of the market for the product that is produced, is uncertain, as a result of which the possibility of a decrease in operation time has to be taken into account. Thirdly, the purchasing cost of a heat exchanger network can only be estimated by some cost function.

The most important parameters of the economic circumstances under which the production system operates, are:

- Current cost of hot utility: 80 \$/kWyr. Expected increase: < 6% annually
- Current cost of cold utility: 20 \$/kWyr. Expected increase: < 10 % annually
- Estimated cost of a heat exchanger: $8600 + 670A^{0.83}$ (\$) (For each heat exchanger; the heat exchanging area A is measured in m^2)
- Possible increase of emission taxes
- Possible change of operation time from continuous towards two shifts (of 8 hours) and 5 days a week, in 6 years from now.

The cost function has to be applied for each individual heat exchanger. It is valid for counter current steel heat exchangers of the shell and tube type (Hall *et al.*, 1989; Ahmad, 1985; Ahmad *et al.*, 1990). In order to obtain the cost of a heat exchanger network, the costs of the individual heat exchangers have to be summed. The (technical) expectation of life of this type of heat exchanger is 15 years. The internal rate of return is defined to be 7.5% per annum.

4.4 Experiment I

4.4.1 Introduction

In this section the Promethee methods are applied as a support in selecting a heat exchanger network for (part of) the demonstration problem presented in the previous section. Most of the situational aspects presented in the previous section are neglected in this section. Only the uncertainties in the costs of hot and cold utility are taken into account. Furthermore, the data on the hot (h1, h2) and cold (c1, c2) flows are restricted to the stationary case, i.e. the variations indicated in table 4.1 are not taken into account (standard TC3-problem, (Linnhoff and Hindmarsch, 1983)). For this problem a heat exchanger network has to be selected from a set of alternatives (Wolters and Lambert, 1992). This heat exchanger network should meet specific technical and managerial requirements.

It should be stressed that the Promethee methods are not meant for designing heat exchanger networks. They only enable the comparison of a number of alternative networks on the basis of several criteria. Each alternative has to be evaluated through the applied criteria. By taking into account the preferences of a specific practical situation (specified by a decision maker), the alternatives are ranked. The resulting ranking indicates in which "sequence" the alternatives are preferable in the specific case.

In the framework of this study, two categories of criteria are applied: intrinsic and extrinsic criteria. Intrinsic criteria can, contrary to extrinsic ones, be measured in an objective way. The intrinsic criteria are:

C_1 Number of active matches
C_2 Number of heat exchangers
C_3 Number of active heaters
C_4 Number of active coolers
C_5 Total heat exchanging area
C_6 Required amount of external hot utility

The extrinsic criteria are:

C_7 Total cost of the heat exchanging network
C_8 Pay back time (discounted)
C_9 Net present value over the total lifetime
C_{10} Complexity

The intrinsic criteria can be measured by simply counting the number of active matches (C_1), the number of heat exchangers (C_2), and the number of active heaters (C_3) and coolers (C_4). This is illustrated in figure 4.1. The total heat exchanging area (C_5), included the area required for the utilities, can be calculated by relation 4.1.

$$C_5 = \sum_i A_i = \sum_i \frac{Q_i}{U_i} \frac{1}{\Delta T_{\ln}} \tag{4.1}$$

A_i [m^2] is the heat exchanging area of heat exchanger with index i, Q_i [kW] is the heat load of that heat exchanger, U_i [kW/m^2°C] is heat transfer coefficient, and

$$\Delta T_{\ln} = \frac{(T - t') - (T' - t)}{\ln \left[\dfrac{T - t'}{T' - t} \right]} \tag{4.2}$$

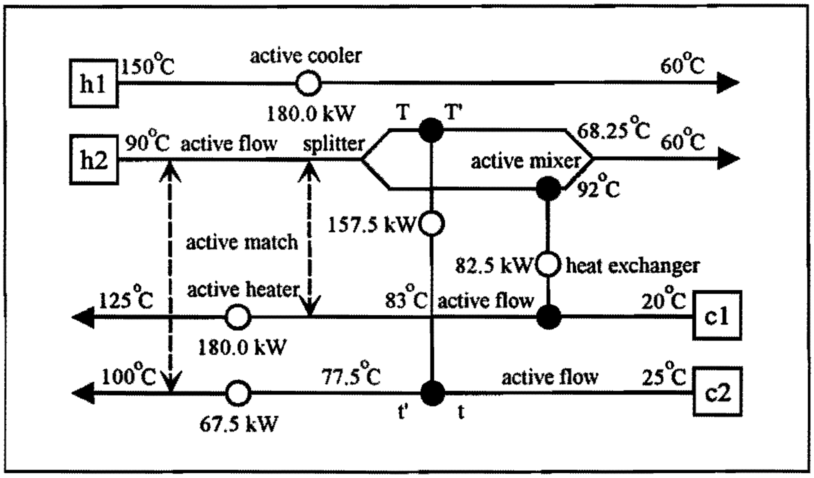

Figure 4.1: An example of a heat exchanger network.

The temperatures *T*, *T'*, *t* and *t'* are taken for each heat exchanger as indicated in figure 4.1. The required amount of external hot utility (C_6) is calculated in a straightforward way.
In many applications the number of active matches (C_1) and the number of heat exchangers (C_2) are to be minimised because of, for instance, the danger of leakages and the consequent contamination. The number of active heaters (C_3) and coolers (C_4) is to be maximised in order to keep the heat exchanger network as flexible as possible. This is important, for instance in case no active heater or cooler is present in a flow and the supply of heat to or from that flow (through a heat exchanger) is interrupted by the breakdown of the flow to which it is connected. In that case, flows without an active heater or cooler might break down as well. The total heat exchanging area (C_5) is to be minimised because the larger the area, the higher the risk of leakages (safety), the more maintenance is required (cleaning of fouled heat exchangers) and the higher the cost. The required amount of additional external hot (and consequently cold) utility (C_6) is to be minimised, because it is desirable to remain as independent as possible of additional energy production and deposition (waste heat), and thus to decrease the unstable and increasing influence of energy in production.

The extrinsic criteria are much more difficult to quantify than the intrinsic ones. It is therefore very important that these criteria are clearly defined. This, however, does not prevent occurrences when only estimates can be made for the evaluation of an alternative on an extrinsic criterion. A criterion for which this is the case is the total cost of the heat exchanging network (C_7). In calculating these costs, the area needed for the hot and cold utilities is excluded since this is already present, and only the costs of those heat exchangers that are involved in the reduction of the required amount of hot and cold utility are taken into account. These costs are estimated by the cost function defined in the previous section. To calculate the (discounted) pay-back time (C_8) and the net present value (C_9) of a heat exchanger network, discounting is applied. The complexity of a heat exchanger network (C_{10}) can be characterised in a number of ways. In this experiment complexity is calculated using relation 4.3.

$$C_{10} = \frac{s + m_a + h_e}{f_a} \tag{4.3}$$

s is the number of splitters, m_a is the number of active mixers (mixing flows of different temperatures), h_e is the number of heat exchangers (excluded the heaters and coolers), and f_a is the number of active heat flows (flows exchanging heat with other flows). The splitters, the active mixers and the active flows are indicated in figure 4.1.

The extrinsic criterion cost (C_7) is to be minimised in order to debit as little as possible the financial position of the company that wants to install the heat exchanger network. Pay-back time (C_8) has to be minimised, in order to reduce the strategic risk of the investment. The longer the pay back time, the more risk is introduced by uncertainties in the future. The net present value (C_9) of a heat exchanger network has to be maximised for obvious reasons. The last criterion, complexity (C_{10}) has to be minimised, in order to increase the controllability of a heat exchanger network.

4.4.2 The scenarios

The design and application of a heat exchanger network is a matter with a strategic (energy) management impact. Possible future developments in the circumstances under which the network has to operate have to be taken into account. This can be done by defining a set of scenarios in which assumptions are made on realistic changes on relevant parameters. In the framework of this study, three scenarios are applied, each with another assumed yearly increase of hot (ϵ_1) and cold (ϵ_2) utility cost. Mathematically, each scenario is described by relation 4.4 respectively 4.5.

$$C_h(t) = C_0(1 + \epsilon_1)^t \qquad [\$/kWyr] \tag{4.4}$$

$$C_c(t) = c_0(1 + \epsilon_2)^t \qquad [\$/kWyr] \tag{4.5}$$

ϵ_1 and ϵ_2 denote the (relative) yearly increase in cold and hot utility costs respectively, $C_h(t)$ and $C_c(t)$ denote the costs of hot and cold utility respectively at time t. C_0 and c_0 are the current costs of hot and cold utility respectively. In table 4.3 the data for the three scenarios are presented.

Table 4.3: The data for the scenarios

	scenario 1	scenario 2	scenario 3
ϵ_1	0	0.01	0.05
ϵ_2	0	0.05	0.05
C_0 [$/kWyr]	80	80	80
c_0 [$/kWyr]	20	20	20

Scenario 1, is a "business as usual" scenario. In scenario 2 and 3, a sharp increase in the cost of cold utility is expected. This is a result of governmental regulations like the prohibition on the use of CFC's, and the intended reduction of subsoil water. These regulations will force companies to switch to other cooling systems, thus substantially increasing the cost of cold utility. The expected increase in hot utility cost is still very uncertain. Therefore, two values of ϵ_1 are taken, a moderate one representing an increase due to a rising fuel price, and a high value for the case of special penalties on environmental pollution.

4.4.3 Data for the simulation experiment

To illustrate the proposed methods, a set of 23 alternative heat exchanger networks (a_1, a_2,..., a_{23}), has been developed by taking solutions from literature (a_2, a_3, a_4: (Gundersen *et al.*, 1991); a_1, a_5 to a_{10}, a_{20}, a_{22}: (Lambert, 1991, 1993)) using a number of values of ΔT_{min}. The other alternatives have been generated by deleting heat exchangers with a relatively low heat load per square meter of heat exchanging area from "optimum" networks (Gundersen and Naess, 1988), and by avoiding the application of splitters and mixers. All heat exchanger networks have been evaluated through all criteria. The results are presented in table 4.4.

In the Promethee methods, a decision maker is able to state his preferences for a specific situation by specifying weights w_j, preference functions P_j (characterised by type and parameters q, p, σ), and objectives for each criterion (see appendix 1). The weights express the relative importance of the criteria. P_j is a function of the difference in criterion scores of two alternatives, and expresses the degree of preference of one alternative over the other.

Table 4.4: The evaluations of the alternative heat exchanger networks ($a_1, a_2, \ldots, a_{23}$) on the criteria ($C_1, C_2, \ldots, C_{10}$).

								Scenario 1		Scenario 2		Scenario 3		
	C_1 [-]	C_2 [-]	C_3 [-]	C_4 [-]	C_5 [m^2]	C_6 [kW]	C_7 [k$]	C_8 [yr]	C_9 [k$]	C_8 [yr]	C_9 [k$]	C_8 [yr]	C_9 [k$]	C_{10} [-]
a_1	3	3	1	0	454.73	67.5	148.7	4.09	235.8	3.93	284.8	3.70	382.1	1.25
a_2	4	5	1	1	292.50	107.5	126.8	3.82	221.1	3.68	265.4	3.52	353.5	2.25
a_3	3	3	2	1	304.54	107.5	105.2	3.09	242.6	3.00	287.0	2.86	375.0	0.75
a_4	3	3	1	1	293.43	116.6	101.3	3.00	238.2	2.96	281.5	2.82	367.5	0.75
a_5	4	5	1	1	306.01	107.5	129.8	3.92	218.1	3.78	262.4	3.56	350.5	1.50
a_6	3	4	2	1	322.63	107.5	123.5	3.70	224.4	3.58	268.7	3.38	356.8	1.25
a_7	3	4	2	1	320.05	107.5	124.1	3.73	223.8	3.59	268.1	3.40	356.2	1.25
a_8	4	5	1	1	308.59	107.5	129.2	3.90	218.7	3.76	263.0	3.54	351.1	1.50
a_9	4	5	1	1	304.14	107.5	129.3	3.91	218.6	3.76	262.9	3.55	351.0	1.50
a_{10}	4	5	1	1	307.43	107.5	130.4	3.94	217.5	3.80	261.8	3.58	349.9	1.50
a_{11}	2	2	2	1	309.77	133.5	89.8	2.80	234.3	2.73	275.6	2.62	357.6	0.50
a_{12}	3	3	1	1	296.81	105.0	110.2	3.23	239.9	3.13	284.6	2.98	373.2	0.75
a_{13}	2	2	2	1	306.27	150.0	87.3	2.86	221.7	2.79	261.1	2.67	339.3	0.50
a_{14}	1	1	2	2	307.42	313.5	57.3	3.76	102.0	3.63	122.3	3.43	162.2	0.25
a_{15}	3	3	1	2	249.24	162.5	85.0	2.90	212.5	2.82	250.5	2.70	325.8	1.00
a_{16}	2	2	1	2	235.18	262.5	55.0	2.72	150.4	2.65	176.3	2.55	228.8	0.50
a_{17}	2	2	1	1	247.31	225.0	65.0	2.73	175.3	2.66	205.9	2.55	266.8	0.50
a_{18}	1	1	2	1	215.34	307.5	32.5	1.93	132.3	1.90	153.3	1.85	195.0	0.25
a_{19}	3	4	1	1	262.11	172.5	96.7	3.47	191.7	3.36	228.4	3.19	301.4	1.00
a_{20}	3	3	1	0	372.04	67.5	131.3	3.54	253.2	3.43	302.2	3.25	399.5	2.00
a_{21}	2	2	1	1	307.95	225.0	81.2	3.50	159.1	3.39	189.7	3.21	250.6	2.00
a_{22}	4	4	1	1	405.67	69.0	125.9	3.39	257.2	3.28	306.1	3.12	403.0	1.50
a_{23}	2	2	2	1	265.12	151.5	76.8	2.50	230.8	2.44	270.0	2.35	347.9	0.50

The weights and preference functions P_j that have been assigned to each criterion C_j are presented in table 4.5. The indicated values are considered to be reasonable estimates. There is a strong emphasis on the economic criteria and a moderate emphasis on the technical ones. This represents the case where the decision maker is primarily concerned with the possible economic benefits of energy conservation by installing a heat exchanger network.

Table 4.5: The weights w_j and the preference functions P_j assigned to the criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
w_j	0.025	0.025	0.050	0.050	0.025	0.075	0.125	0.250	0.250	0.125
P_j-type	4	2	4	4	6	5	6	3	3	4
q	0.5	3.5	0.5	0.5	-	15	-	-	-	0.65
p	1.5	-	1.5	1.5	-	50	-	0.75	100	1.15
σ	-	-	-	-	75	-	50	-	-	-

4.4.4 Results

The alternative heat exchanger networks ranked in the first ten places for scenario 1, 2 and 3 are presented in table 4.6. As discussed in appendix 1, the complete ranking is determined by the net flow ϕ which has a value between -1 and 1. The higher the net flow, the better the alternative. A partial ranking can be obtained from the leaving flow ϕ^+ and the entering flow ϕ^- values, which are defined in appendix 1. The higher ϕ^+ and the lower ϕ^-, the better the alternative. For the first five completely ranked alternatives the values of these flows are presented in figure 4.2.

A sensitivity analysis has been performed to test the stability of the results. It turned out that variations of $\pm$ 10% in the parameters of the preference function have a negligible influence on the partial and complete rankings. Another important indicator for the stability of the results, is obtained from varying the weights given to the criteria. This can be done by determining weight stability intervals, weight stability polygons and weight stability areas. Weight stability intervals indicate within what ranges the weights can vary (one at a time), without changing the complete ranking. The wider the interval, the more stable the ranking.

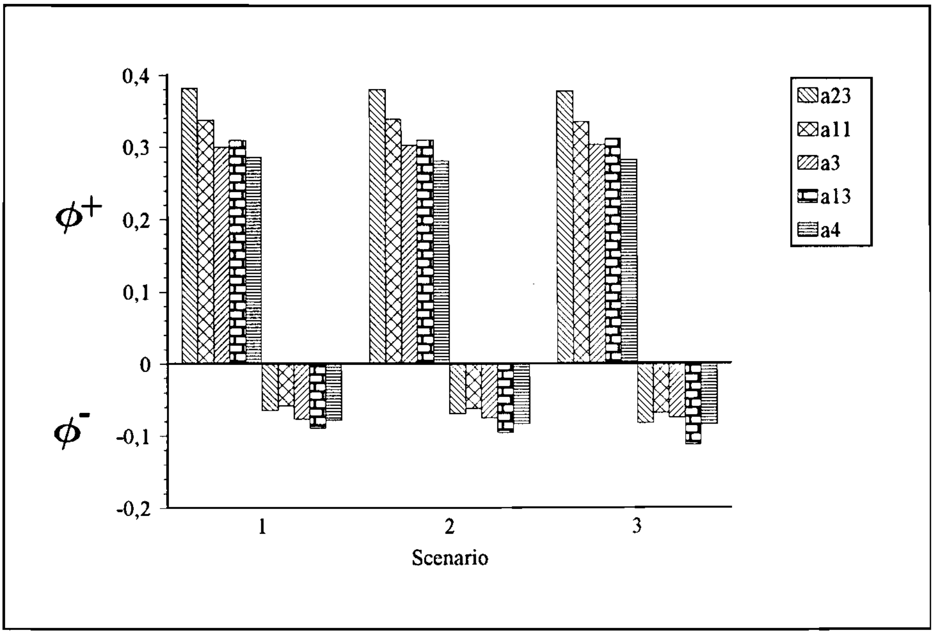

Figure 4.2: ϕ^+ and ϕ^- of the first five completely ranked alternatives.

Table 4.6: The first ten ranked alternatives for scenario 1, 2 and 3.

	Scenario 1		Scenario 2		Scenario 3	
Rank	alternative	ϕ	alternative	ϕ	alternative	ϕ
1	a_{23}	0.31745	a_{23}	0.31097	a_{23}	0.29445
2	a_{11}	0.27995	a_{11}	0.27679	a_{11}	0.26649
3	a_3	0.22258	a_3	0.22697	a_3	0.22716
4	a_{13}	0.22022	a_{13}	0.21374	a_{13}	0.19830
5	a_4	0.20718	a_4	0.19790	a_4	0.19753
6	a_{18}	0.17315	a_{18}	0.15541	a_{12}	0.15592
7	a_{12}	0.14737	a_{12}	0.15274	a_{18}	0.14476
8	a_{15}	0.14199	a_{15}	0.13486	a_{15}	0.11281
9	a_{17}	0.09844	a_{22}	0.07970	a_{22}	0.09819
10	a_{16}	0.06885	a_{17}	0.07294	a_{17}	0.03275

In table 4.7, weight stability intervals of the results obtained for scenario 2 are presented. Two sets of weight stability intervals are presented: One for the complete ranking of all 23 alternatives (stability level: 23) and another one for the alternatives ranked in the first five places (stability level: 5). These results are representative for the weight stability intervals of the results obtained for the other two scenarios.

Table 4.7: The weight stability intervals for the results in scenario 2.

	Value of weight	Weight stability interval Stability level: 23	Weight stability interval Stability level: 5
w_1	0.025	<0.0221 - 0.0315>	<0.0000 - 0.0491>
w_2	0.025	<0.0134 - 0.1157>	<0.0000 - 0.1786>
w_3	0.050	<0.0451 - 0.0947>	<0.0203 - 0.1214>
w_4	0.050	<0.0000 - 0.0814>	<0.0000 - 0.1522>
w_5	0.025	<0.0207 - 0.0323>	<0.0000 - 0.1116>
w_6	0.075	<0.0707 - 0.0769>	<0.0526 - 0.1043>
w_7	0.125	<0.1216 - 0.1365>	<0.0000 - 0.1809>
w_8	0.250	<0.2476 - 0.2577>	<0.1651 - 0.2970>
w_9	0.250	<0.2447 - 0.2517>	<0.2209 - 0.3070>
w_{10}	0.125	<0.1146 - 0.1353>	<0.0000 - 0.2628>

The stability of a ranking can also be studied by means of so-called weight stability polygons and weight stability areas. A weight stability polygon can be obtained for any combination of weights of two criteria. It indicates within which region these two weights are allowed to vary (keeping the other weights constant) without changing the ranking. The larger the area of the polygon, and the further the current weights are from the boundaries of the polygon, the more stable the ranking. Weight stability areas can also be determined for any combination of weights of two criteria; they indicate all the polygons within which the combinations of weights give rise to another ranking (if the other weights are kept constant). If a large number of areas are present in the neighbourhood of the polygons containing the current combination of weights, this means that the crossing of the boundaries of this polygon can give rise to a large number of different rankings, i.e. that the ranking can be unstable. In figure 4.3 an example of a weight stability polygon and weight stability areas for criterion C_8 and C_{10} (scenario 2, stability level: 5) is presented.

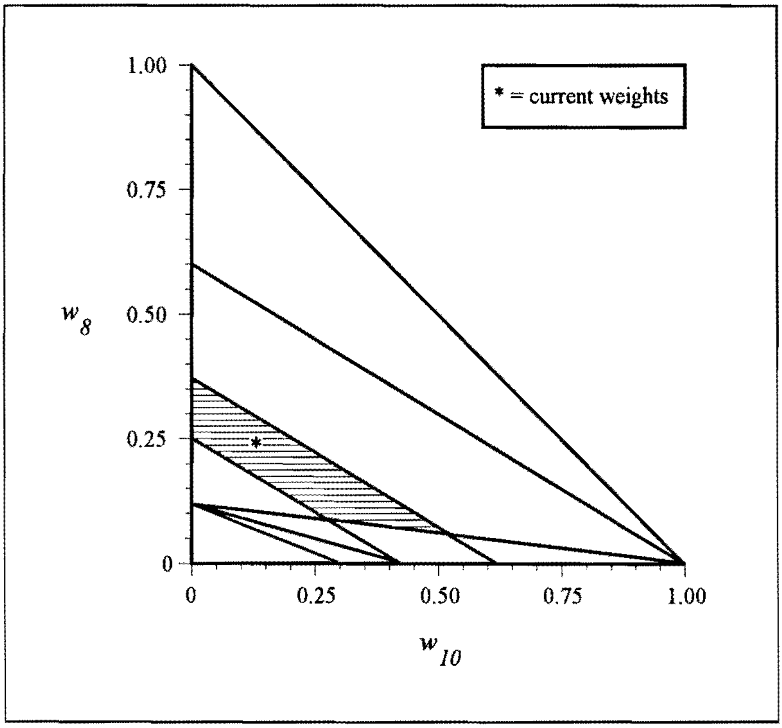

Figure 4.3: The weight stability polygon and areas (stability level: 5).

It is important to realize that some criteria are conflicting while some are in agreement with other. To study this kind of interaction, a principal component analysis of the generalized evaluations of the alternatives, is performed. This is done using the GAIA-method (Mareschal and Brans, 1988). By means of this method a set of orthonormal eigenvectors is determined for the matrix of evaluations. By projection of all alternatives and criteria on the plane spanned by the eigenvectors with the highest eigenvalue, a geometrical representation of the way the generalized criteria interact is obtained. In figure 4.4 the result of the analysis of the evaluations in scenario 2 is presented. In this figure, criteria are represented by axes. Conflicting criteria are opposite to each other, while those that are in agreement with each other are more or less in the same direction. More or less orthogonal axes indicate that the corresponding criteria are independent. The length of a criterion axis indicates to what extent that criterion discriminates between the alternatives. The positions of the alternatives in figure 4.4 is such that their projections on the criterion-axes more or less correspond to the ranking based on that criterion.

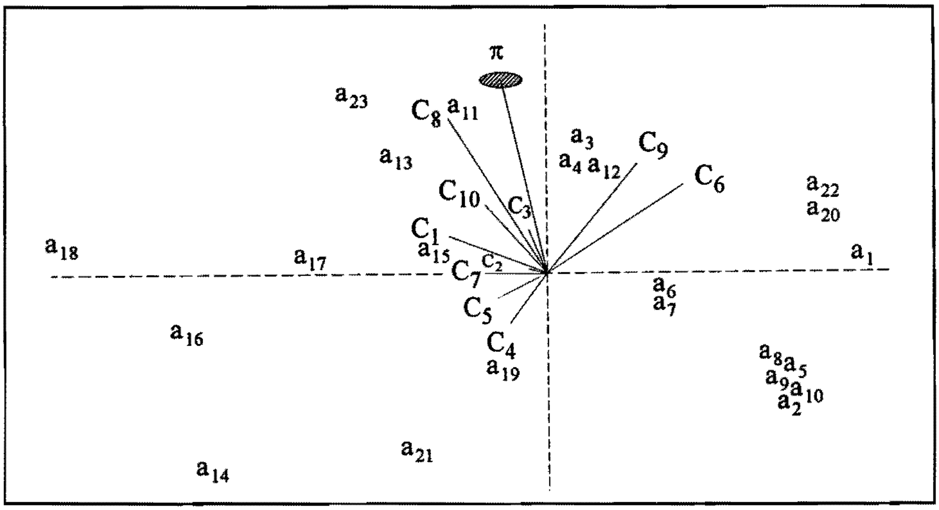

Figure 4.4: The geometrical representation of the decision space.

The π-vector shown in figure 4.4 indicates in what direction to look for "good" alternatives. The projections of the alternatives on the π-vector correspond to their complete ranking. Since the π-vector is determined by the weights assigned to the criteria, it is useful to perform a sensitivity analysis and study how the position of this vector will change if certain weights are changed. If all weights are allowed to vary simultaneously ±10% around their initially specified value, the top of the π-vector will swap within the hatched region indicated in figure 4.4.

In projecting an N-dimensional space on a two dimensional plane, some information is lost. However, since this plane is spanned by those two eigenvectors with the highest eigenvalue, the highest amount of information is preserved. This is indicated by the value of δ, which in the case presented in figure 4.4, equals 82%.

4.4.5 Discussion

From table 4.6, it results that heat exchanger network a_{23}, which is presented in figure 4.5, is the first ranked alternative in the complete (Promethee II) ranking, for all three scenarios. From this it is concluded that, given the expected future developments in the circumstances under which the heat exchanger network has to operate, alternative a_{23} is the best compromise between the applied criteria, taking into account the given preferences and weights. However, according to the Promethee I partial ranking which can be obtained from figure 4.2 (also see

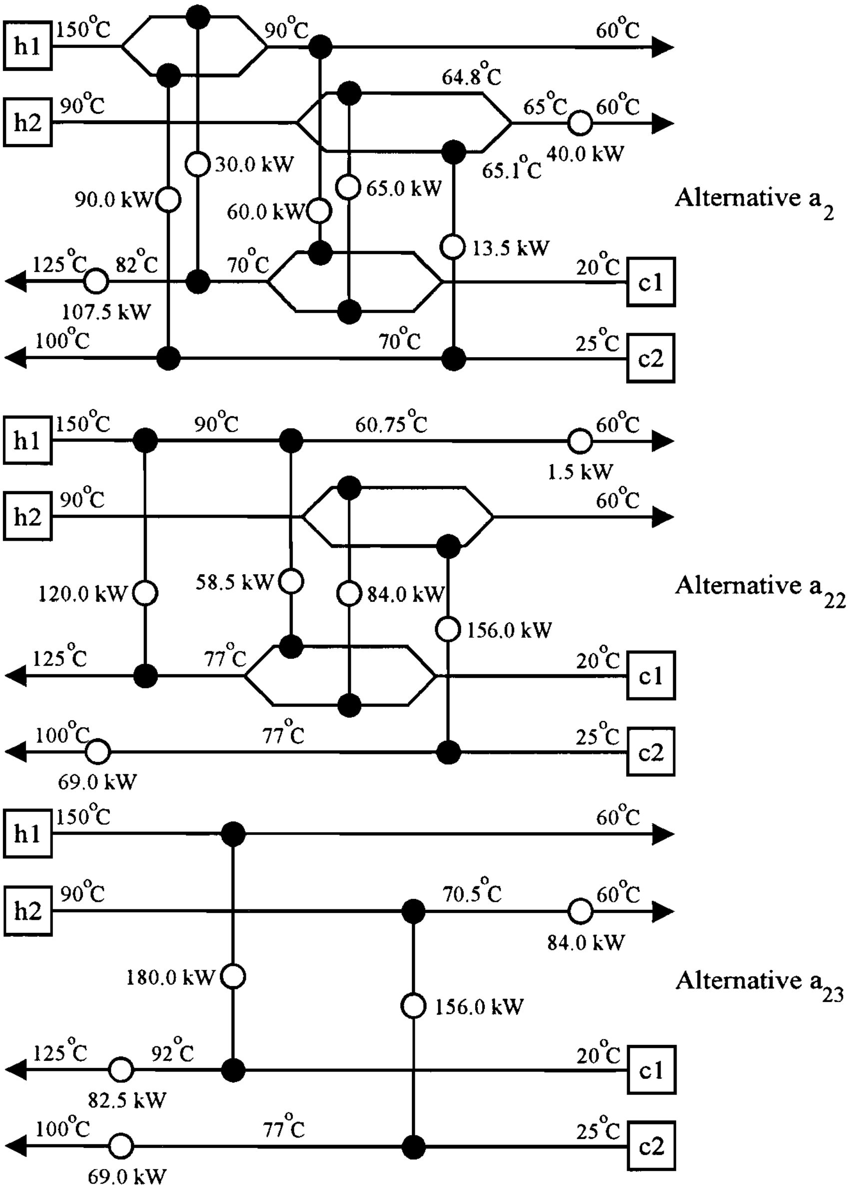

Figure 4.5: Alternatives a_2, a_{22} and a_{23}.

appendix 1), no clear distinction can be made between heat exchanger networks a_{11} and a_{23}, since for all three scenarios $\phi^{-}(a_{11}) < \phi^{-}(a_{23})$. As a result of this, a_{11} may also be considered as a good compromise. Alternative a_{11} and a_{23} are both solutions which do not meet the MER condition. From figure 4.5 it follows that a_{23} is a heat exchanger networks with a relatively simple structure when compared to e.g. a_2 and a_{22}, which do meet the MER condition.

From table 4.6 and figure 4.2, it can also be seen that alternative a_{23} and a_{11} become relatively worse with increasing cost of hot and cold utility (decreasing value of ϕ and ϕ^{+}, and increasing value of ϕ^{-}). However, given the preferences and the weights, a yearly increase of 5% in the hot and cold utility cost (scenario 3) induces no changes in the first five ranked alternatives, although it does in the last part of the ranking.

Table 4.7 and figure 4.3 show that the complete ranking of the 23 alternatives is relatively stable considering the large number of alternatives and criteria. The stability of the first five ranked alternatives turns out to be far more stable.

From figure 4.4 it is concluded that a strive for minimum heating (C_6) (energy conservation) is in agreement with a strive for a maximum net present value (C_9). This is, however, at the expense of (among others) an increase of the number of active matches (C_1) and heat exchangers (C_2), an increase of the total heat exchanging area (C_5) and certain cost (C_7). Furthermore it follows that in this case, a strive for a short pay-back time (C_8) and a high net present value (C_9) are relatively independent of each other. Since criteria C_6, C_8 and C_9 have the longest criterion axes, these criteria discriminate the most between the alternatives. The position of the alternatives in figure 4.4 is such that the alternatives meeting the MER condition are situated in the first and fourth quadrant, while almost all other alternatives are in the second and third one.

4.5 Experiment II

4.5.1 Introduction

In this section a stochastic multiple criteria evaluation of a set of heat exchanger networks is performed (Wolters, 1992). For this purpose five alternative heat exchanger networks (HEN 1, HEN 2, HEN 3, HEN 4, HEN 5) have been evaluated by a number of experts. The alternatives (respectively corresponding to alternatives a_4, a_3, a_{11}, a_{22} and a_5 in table 4.4) are situated in the theoretical production system described in section 4.3. The heat exchanger networks differ in the number of heat exchangers, the heat exchanging area, the resulting decrease in the demand for hot and cold utility, etc.

The alternatives have been evaluated through four criteria: complexity, flexibility, profitability and unsafety. The experts are also asked to express their preferences with respect to the importance of these criteria. To cope with the uncertainties in the evaluations, a stochastic multiple criteria evaluation is performed by means of the Promethee methods (see appendix 1).

4.5.2 Definition of the criteria

The criteria through which each alternative is evaluated, are defined as:

Complexity:	Degree to which the structure (and thus the control) of the production system is complicated by the introduction of heat exchangers, splitters and active and stand-by utilities. Complexity is to be minimised.
Flexibility:	Degree to which the heat exchanger network can cope with the possible variations in initial temperature and heat flow rate, without causing (more) breakdown. Flexibility is to be maximised.
Profitability:	Degree to which the heat exchanger network is able to give a positive net present value over its total lifetime, under the uncertain conditions. Profitability is to be maximised.
Unsafety:	Degree to which the introduction of the heat exchanger network is an extra source of risk. Unsafety is to be minimised.

The complexity of a heat exchanger network is an important feature since it complicates the control of a production system. For instance, the starting and stopping characteristics may be changed by the introduction of a heat exchanger network. The flexibility of the heat exchanger network to be introduced, is important because it directly influences the operational behaviour of a production system. Introduction of an inflexible heat exchanger network leads to extra breakdown. The profitability of the heat exchanger networks is an important criterion for strategic (energy) management reasons. Since safety considerations play an important role in industry, the unsafety introduced by a heat exchanger network has to be taken into account.

All criteria are evaluated on a five-point scale. A scale starts with "very low" and ends with "very high". For calculation purposes this scale is transformed into a numerical scale ranging from 1 (≡ very low) to 5 (≡ very high).

4.5.3 Results

The selected experts have an academic and/or industrial background. Academic experts have been selected on the basis of their publications on the design of heat exchanger networks, while industrial experts have been selected on the basis of personal contacts in the process industries. In all, 18 experts have been asked to evaluate the alternative heat exchanger networks, of which 10 (E.1, E.2,...,E.10) actually responded by returning the completed questionnaire. Another 4 experts responded by indicating that they were unable to complete the questionnaire because they felt they were not qualified or did not have the time.

The evaluations of the five alternative heat exchanger networks (HEN), are presented in table 4.8. The sequence of figures in this table represent the evaluations that have been given to the alternative heat exchanger networks, on the criteria complexity, flexibility, profitability and unsafety respectively. The experts also assigned weights to the criteria. This proceeded by a pairwise comparison of the criteria. The resulting weights are also presented in table 4.8. w_1, w_2, w_3 and w_4 are the weights assigned to the criteria complexity, flexibility, profitability and unsafety respectively.

Table 4.8: The evaluations of the heat exchanger networks and the weights assigned to the criteria by the experts (E.1,..., E.10).

	HEN 1	HEN 2	HEN 3	HEN 4	HEN 5	w_1	w_2	w_3	w_4
E.1	4 3 3 4	4 4 2 5	2 4 4 3	5 2 1 5	5 3 1 5	0	1/6	1/3	1/2
E.2	3 3 4 4	2 4 4 4	2 4 3 4	4 1 5 5	5 1 4 4	0	1/3	1/6	1/2
E.3	2 1 4 3	3 5 5 4	1 4 1 3	4 2 2 5	5 3 3 5	0	1/6	1/3	1/2
E.4	3 2 3 3	3 3 4 4	2 4 4 3	5 4 5 4	5 5 5 4	0	1/6	1/3	1/2
E.5	3 3 4 4	3 3 4 5	2 4 4 4	5 1 5 5	5 1 5 5	1/6	1/6	1/6	1/2
E.6	3 4 4 4	3 4 4 4	2 4 4 4	4 2 4 4	4 4 4 4	0	1/4	1/4	1/2
E.7	3 2 4 3	3 4 4 4	2 4 2 3	4 3 4 5	4 2 2 5	1/3	0	1/6	1/2
E.8	3 3 3 4	3 3 3 4	2 4 4 3	4 2 2 4	5 1 2 5	1/6	1/6	1/6	1/2
E.9	3 4 4 3	3 3 4 5	2 4 2 3	4 3 5 5	4 3 3 5	0	1/6	1/3	1/2
E.10	4 3 4 3	3 3 4 3	2 4 5 4	4 3 3 4	4 3 3 4	1/6	1/6	1/6	1/2

For each expert, the evaluations presented in table 4.8 have been analyzed using the Promethee methods. For each criterion the three level preference function has been used, with parameters q=1.5 and p=2.5. The resulting Promethee II (complete) rankings of the alternative heat exchanger networks are presented in table 4.9. The figures in this table denote the rank number (averaged in the case of ties).

Table 4.9: The Promethee II complete rankings (averaged in the case of ties).

	HEN 1	HEN 2	HEN 3	HEN 4	HEN 5
E.1	2	3	1	5	4
E.2	3	1	2	4	5
E.3	2	1	3	5	4
E.4	5	4	3	2	1
E.5	2.5	2.5	1	4.5	4.5
E.6	2.5	2.5	1	5	4
E.7	1	3	2	4	5
E.8	2.5	2.5	1	4	5
E.9	1	4	2	3	5
E.10	3	2	1	4.5	4.5
s(a) (rank)	2.45 (2)	2.55 (3)	1.7 (1)	4.1 (4)	4.2 (5)

In the last row of table 4.9, the values of the *s(a)* function (see appendix 1) are presented (it is assumed that all experts have equal weights, i.e. $p_l = 0.1$). These values determine the average complete ranking of the alternative heat exchanger networks. The ranking is indicated by the ordinals in the last row of table 4.9. HEN 3 is clearly the "best" alternative, followed by HEN 1, HEN 2, HEN 4 and HEN 5, which are ranked in second, third, fourth and fifth place respectively. Note the relatively large distance between the alternatives ranked in the first three places and the other two. Also note the fact that HEN 1 and HEN 2 are very close to each other.

From the evaluations presented in table 4.8, a partial ranking has been obtained for each expert. Subsequently, a global partial ranking has been determined, assuming equal weights for all experts. The values of S(a,b), and $S^+(a)$ and $S^-(a)$ (see appendix 1) are presented in table 4.10. S^+ and S^- induce two rankings on the set of alternatives (the higher and lower the value of respectively S^+ and S^-, the better the alternative), the intersection of which is a partial ranking as in the Promethee methods. From table 4.10 it follows that HEN 3 is ranked first in the partial ranking. No clear distinction can be made between HEN 1 and HEN 2, since according to the S^+ and S^- ranking, these alternatives are respectively ranked second and third, and third and second.

Table 4.10: The values of S(a,b), $S^+(a)$, and $S^-(a)$.

	HEN 1	HEN 2	HEN 3	HEN 4	HEN 5	S^+ (rank)
HEN 1	1.0	0.5	0.2	0.9	0.9	3.5 (2)
HEN 2	0.4	1.0	0.2	0.8	0.9	3.3 (3)
HEN 3	0.6	0.6	1.0	0.8	0.8	3.8 (1)
HEN 4	0.1	0.1	0.0	1.0	0.6	1.8 (4)
HEN 5	0.1	0.1	0.0	0.4	1.0	1.6 (5)
S^- (rank)	2.2 (3)	1.8 (2)	1.4 (1)	3.9 (4)	4.2 (5)	

To test the stability of the results, weight stability intervals have been determined for each expert. In spite of the rough way the weights have been measured, the rankings are very stable. In table 4.11 weight stability intervals are presented for one of the most instable rankings.

Table 4.11: The weight stability intervals for expert 9.

	Value	Stability interval
w_1 (complexity)	0	<0 - 0.67>
w_2 (Flexibility)	1/6	<0 - ∞>
w_3 (Profitability)	1/3	<0 - 0.36>
w_4 (Unsafety)	1/2	<0.47 - ∞>

4.5.4 Discussion

From the evaluations presented in table 4.8, it follows that some disagreement exists between the experts. Therefore it is interesting to study the concordance between the rankings obtained for each expert by calculating Kendall's W (an increasing function of the degree of agreement between the rankings; $0 \leq W \leq 1$) (Mareschal, 1986; Ferguson, 1976). For the rankings presented in table 4.9, $W = 0.485$, which is a moderate value. From this it is concluded that some disconcordance between the rankings exists.

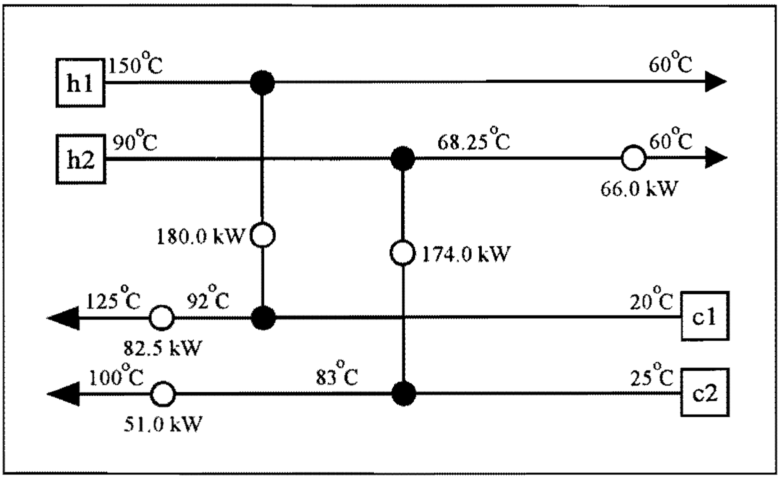

Figure 4.6: The first ranked heat exchanger network (HEN 3).

From table 4.8 and 4.9 it follows that expert 4 has given some peculiar evaluations, which results in a questionable complete ranking. If expert 4 is excluded, Kendall's *W* equals 0.735, which is a satisfying value. The exclusion of expert 4 does not change the complete and partial stochastic ranking of the alternatives.

From table 4.8 it can be seen that a number of non-economical considerations play an important role in the decision process on energy conservation projects. Especially safety considerations are very important. Two (industrial) experts even indicated that these considerations may become the principal constraint on energy conservation by heat exchanger networks.

From table 4.9 it follows that HEN 3 (presented in figure 4.6) is the first ranked alternative, followed by HEN 1 and HEN 2 which are ranked second and third respectively. Since HEN 3 is the alternative that does not result from standard methods on optimum heat exchanger network design, it is concluded that in a specific practical situation, a heat exchanger network is preferred, which does not result from such methods.

4.6 A novel type of sensitivity analysis

4.6.1 Introduction

The results obtained by application of a multiple criteria decision aid method are strongly related to the values assigned to the weights. Therefore, great care has to be taken when the results of such a method are interpreted. To facilitate this task, the use of sensitivity analyses has been promoted in the Promethee methods. This enables the study of the consequences of modifications of the initially specified weights on the results. The sensitivity analyses include the determination of weight stability intervals, weight stability polygons and weight stability areas (Mareschal, 1988). The common factor between these approaches is that boundaries are determined within which the weights can be changed, without modifying the ranking of all or a subset of alternatives. Although this provides sufficient information on the stability of the ranking, it does not give insight into the way the ranking is changed if the boundaries are exceeded. As a result of this, no insight into the total weight-space can be provided to the decision maker. To gain this insight, the minimum modification of the weights required to modify the ranking in such a way that a specific alternative becomes ranked first, is determined. For this purpose, a LP-model is formulated (Wolters and Mareschal, 1993). The proposed sensitivity analysis is illustrated by a demonstration problem.

4.6.2 Mathematical formulation

Consider A, a set of n alternatives a_i (i = 1,...,n), evaluated on k criteria. Given a set of weights w_j (j = 1,2,...k) and preference functions, the Promethee II complete ranking is defined as in appendix 1. If a set of modified weights w_j^* has to be determined such that alternative a^* is ranked first, this means that the following inequalities have to be met:

$$\phi(a^*) \geq \phi(a) , \qquad \forall\, a \in A \tag{4.6}$$

This can be rewritten to give:

$$\sum_{j=1}^{k} \left(\phi_j(a^*) - \phi_j(a)\right) w_j^* \geq 0 , \qquad \forall\, a \in A \tag{4.7}$$

with:

$$\sum_{j=1}^{k} w_j^* = 1 \tag{4.8}$$

$$w_j^* \geq 0 , \quad j = 1,\ldots,k \tag{4.9}$$

$$\phi_j(a) = \sum_{b \in A} \left(P_j(a,b) - P_j(b,a)\right) \tag{4.10}$$

Relations 4.7 to 4.10 define a polyhedron in the space of the weights. Each set of weights w_j^* satisfying these relations, is such that alternative a^* is ranked first. To measure the minimal distance between the initial and modified weights, the following objective function is introduced:

$$MIN \sum_{j=1}^{k} \left| w_j^* - w_j \right| \tag{4.11}$$

Although relation 4.11 is linear, it cannot be optimised directly by applying linear programming (LP) because of its discontinuous character. To overcome this problem w_j^* has to be rewritten as:

$$w_j^* = w_j + d_j^+ - d_j^- \tag{4.12}$$

Where d_j^+ and d_j^- are positive variables, respectively representing the increase or decrease of w_j. Using relation 4.12, relation 4.11 is rewritten as:

$$MIN \sum_{j=1}^{k} \left(d_j^+ + d_j^-\right) \tag{4.13}$$

Subject to:

$$\sum_{j=1}^{k} \left(\phi_j(a^*) - \phi_j(a)\right)\left(w_j + d_j^+ - d_j^-\right) \geq 0 , \quad \forall\, a \in A \tag{4.14}$$

$$\sum_{j=1}^{k} \left(d_j^+ - d_j^-\right) = 0 \tag{4.15}$$

$$d_j^+ - d_j^- \geq -w_j\,, \qquad j = 1,\ldots,k \tag{4.16}$$

$$d_j^+ \geq 0\,, \qquad d_j^- \geq 0\,, \qquad j = 1,\ldots,k \tag{4.17}$$

Relation 4.13 can be solved as a LP problem with relations 4.14 to 4.17 as constraints. It involves *2k* variables and *3k* + *n* constraints.

4.6.3 Extensions to the model

1° Constraints on the absolute importance of specific criteria

In most sensitivity analyses, it is assumed that all weights can vary independently of each other (Mareschal, 1988; Insua and French, 1991). However, in practice this might not always be the case. For instance, a decision maker may be able to state that a certain subset of criteria has to determine the result of the multiple criteria evaluation to a certain fixed degree, i.e. that the sum of the normalised weights of the criteria from the subset has to remain constant. This requirement can be included in the formulation developed in the previous section. Let *C* be the set of criteria, and let *S* be a subset of *C*. If the sum of the weights of the criteria of *S* has to remain constant:

$$\sum_{j \in S} w_j = \sum_{j \in S} w_j^* \tag{4.18}$$

and, using relation 4.12, the following constraint should be added to the LP-problem:

$$\sum_{j \in S} \left(d_j^+ - d_j^-\right) = 0 \tag{4.19}$$

2° Constraints on the relative importance of specific weights

The decision maker might also be able to state that the relative importance of two criteria or subsets of criteria must remain constant. This is expressed by relation 4.20 for two criteria with indices *j* and *j'*. This relation can also be transformed into a linear constraint and included in the LP model by means of relations 4.21.

$$\frac{w_j}{w_{j'}} = \frac{w_j^*}{w_{j'}^*} \tag{4.20}$$

$$w_j\left(d_{j'}^+ - d_{j'}^-\right) = w_{j'}\left(d_j^+ - d_j^-\right) \tag{4.21}$$

3° Cost coefficients in the objective function

In deriving the objective function 4.13 it is assumed that all weights are equally likely to change. Consequently their contributions to the objective function are equal. However, in practice a decision maker may state that some weights are more likely to change than others, or that a certain weight is more likely to increase than to decrease. To take such effects into account, cost coefficients can be included in 4.13. The objective function then becomes:

$$MIN \sum_{j=1}^{k} \left(c_j^+ d_j^+ + c_j^- d_j^-\right) \tag{4.22}$$

The coefficients c_j^+ and c_j^- are positive numbers, representative of the cost or likelihood of respectively increasing and decreasing the value of w_j: a higher/lower value indicates a higher/lower cost or a lower/higher likelihood.

4° Bounds on the values of the weights

In some cases, the decision maker may specify bounds on the values that the weights can take. For instance, for criterion *j*:

$$w_j^{lo} \leq w_j \leq w_j^{hi} \tag{4.23}$$

This requirement is introduced in the LP model by adding the following constraints:

$$d_j^+ \leq w_j^{hi} - w_j \tag{4.24}$$

$$d_j^- \leq w_j - w_j^{lo} \tag{4.25}$$

In this way it becomes possible to test whether an alternative can be ranked first with the weights of the criteria limited to the specified intervals.

4.6.4 The demonstration problem

To demonstrate the proposed sensitivity analysis, a reduced version of the problem treated in section 4.3 has been analyzed. This problem comprises alternative heat exchanger networks a_1, a_3, a_4, a_{11}, a_{12}, a_{13}, a_{15}, a_{20}, a_{22} and a_{23} from table 4.4, which will be called respectively A1, A2,...A10 in this section. These alternatives are evaluated in the "business as usual" scenario through the same criteria as in section 4.4.

Additional constraints expressing that the relative importance of the following sets of criteria remains constant are specified: C_1 versus C_2, C_2 versus C_5, C_3 versus C_4, C_7 versus C_8, and C_7 versus C_9. Furthermore, two additional constraints expressing that the absolute importance of the subsets of criteria C_1, C_2, C_5, and C_7, C_8, C_9 have to remain constant, are added. In order to take into account that some weights are more likely to vary than others, cost-coefficients (c_j) are specified ($c_j = c_j^+ = c_j^-$). These are presented in table 4.12. The boundaries of the weight intervals have been specified to be w_j ± 25%.

Table 4.12: The cost coefficients c_j specified for the criteria.

	$j=1$	$j=2$	$j=3$	$j=4$	$j=5$	$j=6$	$j=7$	$j=8$	$j=9$	$j=10$
c_j	15	15	6	6	10	50	9	10	6	40

4.6.5 Results and discussion

The proposed sensitivity analysis is performed for each alternative. Five cases are considered; in case 1 no additional constraints and no cost coefficients are added to the LP problem. In case 2 the specified constraints on the relative and absolute importance of specific criteria are added. In case 3 the specified weight intervals are taken into account. In case 4 and 5 the cost coefficients are introduced in the objective function, and the LP-problem is solved respectively without and with the same specified constraints as in case 2.

In table 4.13 the complete ranking of the alternatives is presented. The results of the sensitivity analysis for case 1 through 5 are presented in table 4.14. It appears that in case 1 no set of weights $\{w_j^*\}$ exists for which alternative A3 or A6 is ranked first. This can lead to the exclusion of these alternatives. If the complete ranking and the results for case 1 are compared, it follows that the calculated minimum modification is relatively low for high ranked alternatives (e.g. A2, A9), and relatively high for low ranked ones (e.g. A1, A7, A5). Despite this, ranking of the alternatives based on the minimum modification, does not yield the same result as in table 4.13. From this it is concluded that a high ranked alternative might be "further" away than a lower ranked alternative. This is, for instance, the case with alternative A4 and A9. This may lead the decision maker to the conclusion that A9 might be a better alternative than A4.

Table 4.13: The ϕ values and the complete ranking of the alternatives.

	A1	A2	A3	A4	A5
ϕ value	-0.33259	0.12167	0.07016	0.14054	0.01886
Rank	10	3	4	2	6
ϕ value	-0.01222	-0.013617	-0.10422	0.04203	0.19194
Rank	7	9	8	5	1

Table 4.14: The results of the sensitivity analysis (-- = impossible).

	Case 1	Case 2	Case 3	Case 4	Case 5
A1	0.84181	--	--	16.10594	--
A2	0.10227	--	0.11058	0.92310	--
A3	--	--	--	--	--
A4	0.25365	--	--	2.90110	--
A5	0.79149	--	--	8.50293	--
A6	--	--	--	--	--
A7	0.55900	--	--	3.35401	--
A8	0.42701	--	--	5.95399	--
A9	0.13844	0.16832	0.15569	1.12835	5.58380
A10	0.00000	0.00000	0.00000	0.00000	0.00000

In case 2, additional constraints on the absolute and relative importance of specific criteria are added to the LP-problem. In the second column of table 4.14 the results that are obtained in this case are presented. The introduction of the additional constraints makes the LP problem more restricted, as a result of which most alternatives cannot be ranked first. From this it is concluded that introducing such additional constraints facilitates the selection process. In the third, fourth and fifth column of table 4.14, the results obtained for respectively case 3, 4 and 5, are presented. From the results of case 3 it follows that if the weights are allowed to vary within intervals of ±25% around the initial values, only A2 and A9 can become ranked first, which reduces the selection procedure drastically.

If the results of the fourth case are compared to the results of the first case, it becomes clear that in the fourth case the minimum modification of the weights is changed relatively (e.g. A1 and A2), and that the sum of the modifications becomes larger. In table 4.15 the values of d_j^+ and d_j^- are presented for A1 in case 1 and 4. It shows that by introducing the cost coefficients other weights have to be changed, i.e. another longer path has to be taken in the weight space. If the results of case 2 and 5 are compared, the same observations hold true as in the comparison of the results of case 1 and 4.

Table 4.15: The values of d_j^+ and d_j^-.

		Case 1			Case 4		
	w_j	d_j^+	d_j^-	w_j^*	d_j^+	d_j^-	w_j^*
$j=1$	0.025	0.135	0.000	0.159	0.000	0.000	0.025
$j=2$	0.025	0.000	0.000	0.025	0.584	0.000	0.609
$j=3$	0.050	0.000	0.000	0.050	0.000	0.050	0.000
$j=4$	0.050	0.000	0.000	0.050	0.000	0.050	0.000
$j=5$	0.025	0.000	0.000	0.025	0.000	0.025	0.000
$j=6$	0.075	0.272	0.000	0.347	0.042	0.000	0.117
$j=7$	0.125	0.000	0.000	0.125	0.000	0.125	0.000
$j=8$	0.250	0.000	0.250	0.000	0.000	0.250	0.000
$j=9$	0.250	0.000	0.171	0.079	0.000	0.127	0.123
$j=10$	0.125	0.015	0.000	0.140	0.000	0.000	0.125

4.7 Conclusions

In section 4.4 of this chapter it is demonstrated that by using the Promethee methods it is possible to support a decision maker in the process of selecting a heat exchanger network from a set of alternative solutions, taking into account possible future developments in the economic circumstances. The results show that, if heat exchanger networks are ranked on the basis of a combination of technical and managerial criteria, entirely different "optimal" solutions than the ones presented in the literature to date, are ranked in the first places. In fact, it is demonstrated that a solution which does not meet the MER condition, may be preferable (given the preferences) from the point of view of strategic management, since it is the first ranked alternative for all three scenarios.

Furthermore, it is demonstrated that by extensive sensitivity analyses and a geometrical representation, information is provided that may give insights into the selection problem.

The practical applicability of the proposed methods is illustrated by a stochastic multiple criteria evaluation of a set of alternative heat exchanger networks for a specific case. The results, presented in section 4.5, show that with a high degree of agreement between the experts, the first ranked alternative is the one that does not result from the standard methods on heat exchanger network design. From this it is concluded that in a practical situation such a "non-optimal" (Gundersen and Naess, 1988; Gundersen *et al.*, 1991) heat exchanger network is preferred. This strengthens and validates the conclusion of the simulation experiment of section 4.4. In practice, it may therefore be useful to evaluate a number of "optimal" and "non-optimal" heat exchanger networks through multiple criteria, and to rank them by using methods such as Promethee.

In section 4.6 a novel type of sensitivity analysis is presented. This comprises the determination of the minimum modification of the weights, to make a specific alternative ranked first, meanwhile taking into account specific requirements on the weight variations. It is demonstrated that this is a tool to analyze the total weight space, and thus to eliminate a number of alternatives. Furthermore it enables the determination of wether an alternative can reasonably be selected, given the requirements on the weight variations specified by the decision maker. The minimum weight modification that is determined, enables the definition of a proximity ranking. Thus it can be studied which alternative is closer and, consequently, more likely of being ranked first, given an initial set of weights. Results show that the proximity ranking does not fully correspond to the complete ranking of the alternatives. This indicates that some lower ranked alternatives (in the

complete ranking) may be more likely to be ranked first than higher alternatives. Thus the insight into the total weight space is enhanced, and feasible alternatives can be identified.
The sensitivity analysis described in section 4.6 is of particular interest in the case where large uncertainties arise in the weight assignment procedure. For instance, decision makers that are dealing with problems with which they have no or very little experience, may feel very uncomfortable about specifying "exact" weights. This may be the case when an alternative has to be selected from a set of more energy efficient production systems which are based on alternative technological concepts. In such a situation the determination of the stability of a ranking may not give sufficient insight into the total weight space. After the specification of an initial set of weights, the proposed sensitivity analysis enables the decision makers to determine which alternatives can be ranked first, taking into account specific considerations they may have.

From the results of the experiments described in this chapter, it is concluded that multiple criteria decision aid methods (viz. the Promethee methods), combined with extensive sensitivity analyses, are good tools for the evaluation of a number of alternative production systems for the production of a specific commodity. The application of such methods fills the fourth gap identified at the end of chapter 2.

Chapter 5

Case study

5.1 Introduction

In the framework of this study, a case study was conducted in the Dutch paper and board industry. In this chapter, the results are presented.

In section 5.2, the general objective of the case study is presented. The paper making process is described and analyzed in section 5.3. For each task that is distinguished, a number of alternative technological concepts have been identified. These are presented and discussed briefly. Subsequently, eight alternative paper production systems are distinguished. In section 5.4, the periphery in which these alternatives have to operate, is introduced. To indicate which alternative is preferred within this periphery, a set of criteria are defined and a multiple criteria evaluation is performed. The results of this evaluation are presented and discussed. Finally, a number of conclusions are presented.

5.2 The project "Sustainable Industrial Production"

The case study was a contribution to the project "Sustainable Industrial Production", which was carried by TNO (Netherlands Organisation for Applied Scientific Research) and Eindhoven University of Technology. The project was conducted on behalf of the Dutch Ministry of Economic Affairs. It can be considered as the prototyping phase of a series of similar studies in several branches of industry. The objective of this project was formulated as (Melman, 1992):

- to investigate the limits to the introduction of energy efficient and clean technologies in industrial production systems in the long term (e.g. by the year 2040), taking into account technical, managerial and economical constraints
- to determine the economical consequences of the identified technological options
- to gain insight into the dynamics of technology development
- to gain insight into the parameters characteristic of the periphery, which are determining the viability of new technologies

To select a branch of industry for the project, the following aspects were considered (Melman, 1992):

- the availability of knowledge and information on the branch
- the importance of the branch to the Dutch economy
- the importance to the branch of energy as a production factor
- the relative contribution of the branch to the total industrial energy consumption
- the prospect of technological innovations
- the uniformity of the applied production processes

These aspects were translated into a number of operational criteria. In all, 12 energy intensive branches of industry were evaluated with respect to these criteria. Finally, the paper and board industry was selected. This was mainly due to the fact that the availability of knowledge and information on that branch is very good, and the importance of energy as a production factor is relatively high. Furthermore, the prospects for future technological innovations with respect to energy efficiency, are very good (IEA, 1991; Melman *et al.*, 1990), and the uniformity of the applied production processes is relatively high.

The backbone of the project consisted of three main sub-projects. One sub-project was aimed at the analysis and modelling of the existing transformation subsystem for paper production, and at the identification of alternative elements for this system. Another sub-project was aimed at determining the socio-economic factors that are important to the introduction of alternative technologies. The third main sub-project was aimed at identifying a set of alternative production systems and at determining the pro's and con's of these systems. For the purpose of the latter, a multiple criteria evaluation has been performed. The results of this sub-project are presented in this chapter.

Besides the three main sub-projects discussed above, there were a number of additional sub-projects. One of these was aimed at determining the thermodynamic minimum energy consumption of a number of production processes, the paper production system being one of them. Another one was aimed at studying the possibilities for process integration in the paper and board industry. In yet another sub-project, the paper and board industry was reviewed in an integral chain approach.

5.3 The identification of alternative paper production systems

5.3.1 Introduction

In this study, there is a strong focus on the typical Dutch situation for paper and board production. This situation is briefly sketched in subsection 5.3.2. Subsequently, the papermaking process is analyzed, and alternative production systems are identified in subsections 5.3.3 and 5.3.4 respectively.

5.3.2 The Dutch paper and board industry

The Dutch paper and board industry can be characterised by the macro-economic parameters presented in table 5.1

Table 5.1: A characterisation of the Dutch paper and board industry in 1991 (CBS, 1992; VNP, 1993).

Number of enterprises		27
Number of employees		8858
Value of production	[10^6 Fl]	3768
Value added	[10^6 Fl]	1395
Production volume	[kton]	
- printing and writing grades		830
- wrapping and packaging grades		1555
- newsprint		309
- tissue & specialties		168
- total production volume		2862
Fibre consumption	[kton]	
- recycled fibre		1895
- imported virgin fibre		623
- self produced virgin fibre		175
- total fibre consumption		2693

Clearly the combined production volume of the printing and writing grades, and the wrapping and packaging grades, is the vast majority of the total production volume. Therefore, the rest of this study is focused on the production of these grades.

The raw materials for the different grades produced in the Netherlands can be divided into three categories: imported virgin fibre, self produced virgin fibre, and recycled fibre. In table 5.2, it is indicated which category of fibres is currently applied in the production of the four different product groups. Note that the figures in this table do not represent the average situation in the Netherlands, but represent the situation in a standard production system.

Table 5.2: The fibre consumption in a standard production system (CTPK, 1993).

	Printing and writing	Newsprint	Wrapping and packaging	Tissue and specialties
Imported virgin fibre	100%	-	10%	30%
Produced virgin fibre	-	30%	-	-
Recycled fibre	-	70%	90%	70%

5.3.3 Analysis of the papermaking process

The papermaking process generally consists of two parts: the pulp production part and the papermaking part. In the Dutch situation no pulp is produced from virgin fibre for the selected grades. Therefore, only that part of the pulp production that is aimed at preparing the pulp in order to give the right quality of paper, is studied. This is called the *stock preparation section*. The papermaking part can be divided into two sections, the *wire section* where the paper is actually made, and the *dewatering section*, where the wet paper is dried. Each section consists of a number of unit operations that are performing specific tasks. In the framework of this study, the internal water treatment is treated as if it is part of the wire section. In table 5.3, the tasks that have to be performed within the three sections are listed. It shows that the production systems for the production of printing and writing grades, and for wrapping and packaging grades, are quite similar. The only differences occur in the stock preparation.

For each of the tasks listed in table 5.3, alternative technological concepts have been determined (Lemmen, 1993). The results of that study are summarized in this subsection.

Table 5.3: The tasks that have to be performed in the production of printing and writing and wrapping and packaging grades.

<table>
<tr><th rowspan="2"></th><th colspan="2">Wrapping and packaging grades</th><th>Printing and writing grades</th></tr>
<tr><th>Recycled fibre</th><th>Virgin fibre</th><th>Virgin fibre</th></tr>
<tr><td>Stock preparation section</td><td></td><td></td><td></td></tr>
<tr><td><i>1 Slushing</i></td><td>*</td><td>*</td><td>*</td></tr>
<tr><td><i>2 Grinding</i></td><td>-</td><td>*</td><td>*</td></tr>
<tr><td><i>3 Cleaning</i></td><td>*</td><td>*</td><td>*</td></tr>
<tr><td><i>4 Disperging</i></td><td>*</td><td>-</td><td>-</td></tr>
<tr><td>Wire section</td><td colspan="2"></td><td></td></tr>
<tr><td><i>5 Sheet forming</i></td><td colspan="2">*</td><td>*</td></tr>
<tr><td><i>6 Internal water treatment</i></td><td colspan="2">*</td><td>*</td></tr>
<tr><td>Dewatering section</td><td colspan="2"></td><td></td></tr>
<tr><td><i>7 Press draining</i></td><td colspan="2">*</td><td>*</td></tr>
<tr><td><i>8 Thermal drying</i></td><td colspan="2">*</td><td>*</td></tr>
</table>

Stock preparation

1 Slushing

Slushing is a separation process which is aimed at freeing the fibres from the imported dried pulp or recycled paper. Three alternatives can be distinguished:

1.1 conventional combined with pre-wetting and improved stirring devices
1.2 high-consistency pulping
1.3 steam explosion pulping

2 Grinding

Grinding is a process in which the shape of the fibres is transformed. In the paper production system it is aimed at making them more flexible, enlarging their binding area, and processing their length. The only feasible alternative is:

2.1 improved conventional grinding

3 Cleaning

Cleaning is a separation process which is aimed at removing the non-fibre and the useless organic compounds from the pulp. The alternative technological concepts for cleaning are:

3.1 centrifugal cleaning
3.2 screening
3.3 centrifugal cleaning combined with screens

The effort to clean pulp from recycled fibre is much higher than the one required for pulp from virgin fibre. In case recycled fibres are used for the production of printing and writing grades, not only cleaning but also deinking has to be applied.

4 Disperging

Disperging is a mixing process which is aimed at reducing the detrimental effects of the pollutants in the pulp. This is achieved by reducing the size of those pollutants and by distributing them more uniformly throughout the pulp. Additionally, the length of the recycled fibres can be adapted to the desired quality standards. The alternatives for disperging are:

4.1 conventional disperging
4.2 kneading at low temperature and with a high consistency

Wire section

5 Sheet forming

Sheet forming is aimed at giving the pulp the shape of a sheet of paper. Subsequently, water is removed on the wire by means of gravity and vacuum. In all, nine alternatives can be distinguished for this step:

5.1 formation screen
    5.1.1 with improved wet-end chemistry
    5.1.2 formation at high consistencies
    5.1.3 formation using foam

5.2 gap former
  5.2.1 with improved wet-end chemistry
  5.2.2 formation at high consistencies
  5.2.3 formation using foam
5.3 top wire former
  5.3.1 with improved wet-end chemistry
  5.3.2 formation at high consistencies
  5.3.3 formation using foam

6 Internal water treatment

The internal water treatment is a separation process which is aimed at reducing the pollution level of the process water that is recycled. Five alternatives can be distinguished for this:

6.1 scrubbing and floating
  6.1.1 conventional (aerobic, anaerobic)
  6.1.2 conventional supported by chemistry/biotechnology (enzymes, cellulase)
  6.1.3 conventional supported by membranes
  6.1.4 conventional supported by organic solvents
  6.1.5 conventional supported by evaporation

Note that the extent to which the above mentioned alternatives have to be applied, strongly depends on the recycling rate of the process water. If no water is recycled, no internal water treatment will be required. In the case of a totally closed mill (zero influent), a very large internal water treatment will be necessary. Both situations sketched above are very extreme. Therefore, three recycling rates are considered in this study. The conventional one resulting in a specific water consumption of 21 m^3/ton, a second one corresponding to a reduction of 50% of the specific water consumption, and a third one corresponding to a reduction of 90%.

Dewatering section

7 Press draining

Press draining is a separation process. The following alternatives for press draining have been identified:

7.1 conventional press
7.2 shoepress
7.3 hotpressing
7.4 impulse drying

8 Thermal drying

Thermal drying is a separation process for which the following alternatives can be distinguished:

8.1 conventional cylinder-drying
    8.1.1 optimised (improved process control, heat recovery)
    8.1.2 controlling moisture profile (using infrared and electro-magnetic techniques)
    8.1.3 optimised and controlling moisture profile
8.2 press drying
8.3 steamdrying

Note that alternative 8.1.1, 8.1.2 en 8.3 can be applied only in combination with alternative 7.1. In practice infrared techniques are sometimes applied additionally to conventional cylinder drying.

5.3.4 The identification of a set of alternative production systems

If it is assumed that all technological concepts identified in the previous subsection can be combined with each other, one can calculate the total number of alternative production systems. For the production of printing and writing grades this number equals 8100, and for wrapping and packaging grades it equals 145800. These numbers only hold true for the transformation subsystem. If the degrees of freedom in the utility subsystem and the heat recovery subsystem are also taken into account, the number of alternatives is even enlarged. This large number illustrates the necessity for the method developed in chapter 3. Only by means of this method, the most energy efficient production system can be identified and included in the set of alternatives that are considered for further evaluation. In this project the following rules of thumb have been used to generate a manageable set of alternatives:

1 Select one of the almost identical concepts and eliminate the others.
2 Build alternative production systems from the conventional technological concepts, and eliminate them subsequently from further analysis.
3 Build alternative production systems based on the novel technological concepts. Try to cover the whole range of more and less advanced systems.

Application of the heuristics presented above, results in the alternative production systems listed in table 5.4 and 5.5 for the production of printing and writing grades and for the production of wrapping and packaging grades. For both product groups, alternative a1 is the conventional production system. Alternative a2, a3 and a4 can be considered to be technologically more advanced, and alternative a5, a6, a7 and a8 are technologically very advanced systems. Note the similarity between the alternatives for both product groups.

Table 5.4: The alternatives for the production of printing and writing grades and wrapping and packaging grades.

	Alternative a1	Alternative a2	Alternative a3	Alternative a4
Slushing	Conventional combined with pre-wetting and improved stirring devices			
Grinding	Conventional grinding (improved)			
Cleaning	Centrifugal cleaners combined with screens			
Disperging	Conventional disperging			
Sheet forming	Conventional formation wire	Formation wire with improved wet-end chemistry	Gap-former with improved wet-end chemistry	
Internal water treatment	Conventional scrubbing and floating		Scrubbing and floating supported by chemistry /biotechnology with a reduction of the specific water consumption of 50%	
Press-draining	Conventional press		Shoepress	
Thermal drying	Conventional cylinder-drying (optimised)	Steamdrying	Conventional cylinder-drying, optimised and controlling of moisture profile	Press drying

Table 5.4 (continued)

	Alternative a5	Alternative a6	Alternative a7	Alternative a8
Slushing	Pulping at high consistencies			
Grinding	Conventional grinding (improved)			
Cleaning	Centrifugal cleaners combined with screens			
Disperging	Kneading at low temperatures and with high consistency			
Sheet forming	Gap-former with formation at high consistencies			
Internal water treatment	Scrubbing and floating supported by membranes, with a reduction of the specific water consumption of 90%		Scrubbing and floating supported by organic solvents, with a reduction of the specific water consumption of 90 %	
Press draining	Hotpressing	Impulse drying	Hotpressing	Impulse drying
Thermal drying	Press drying			

5.4 The future economic situation in the Netherlands

In chapter 4 it has been argued that to enable decision makers to specify weights for the applied criteria, the alternative production systems have to be seen in retrospect within the periphery in which they have to operate. In the project Sustainable Industrial Production, the alternative production systems are judged at a point in time that is so far in the future that the production technology applied at that moment, can be considered to be independent of the currently applied technology; i.e. the chosen moment in time has to be so far in the future that discontinuous innovations in applied production technology may have occurred. An additional advantage of this approach is that the very long term character of this study makes decision makers feel less reluctantly to give their opinion.

The fundamental problem that arises whenever one has to predict the future, is that uncertainty increases rapidly with time. The only way to deal with this problem is to assume that the current situation will develop itself according to a set of well defined scenario's. By studying the influence of the different scenarios, the sensitivity of the results with respect to the assumptions underlying the scenarios, can be studied. In this study, the scenarios should provide information on the general economic situation, and more specifically on the situation of the Dutch paper and board industry. Three scenarios have been used in this study:

- the Global Shift scenario
- the Balanced Growth scenario
- the European Renaissance scenario

These scenarios have been developed by the Dutch Central Planning Bureau. A detailed description can be found elsewhere (CPB, 1992a, 1992b). By means of additional literature research, the situation of the Dutch paper and board industry has been sketched. The results of this analysis are presented in appendix 5.

5.5 The evaluation of the alternative production systems

5.5.1 The criteria

The alternative production systems listed in table 5.4 have been evaluated through a number of criteria. These have been determined by means of interviews with experts and decision makers from the paper and board industry. The criteria have been grouped in five categories: economy, quality, technology, logistics and environment.

Economy

C1 - Investment

The investment related to purchasing a papermachine (including stock-preparation) is a very important criterion. In the framework of this study, the alternatives have been evaluated through this criterion for a production system with a capacity of 150 kton/yr for the printing and writing grades, and 100 kton/yr for the wrapping and packaging grades. For reasons of confidentiality, the evaluations have been mapped on a relative scale, on which the conventional alternative a1 has been given the value hundred.

Another important economic criterion, the production cost, is not taken into account in this project since it is determined to a large extent by the investments.

Quality

C2 - Whiteness/greyness
C3 - Printability
C4 - Physical-mechanical properties

In appendix 5 it is indicated that quality requirements are expected to become stricter in future. Therefore, a number quality related criteria have been selected. Whiteness and greyness are criteria which are related to the appearance of the product. Whiteness is important to printing and writing grades, greyness to wrapping and packaging grades. Obviously printability is also a very important criterion.

Furthermore the physical-mechanical properties (e.g. tear-strength) are considered to be very important. Each criterion has been judged on a five point scale.

Technology

C5 - Breakdown sensitivity
C6 - Demand for maintenance

Due to the very high capital investments that are required in the paper and board industry, it is absolutely essential that the papermachine is operational as much as possible. This implies that the number of breakdowns has to be minimised, and that a minimum amount of time should get lost on planned maintenance. This illustrates the importance of the criteria mentioned above. Each of them is judged on a five point scale.

Logistics

C7 - Potential increase in capacity

A papermachine is built at a certain capacity. In practice, it turns out that in time, producers try to increase that capacity (e.g. by increasing the machine-speed). Given the expected increase in production volume, it is expected that will also be the case in future. The extent to which the capacity can be increased, is strongly related to the technological concepts that are applied. This criterion is judged on a five point scale.

Environment

C8	-	Energy intensity	[GJ/ton]
C9	-	Specific water consumption	[m^3/ton]

In appendix 5, it is indicated that environmental criteria are expected to become even more important than they are today. The criteria C8 and C9 are important to the sustainability of the paper production system.

5.5.2 The evaluations of the alternatives

The alternatives which are listed in table 5.4, have been evaluated through the criteria which have been listed in the previous subsection. This evaluation has been performed by means of interviews and discussions with experts from TNO and a supplier of equipment. The results are presented in table 5.9 for the printing and writing grades, and in table 5.10 for the wrapping and packaging grades.

Table 5.9: The evaluations of the alternative production systems for printing and writing grades (1 ≡ very low,..., 5 ≡ very high).

	C1	C2	C3	C4	C5	C6	C7	C8	C9
a1	100	5	4	4	3	2	2	12.6	21.0
a2	115	5	5	5	4	2	2	10.1	21.0
a3	129	3	3	5	4	2	3	10.6	10.5
a4	158	3	3	5	4	4	3	10.1	10.5
a5	175	4	2	2	5	5	4	9.6	2.1
a6	180	4	2	2	5	5	4	8.1	2.1
a7	175	3	2	2	5	4	4	9.6	2.1
a8	180	3	2	2	5	4	4	8.1	2.1

Table 5.10: The evaluations of the alternative production systems for wrapping and packaging grades (1 ≡ very low,..., 5 ≡ very high).

	C1	C2	C3	C4	C5	C6	C7	C8	C9
a1	100	5	4	4	3	2	2	12.6	21.0
a2	114	5	5	5	4	2	2	10.1	21.0
a3	128	3	4	5	4	2	3	10.6	10.5
a4	154	3	4	5	4	4	3	10.1	10.5
a5	165	4	2	2	5	5	4	9.6	2.1
a6	170	4	2	2	5	5	4	8.1	2.1
a7	165	3	2	2	5	4	4	9.6	2.1
a8	170	3	2	2	5	4	4	8.1	2.1

From table 5.9 and 5.10 it becomes clear that alternative a2 through a8 require a higher investment (C1) than the conventional alternative a1. Furthermore, it seems that the more advanced an alternative, the higher are the investments. Note that there is a slight difference between the investments for the printing and writing grades and the wrapping and packaging grades. This results from the different types of applied raw material (virgin fibre respectively recycled fibre) and from differences in quality standards.

Alternative a1 and a2 will give the best result on the criterion whiteness (C2). It is expected that if the specific water consumption is reduced by 50%, scrubbing and floating supported by chemistry/biotechnology will not be able to remove all polluting elements from the process water. As a result of this, accumulation of these pollutants (e.g. different kinds of salt) will take place. Since this will have a negative influence, the whiteness of the paper produced by alternative a3 and a4 is lower. A similar effect will occur with alternatives a5 and a6, although this will be of a lesser extent. For alternatives a7 and a8, the negative influence from the internal watertreatment will be of the same extent as for alternatives a3 and a4.
The printability (C3) of paper is determined mainly by the structure of the paper and by its hydrophobic properties. These properties are influenced in the formation, the internal watertreatment, and in the press section. The printability of the conventional alternative a1 has been evaluated as "high". It is expected that this can be improved by the application of another wet-end chemistry (alternative a2). This effect however, will be more neutralised by the introduction of a shoepress (alternative a3 and a4). The expectations for alternative a5 through a8 are not too good, as a result of the structure of the paper resulting from the formation at a high consistency.
The physical mechanical properties (C4) of paper are determined by its structure, and more specifically by the orientation of the fibres in the paper. In the case of formation at a normal consistency (± 1% dry matter content) the majority of the fibres are orientated in the direction in which the paper is running through the production system. This causes the physical-mechanical properties, and more specifically the tear-strength, to be much higher in the machine direction than in the transverse direction. If the formation takes place at a higher consistency, the orientation of the fibres is more uniformly distributed over the three dimensions of a sheet of paper. This causes the strength of the paper in the machine direction to be less. In the transverse direction however, the tear strength will of improve. The above explains the evaluations of the alternatives.

The evaluations of the alternatives reveal that every alternative is rather sensitive to breakdowns (C5). Only the conventional alternative a1 has been evaluated as "reasonable". All other alternatives are even more sensitive to breakdowns. The cause of this is the application of wet-end chemistry in the formation (alternative a2 through a4), and in the application of formation at high consistencies (alternative a5 through a8). The latter causes the sheet of paper to break more often as a result of the decreased tear-strength.

The demand for maintenance (C6) of alternative a1 through a3 has been evaluated as "low". The other alternatives have been evaluated as "high" or "very high". This is caused by the presence of more technologies operating at high or higher temperatures in the dewatering section. It is expected that as a result of these higher temperatures, more wear will occur. Consequently, more maintenance will be required. To some extent this can be compensated for by applying more wear-resistant construction materials. The demand for maintenance of alternative a5 and a6 has been evaluated as "very high". This is caused by the presence of membranes in the internal water treatment. It is most likely that these will silt up, which will cause an extra demand for maintenance.

The potential increase in capacity (C7) of an alternative is determined by the applied technologies. The conventional alternative a1 has been evaluated as "low". This is caused by the bottlenecks in the conventional formation wire (this may become too short if the machine is running faster) and the conventional cylinder-drying (if the machine is running faster, additional cylinders may be required). This situation can be improved by the application of improved wet-end chemistry (improved dewatering properties) combined with steam-drying (alternative a2), or by the application of a gap-former (alternative a3 and a4). Further improvements can be achieved by the introduction of formation at high consistencies (alternative a5 through a8).

The energy intensity (C8) is determined by the applied technologies and by the dewatering properties of the paper. The latter are determined mainly in the formation, and can be improved by another wet-end chemistry and by changing the structure of the paper (by formation at a high consistency). This causes water to be less bounded with the fibres. Furthermore, paper produced at a high consistency will have a more open structure. As a result of all this, more water can be removed in a mechanical way and, consequently, less water has to be removed by thermal dewatering.

To evaluate the alternatives through the criterion energy intensity, the results of another sub-project have been used (Lemmen, 1993). It should noted that in performing the evaluations, only the changes in the transformation subsystem (see chapter 3) have been studied in detail. The energy conservation potential resulting from the other two subsystems has been estimated using indications from literature (Lemmen, 1993).

Paper produced by the conventional alternative a1 has an energy-intensity of ±12.6 GJ/ton. This figure can be reduced by 2.5 GJ/ton by applying improved wet-end chemistry combined with steam-drying. Application of alternative a3 and a4 results in an energy intensity of 10.6 and 10.1 GJ/ton respectively. The energy intensity may be reduced even further by applying formation at a high consistency combined with hotpressing, impulse drying, or press drying (alternative a5 through a8). In case of hot-pressing, it is most likely that the energy intensity can be decreased even further, because of the increased possibilities for heat recovery. Within the framework of the this project however, this effect not be accounted for.
The specific water consumption (C9) of 21 [m^3/ton] of alternative a1 and a2 is reduced by 50% (alternative a3 and a4) or 90% (alternative a5 through a8). However, in doing this, the chemical oxygen demand (COD) of the effluent (the water that is removed from the internal water cycle) increases. This is due to the fact that almost the same amount of pollutants is removed by less water. This can only be compensated for by enlarging the effluent water treatment.

The brief elucidation presented above, holds true for both the printing and writing grades and the wrapping and packaging grades. Only for the evaluations with respect to the criterion printability does a small difference occur between the two product groups. The printability of alternative a3 and a4 for the production of wrapping and packaging grades, has been evaluated as "good" instead of "reasonable". This is caused by the fact that for wrapping and packaging grades the requirements with respect to the criterion printability are not as strict as they are for printing and writing grades.

5.6 Analysis of the evaluations

5.6.1 Introduction

In this section, the evaluations of the alternative production systems are analyzed by means of the Promethee methods. To determine the weights and preference functions that have to be assigned to the applied criteria, a number of interviews have been conducted with decision makers from the paper and board industry. The results of these interviews are presented and discussed in subsection 5.6.2. Subsequently, the results of the analysis of the evaluations are presented, and discussed in subsection 5.6.3 and 5.6.4 respectively.

5.6.2 The weights and preference functions

In chapter 4 it has been mentioned that to perform a multiple criteria evaluation, a set of weights, preference functions and an objective have to be specified. In the framework of this project these have been determined by means of a number of interviews with decision makers from the paper industry. These decision makers come from companies producing printing and writing grades, as well as from companies producing wrapping and packaging grades. In each interview three procedures have been applied to determine the weights: the rank reciprocal, the rank sum, and the direct weighting procedure (see appendix 4). In all, three decision makers from the largest companies have been interviewed, which has resulted in 6 sets of weights. In table 5.11 the results of the interviews are presented. The values of the weights are average values. In the framework of this project it has been decided to use these values and perform a deterministic evaluation, instead of a stochastic one. There are a number of reasons for this. Firstly, one should realise that the evaluations of the alternatives are also average values since they result from the judgements of several experts. Secondly, a stochastic evaluation would make more sense if all the decision makers would have the same background and would give their opinion from the same situation. During the interviews it turned out that this was not the case. Although they were asked to specify their judgements in the situation that has been sketched in appendix 5, it turned out that the decision makers had some difficulties abstracting themselves from their own business situation. For instance, a decision maker from a company which was having some problems with its water supply, felt that specific water consumption was much more important than energy intensity. The opposite was the case with a decision maker from a company which had more than sufficient water resources. Furthermore, the decision makers tended to give their judgements from the position they were having within their company. For instance, decision makers who have their main duties on the operational level (e.g. managing director), will give other judgements than decision makers with their main duty on the strategic level. To indicate the level to which the judgements of the decision makers varied, the standard deviation σ_{nj} is also presented in table 5.11.

With respect to the weights assigned to the quality related criteria, all decision makers stated that if an alternative is not able to meet the quality requirements from the market, this alternative is considered to be infeasible; i.e. it is excluded from the decision making process. This implies that quality may become a constraint that determines which alternatives are feasible and which are not. In the rest of this study it is assumed that all alternatives are able to meet the future quality requirements or can be altered to do so.

Table 5.11: The averaged weight w_j, the preference functions P_j, and the objective assigned to criterion C.

	w_j	σ_{nj}	P_j-type	q	p	obj.
C1 Investment cost	0.384	0.071	2	10	-	min
C2 Whiteness/greyness	0.083	0.056	4	0.5	1.5	max
C3 Printability	0.088	0.051	4	0.5	1.5	max
C4 Phys. mech. properties	0.056	0.022	4	0.5	1.5	max
C5 Breakdown sensitivity	0.081	0.056	4	0.5	1.5	min
C6 Demand for maintenance	0.050	0.018	4	0.5	1.5	min
C7 Potential capacity increase	0.125	0.035	4	0.5	1.5	max
C8 Energy intensity	0.082	0.044	1	-	-	min
C9 Specific water consumption	0.051	0.027	1	-	-	min

The preference functions P_j have been assigned to the criteria by a decision maker. P_1 indicates that if the evaluations on C1 of two alternatives differ less than 10, there is no preference of one alternative over the other. Thus it is accounted for uncertainties in the evaluations. However, if the difference is greater than or equal to 10, there is instantly a maximum preference, regardless of the exact difference. This seems to be a rather undifferentiated approach, since generally the preference increases more continuously from zero to one.

P_2 through P_7 indicate that if the evaluations on the corresponding criteria differ one point, there is only a small preference; only if the differences in evaluations is two points or more, there is a maximum preference. Given the evaluations on these criteria, these preference function can be considered to be a differentiated choice. For P_8 and P_9 the same problem arises as for P_1.

5.6.3 Results

The evaluations of the alternatives have been analyzed by means of the Promethee methods, using the weights and preference functions presented in the previous subsection. This analysis has been performed twice: one time without taking the economic criterion into account, and another time with that criterion. Each analysis has resulted in a complete and partial ranking of the alternatives for the production of both the printing and writing grades and the wrapping and packaging grades. The results are presented below. For each analysis, sensitivity analyses are performed with respect to the weights to the preference functions assigned to criterion C1, C8 and C9.

Analysis I

In the first analysis the economic criterion has not been taken into account. In this way the physical aspects that are preventing the introduction of more energy efficient production systems, can be studied in more detail. The results of this analysis are presented in table 5.12 (printing and writing grades) and 5.13 (wrapping and packaging grades) in terms of the leaving flow ϕ^+, the entering flow ϕ^- and net flow ϕ (see appendix 1). The complete ranking is indicated between the brackets in the right column of table 5.12 and 5.13. The partial ranking is visualised in figure 5.1 (printing and writing grades) and 5.2 (wrapping and packaging grades).

Table 5.12: The leaving flow ϕ^+, the entering flow ϕ^- and the net flow ϕ of the alternatives for producing printing and writing grades.

	ϕ^+		ϕ^-		ϕ	
a1	0.41153	(2)	0.37871	(8)	0.03282	(3)
a2	0.42092	(1)	0.30137	(5)	0.11955	(1)
a3	0.26647	(4)	0.31714	(7)	-0.05067	(6)
a4	0.23910	(7)	0.31389	(6)	-0.07479	(8)
a5	0.24884	(6)	0.26960	(3)	-0.02076	(5)
a6	0.28687	(3)	0.23156	(1)	0.05531	(2)
a7	0.22194	(8)	0.29070	(4)	-0.06876	(7)
a8	0.25997	(5)	0.25267	(2)	0.00731	(4)

Table 5.13: The leaving flow ϕ^+, the entering flow ϕ^- and the net flow ϕ of the alternatives for producing wrapping and packaging grades.

	ϕ^+		ϕ^-		ϕ	
a1	0.39112	(2)	0.37871	(8)	0.01241	(3)
a2	0.40051	(1)	0.30137	(6)	0.09914	(1)
a3	0.30728	(3)	0.29673	(5)	0.01055	(4)
a4	0.27992	(5)	0.29348	(4)	-0.01357	(6)
a5	0.24884	(7)	0.29000	(3)	-0.04116	(7)
a6	0.28687	(4)	0.25197	(1)	0.03490	(2)
a7	0.22194	(8)	0.31111	(7)	-0.08917	(8)
a8	0.25997	(6)	0.27308	(2)	-0.01310	(5)

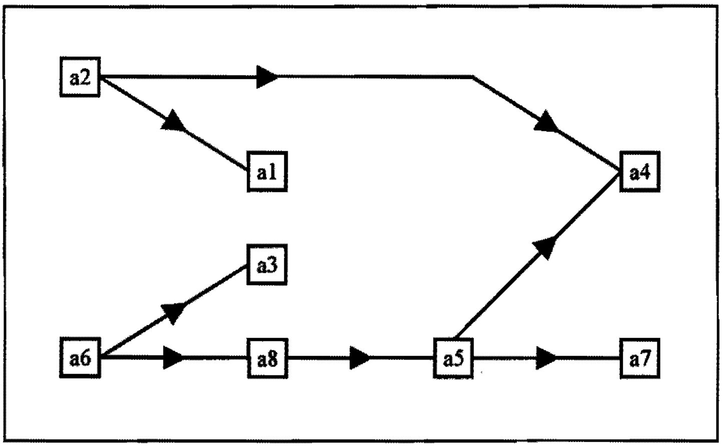

Figure 5.1: The partial ranking of the alternatives for producing printing and writing grades.

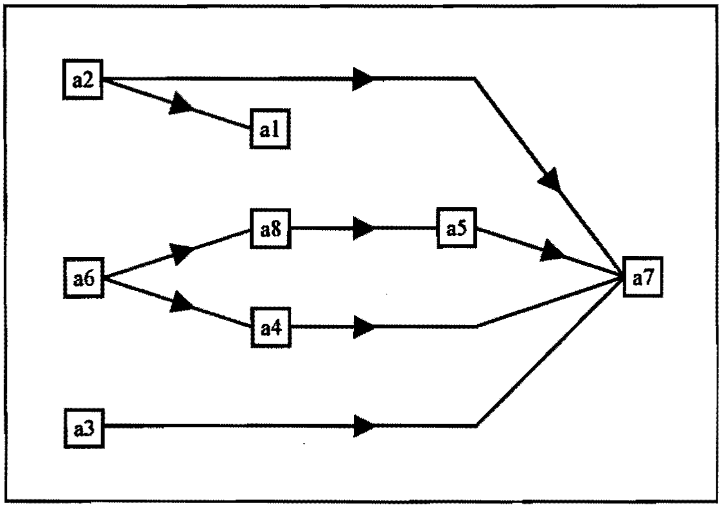

Figure 5.2: The partial ranking of the alternatives for producing wrapping and packaging grades.

From the ϕ-values in table 5.12 and 5.13 it follows that if the economic criterion is not taken into account, the alternatives are relatively "close" to each other. Especially alternative a6, which is ranked second in the complete ranking, seems to be a promising compromise between the environmental and other criteria.

The partial rankings which are visualised in figure 5.1 and 5.2, are aimed at indicating indistinctness between the alternatives (see appendix 1). From these figures it becomes clear that alternative a2 and a6 (ranked first respectively second in the complete ranking) are in fact indistinct, i.e. they are good alternatives for different reasons. Furthermore, it becomes clear that for both product groups, alternative a6 is preferred to the other very advanced alternatives (a5, a7, a8). Both aspects reinforce the conclusion from table 5.12 and 5.13 that alternative a6 is the most promising energy efficient production system.

To study the stability of the complete rankings, weight stability intervals have been determined. Since the results are very similar, only the results for the printing and writing grades are considered. These weight stability intervals are presented in table 5.14.

Table 5.14: The weight stability intervals for the complete ranking of the printing and writing grades.

	Value of weight	Weight stability interval
		Stability level: full
w_2	0.083	<0.0693 - 0.1073>
w_3	0.088	<0.0733 - 0.0954>
w_4	0.056	<0.0468 - 0.0591>
w_5	0.081	<0.0673 - 0.0875>
w_6	0.050	<0.0389 - 0.0602>
w_7	0.125	<0.1185 - 0.1388>
w_8	0.082	<0.0755 - 0.0905>
w_9	0.051	<0.0467 - 0.0620>

From table 5.14 it follows that the complete ranking is rather stable, despite of the fact that the alternatives are "close" to each other. Besides the weight stability interval, a proximity ranking of the alternatives has been determined. In section 4.6 it has been argued that such a proximity ranking indicates which alternatives is most likely to become ranked first, if all weights are varied at the same time. In the framework of this study, two proximity rankings have been determined for both product groups. In the first proximity ranking no additional constraints are included in the optimisation model. In the second one, bounds on the values of the weights are taken into account. These bounds are determined by the standard deviation σ_{nj} of each weight. This implies that each weight w_j^* has to meet relation 5.1.

$$w_j - \sigma_{nj} \leq w_j^* \leq w_j + \sigma_{nj} \tag{5.1}$$

The proximity ranking of the alternatives has been determined for both product groups. These results are presented in table 5.15. It should be noted that in determining the proximity ranking it is assumed that all weights are equally likely to vary, i.e. all cost coefficients are equal (see section 4.6).

Table 5.15: The minimum modification of the weights and the corresponding proximity ranking of the alternatives without (case 1) and with (case 2) additional constraints (-- = impossible).

	Printing and writing grades				Wrapping and packaging grades			
	Case 1		Case 2		Case 1		Case 2	
a1	0.08308	(3)	0.08308	(3)	0.08308	(4)	0.08308	(4)
a2	0.00000	(1)	0.00000	(1)	0.00000	(1)	0.00000	(1)
a3	0.15183	(5)	0.16129	(5)	0.06883	(3)	0.06883	(3)
a4	0.18030	(6)	--		0.16197	(6)	--	
a5	--		--		--		--	
a6	0.02848	(2)	0.02848	(2)	0.02843	(2)	0.02843	(2)
a7	--		--		--		--	
a8	0.08370	(4)	0.08370	(4)	0.08451	(5)	0.08451	(5)

From table 5.15 it follows that for alternative a5 and a7 no set of weights exists that would make them rank first. This implies that these alternatives may be considered to be infeasible and, consequently, may be eliminated from the set of alternatives. Furthermore it follows that for alternative a6, which is ranked second in the complete ranking, the weights have to be altered just a very little to make it ranked first. This strengthens the conclusion from table 5.12 and 5.13, namely that alternative a6 is a very promising energy efficient production system. Note that the minimum modifications of the weights required to make alternative a1 ranked first, is almost equal to that of alternative a8. This indicates that these alternatives are more or less equally likely to be ranked first. Since the net flow of alternative a1 is close to that of a6, a8 can also be considered to be a promising energy efficient production system. For the wrapping and packaging grades this also holds true for alternative a3.

If the minimum modification of the weights is determined with bounds on the values of the weights as additional constraints, it follows that for alternative a4 there exists no set of weights that will make it ranked first. Consequently, this alternative may also be eliminated from the set of alternatives.

The influence of the preference functions assigned to criterion C8 and C9 has been studied by performing a sensitivity analysis with respect to these functions. For this purpose, preference function type no.1 has been replaced by no. 3. Given the evaluations, the parameter p has been given the value 2.0 for C8 and 11.53 for C9. Repeating the analysis with these parameters reveals that the influence on the complete ranking is not very large. For the printing and writing grades, the alternatives ranked in the first three places remain the same. Alternative a3 and a4 are shifted upwards to the fourth respectively sixth rank, and a8, a5 and a7 are shifted backwards. Alternative a6 remains the highest ranked very advanced alternative. In the partial ranking the most important change is that alternative a1 becomes indistinct to a2 and a6.

Repeating the analysis for the wrapping and packaging grades reveals that in this case alternative a3 and a4 are shifted upwards to the second and fifth rank. Alternative a6 and a1 become ranked third respectively fourth, and a8, a5 and a7 are shifted to the tail of the ranking. In the partial ranking, a3 becomes preferred to a6. Similar to the printing and writing grades, alternative a6 remains the highest ranked very advanced alternative.

For both grades, the weight stability intervals and the proximity ranking show the same characteristics as in the original analysis.

To study the interactions between the applied criteria, the so-called GAIA-analysis has been performed (see chapter 4). This has resulted in the geometrical representation of the decision space which is presented in figure 5.3. Since the results for both products groups are again quite similar, only the results for the printing and writing grades are presented.

From figure 5.3 it follows that two groups of alternatives exist: the conventional and the less advanced alternatives (a1 through a4) which are located on the right side of the vertical axis, and the very advanced alternatives which are located left of this axis. From the projections of the alternatives on the criterion-axes, it becomes clear that the very advanced alternatives (a5 through a8) are all rather bad on the criteria related to quality (C2, C3 and C4) and technology (C5 and C6). On the other hand they are among the best on the logistical criterion (C7) and the environmental criteria (C8 and C9). The direction of the criterion-axes visualises the interactions between the applied criteria. Clearly, the environmental criteria are conflicting with the quality related and technical criteria. The weights that have been used to determine the ranking of the alternatives, also define the decision axis which is indicated as the π-vector in figure 5.3.

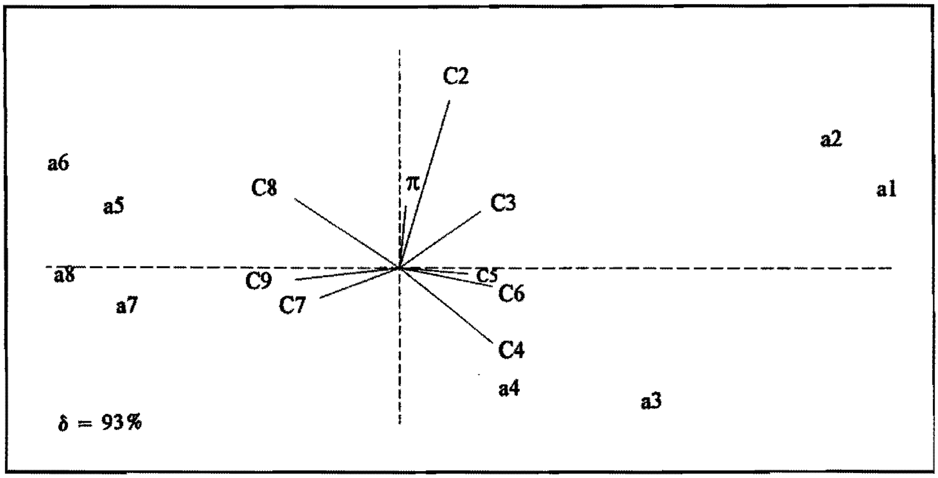

Figure 5.3: The geometrical representation of the decision space for the alternatives for producing printing and writing grades.

Analysis II

In the second analysis the economical criterion is also taken into account. By comparing the results of the first and second analysis, the influence of this criterion can be studied in more detail. The ranking of the alternatives for producing the printing and writing grades and the wrapping and packaging grades is presented in table 5.16 and 5.17 respectively. From the ϕ values presented in these tables it follows that alternative a1 is strongly preferred to the other alternatives. From the ϕ^+ and ϕ^- values it furthermore follows that the partial ranking is identical to the complete ranking, which indicates the absence of indistinctness. Note that of the very advanced alternatives (a5 through a8), alternative a6 is the "best" one, which corresponds to the results obtained in the first analysis.

To study the stability of the complete ranking, weight stability intervals have been determined. The results are presented in table 5.18. In this table only the results for the printing and writing grades are presented since the ones for the other grades are almost identical. It follows that the obtained complete ranking is very stable. Note that varying the weight assigned to criterion C5 does not have any influence on the complete ranking. However, if this weight is varied over the stability interval, indifference between the alternatives will occur as a result of identical evaluations.

Table 5.16: The leaving flow ϕ^+, the entering flow ϕ^- and the net flow ϕ of the alternatives for producing printing and writing grades.

	ϕ^+		ϕ^-		ϕ	
a1	0.63750	(1)	0.23329	(1)	0.40421	(1)
a2	0.58843	(2)	0.24050	(2)	0.34793	(2)
a3	0.43843	(3)	0.30507	(3)	0.13336	(3)
a4	0.36671	(4)	0.35793	(4)	0.00879	(4)
a5	0.15329	(7)	0.38550	(7)	-0.23221	(7)
a6	0.17671	(5)	0.36207	(5)	-0.18536	(5)
a7	0.13671	(8)	0.39850	(8)	-0.26179	(8)
a8	0.16014	(6)	0.37507	(6)	-0.21493	(6)

Table 5.17: The leaving flow ϕ^+, the entering flow ϕ^- and the net flow ϕ of the alternatives for producing wrapping and packaging grades.

	ϕ^+		ϕ^-		ϕ	
a1	0.62493	(1)	0.23329	(1)	0.39164	(1)
a2	0.57586	(2)	0.24050	(2)	0.33536	(2)
a3	0.46357	(3)	0.29250	(3)	0.17107	(3)
a4	0.39186	(4)	0.34536	(4)	0.04650	(4)
a5	0.15329	(7)	0.39807	(7)	-0.24479	(7)
a6	0.17671	(5)	0.37464	(5)	-0.19793	(5)
a7	0.13671	(8)	0.41107	(8)	-0.27436	(8)
a8	0.16014	(6)	0.38764	(6)	-0.22750	(6)

The stable character of the complete ranking already indicates that large changes of weights will be required to make a specific alternative ranked first. To gain more insight into this, a proximity ranking has been determined for the same two cases as in the first analysis. The results are presented in table 5.19. From this table it follows that for both grades no set of weights exists for which alternative a5 and a7 become ranked first. This indicates that, similar to the first analysis, these alternatives may be eliminated from the set of alternatives. Furthermore, it follows that the proximity ranking does not fully correspond to the complete ranking. Alternative a6 and a8 require less changes in the weights to become ranked first than alternative a4, although this alternative is ranked higher in the complete ranking.

Table 5.18: The weight stability intervals for the complete ranking of the printing and writing grades.

	Value of weight	Weight stability interval Stability level: full
w_1	0.384	<0.2329 - 1.0000>
w_2	0.083	<0.0330 - 0.1099>
w_3	0.088	<0.0000 - 0.2381>
w_4	0.056	<0.0000 - 0.2114>
w_5	0.081	<0.0000 - 1.0000>
w_6	0.050	<0.0017 - 0.1226>
w_7	0.125	<0.0000 - 0.3469>
w_8	0.082	<0.0534 - 0.1491>
w_9	0.051	<0.0000 - 0.2263>

Table 5.19: The minimum modification of the weights and the corresponding proximity ranking of the alternatives without (case 1) and with additional constraints (-- = impossible).

	Printing and writing grades				Wrapping and packaging grades			
	Case 1		Case 2		Case 1		Case 2	
a1	0.00000	(1)	0.00000	(1)	0.00000	(1)	0.00000	(4)
a2	0.08758	(2)	0.08758	(2)	0.08758	(2)	0.08758	(1)
a3	0.39107	(3)	--		0.30305	(3)	--	
a4	0.59379	(6)	--		0.48635	(6)	--	
a5	--		--		--		--	
a6	0.39302	(4)	--		0.39319	(4)	--	
a7	--		--		--		--	
a8	0.42333	(5)	--		0.43045	(5)	--	

In case additional constraints are introduced in the optimisation procedure, it follows that for alternative a3 through a8 there exists no set of weights that will make them ranked first. This reinforces the conclusion from table 5.18 that the obtained ranking is very stable and that large changes in the weights are required to make an alternative ranked first.

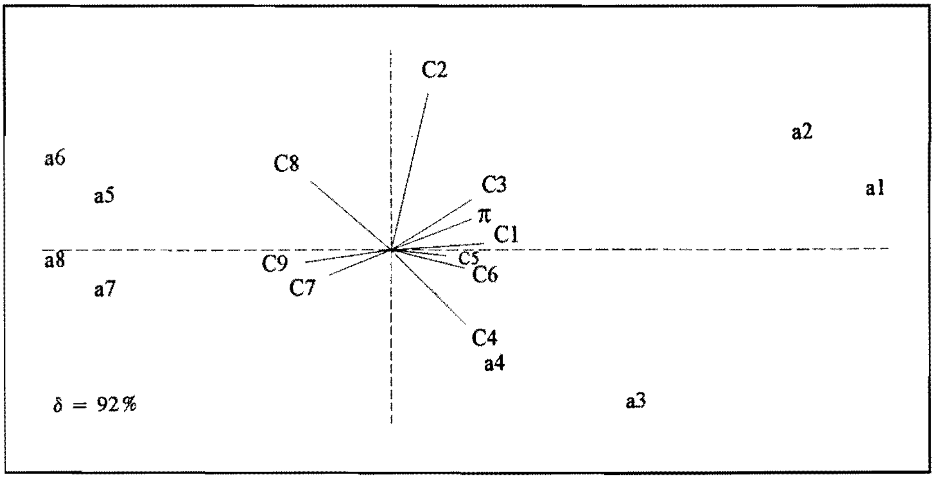

Figure 5.4: The geometrical representation of the decision space.

A sensitivity analysis has been performed to study the influence of the preference functions assigned to criterion C1, C8 and C9. For this purpose, preference function type no. 5 has been assigned to criterion C1. The parameter q has been given the value 10 (similar to the originally specified value) and the parameter p has been given the value 50. The preference functions assigned to C8 and C9 have been altered in the same way as in the first analysis. Repeating the analysis with these preference functions reveals that the influence on the complete ranking for both grades is limited to the transposition of ranks of alternative a1 and a2, which become ranked second and first. In the partial ranking these two alternatives become indistinct. Also a3 becomes indistinct to a1, however this alternatives is still dominated by a2. Alternative a5 and a8 also become indistinct. Note that a6 remains the highest ranked very advanced alternative.

For both grades the weight stability intervals are similar to the ones in the original analysis. The proximity ranking reveals that if no additional constraints are taken into account in the optimisation procedure, alternative a5 and a7 are no longer infeasible. If these constraints are taken into account, the proximity rankings are quite similar to the ones obtained in the first analysis, except that a3 is no longer infeasible.

Similar to the first analysis, a geometrical representation of the decision space has been determined. The results are presented in figure 5.4. and 5.5. From figure 5.4 it follows that similar to the first analysis two groups of alternatives can be distinguished, i.e. the very advanced alternatives which are located left of the vertical axis and the conventional and less advanced ones which are located on the right side of this axis.

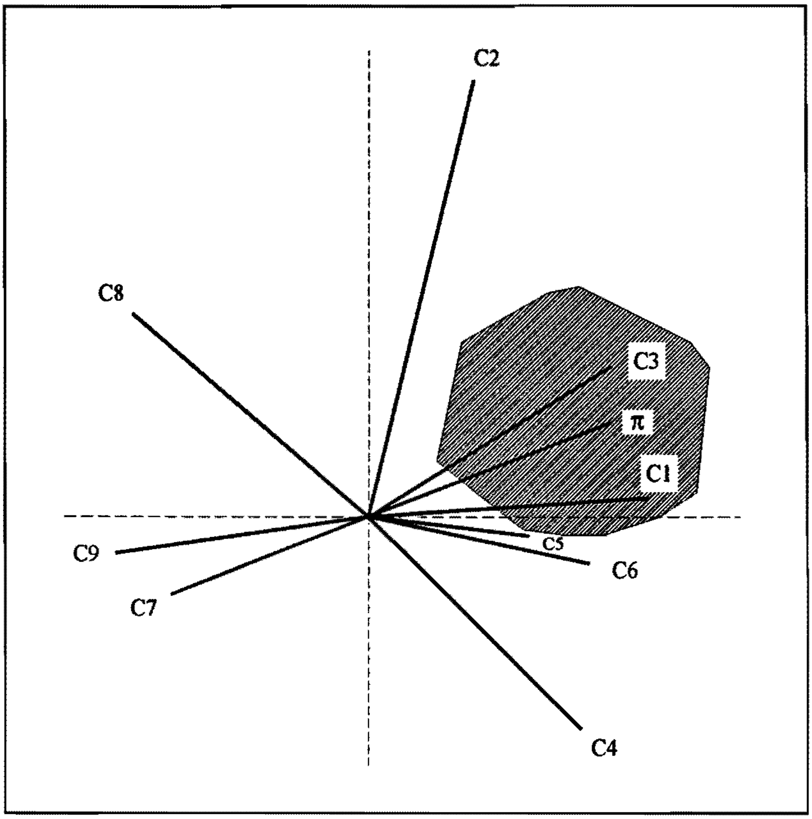

Figure 5.5: The interactions between the applied criteria.

In figure 5.5, the interactions between the applied criteria are studied in more detail. From this figure it follows that the economic criterion is in agreement with the quality and technology related criteria, and conflicting with the logistical and environment related ones. Since the economic criterion C1 has a rather high weight, the decision vector is almost parallel to the axis representing this criterion. Since the very advanced, energy efficient alternatives are located in the area opposite to the decision vector, it can be concluded that the economic criterion is one of the main factors counteracting the introduction of these alternatives. In figure 5.5 it is also indicated which area is covered by the end of the π-vector if all weights are allowed to vary simultaneously between the bounds defined by relation 5.1. The results again indicate that the obtained ranking is very stable.

5.7 Discussion and conclusions

From both analyses it follows that alternative a6 is the best of the very advanced production systems. Since it is the best on both environmental criteria (see table 5.9 and 5.10), this alternative should be preferred from the point of view of a sustainable development of the paper and board industry. From figure 5.3 and 5.4 it follows that a6 is not only the best on the environmental criteria, but also on the logistical criterion. However, it also follows that it is rather bad on the economic, quality and technology related criteria. From the direction in which the π-vector is pointing in figure 5.4, and from the weights that are presented in table 5.11 it follows that these criteria are counteracting the introduction of alternative a6. However, because it is expected that in the long term environmental issues will determine the viability of a production system, alternative a6 could be preferred from the point of view of strategic management of production technology. To facilitate its introduction in the long term, research efforts should be directed at diminishing the counteracting negative aspects. A study like the one described in this chapter can be of support in directing these efforts, since it indicates what these aspects are and, more importantly, what causes them. For instance, in section 5.2.2 it has been discussed that the quality of paper is determined mainly by the sheet forming and the internal watertreatment. To enhance the whiteness/greyness of the paper produced by alternative a6, research efforts should be directed at more efficiently removing pollutants from the process water by membranes. The physical mechanical properties can be improved by directing research efforts at changing the structure of paper resulting from formation at high consistencies, i.e. at orienting the fibres more uniformly in the machine direction. Such research has already been performed successfully (Sulzer, 1994). However, such a change in structure will decrease the dewatering properties of the paper, as a result of which the energy intensity will increase by approximately 0.5 GJ/ton (Lemmen, 1993). Analyses as presented above can be performed for each criterion. Special attention should be paid to diminishing the negative influence of the economic criterion which is the largest counteraction to the introduction of alternative a6. The national government could play an important role in this by providing a subsidy for alternative a6. By means of the proposed evaluation method it has been determined that the evaluation of a6 on criterion C1 has to be reduced to 104 (on the relative scale that is used in table 5.9 and 5.10) to make it ranked first. This corresponds to a reduction of ±42% of the total investment.

Summarised, it can be concluded that by means of the tools described in chapter 3 and 4 of this thesis, the objective of this case study has been realised. Furthermore, it is concluded that the proposed approach is not only useful in the strategic decision making process, but can also play a role in the policy formulating process.

Chapter 6

Reflections upon the study

6.1 Introduction

In the preceding chapters the tool that has been developed within the framework of this study has been described. In this chapter some reflections upon this tool are presented. Section 6.2, deals with the place of a production system within a chain of production systems. Two types of production chains are discerned: those based on material flows, and those based on energy flows. Subsequently, it is discussed in which situations and by whom the tool can be applied. Finally, in section 6.4 some recommendations for further research are presented.

6.2 Chain aspects

Sofar, a production system has been studied almost as if it is not connected to other production systems. In practice, this is never the case since each production system is an element in a production chain. A simplified example of such a chain is presented in figure 6.1. Note that this chain is far from linear and has many branches and loops. In applying the tool developed in this study, one should realise that one of the real issues underlying the concept of sustainability is to minimise the energy consumption in the whole production chain. This implies that not only the energy consumed directly and indirectly in the production of a commodity has to be studied (IFIAS, 1974; appendix 2), but also the energy consumed in that part of the chain that comes after the actual production of the commodity. Examples of this are the energy consumed by the commodity during its lifetime, the energy required to recycle or dispose of the discarded commodity, etc. A conceptual model of all stages during which the energy consumption has to be taken into account, is presented in figure 6.2. In this figure it is indicated during which stages the total energy consumption can be influenced by adaption of design parameters. These may be intrinsic either to the applied production systems, or to the commodity itself. It is clear that there are many degrees of freedom which can be used to optimise the specific energy consumption in of a production chain. Obviously this is a very complex problem, if all degrees of freedom are taken into account simultaneously. The tool presented in this thesis can be considered as one of the steps towards its solution.

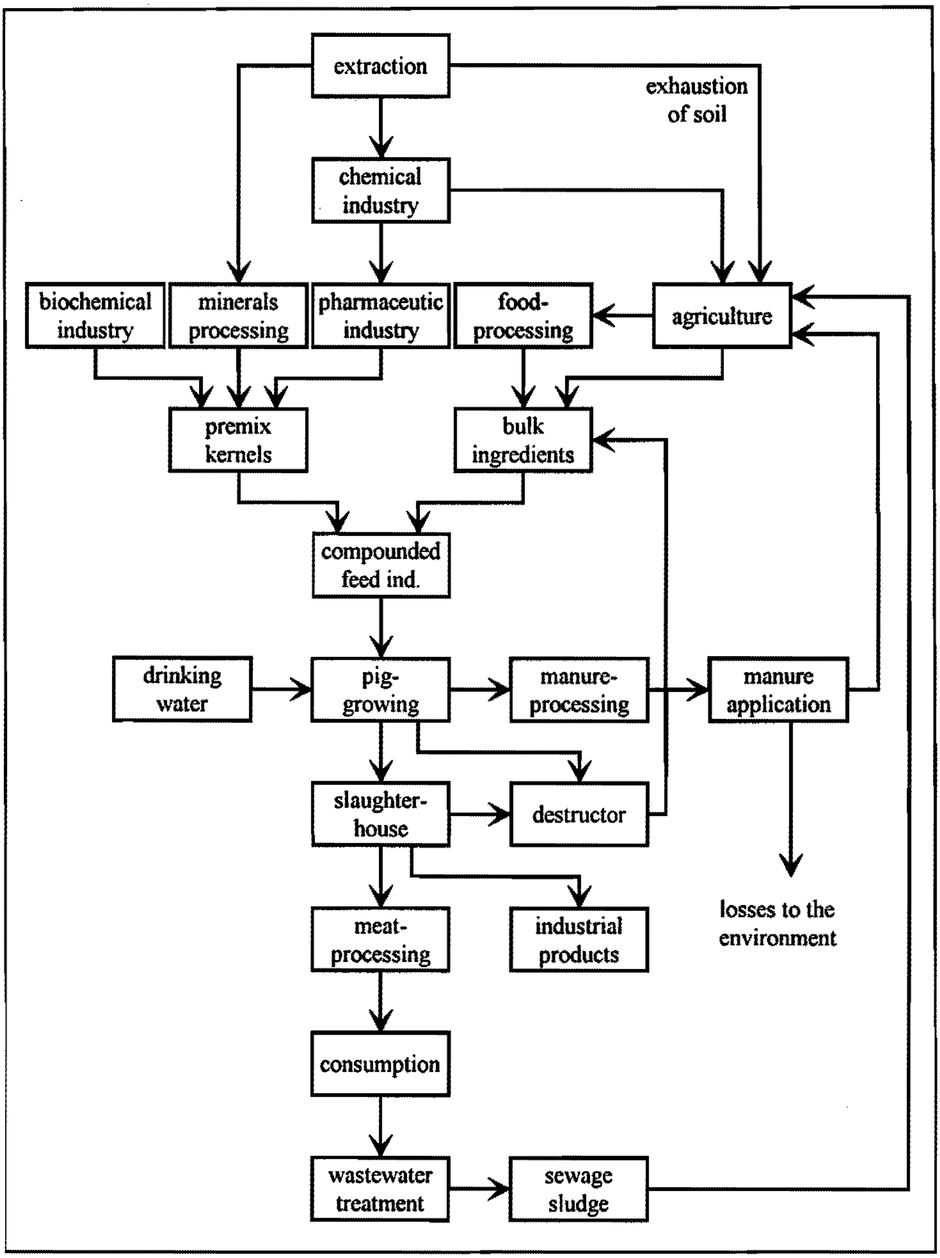

Figure 6.1: An example of a chain of production systems, viz. the pork meat production systems (Lambert *et al.*, 1992).

Besides a chain in which production systems are connected by material flows, there may also a chain based on energy flows. An example of such a chain is a greenhouse consuming the residual heat of a public utility. In this way, an energy

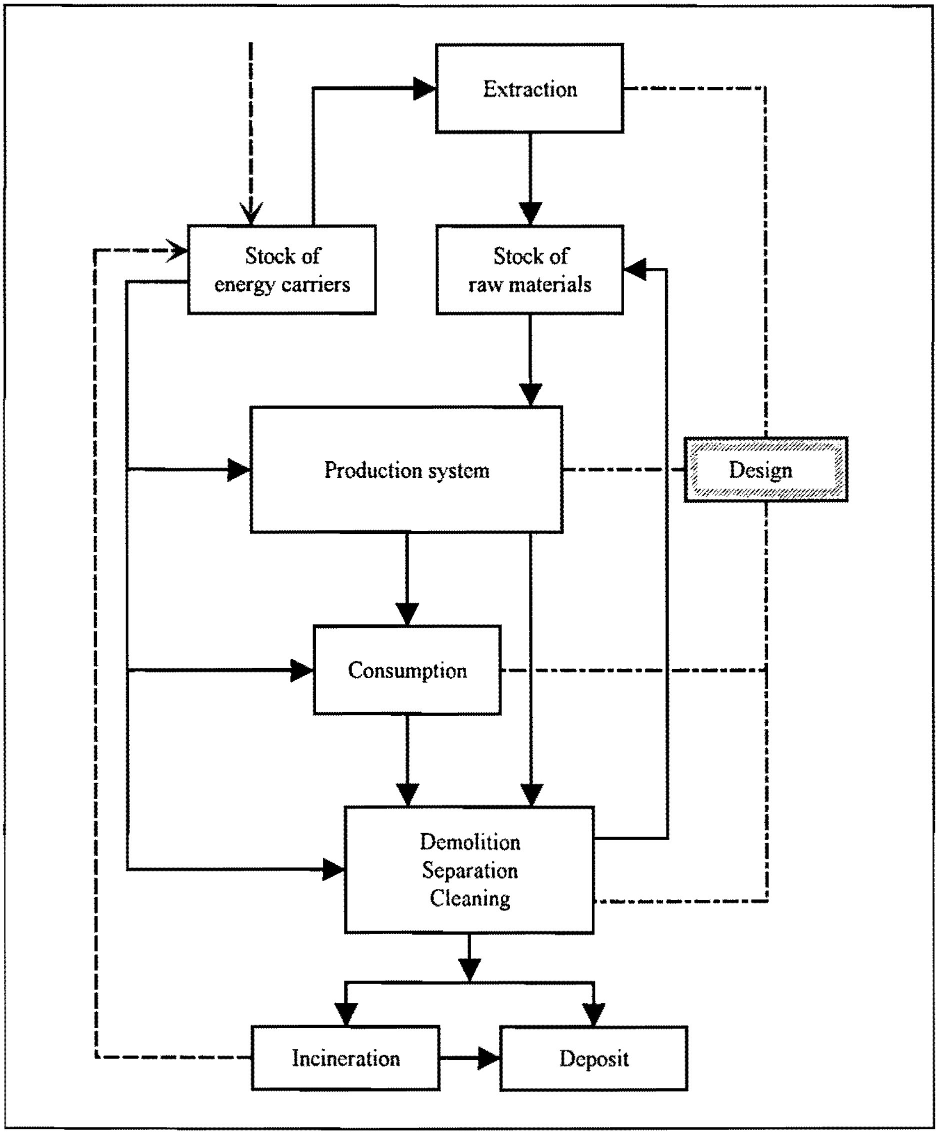

Figure 6.2: Conceptual model of all stages that have to be taken into account (Claus, 1992).

cascade can be constructed between several production systems requiring energy of a gradually lower quality. As has been demonstrated in chapter 3, a chain based on such a cascade can also be studied by using the tool described in this thesis.

6.3 Using the tool

6.3.1 The use in the strategic decision making process

The tool in its initial form has been developed to support decision makers in the strategic process of identifying and selecting novel, more energy efficient production systems. This implies that it has to be able to play a role in the strategic decision making process that precedes the introduction of such systems. This process has been studied extensively, and several proposals have been done to divide it into a number of phases (Mintzberg *et al.*, 1976; Simon 1959, 1976, 1977; Sprague and Carlson, 1982; Witte, 1972). One of the best-known examples is the phase model presented in figure 6.3 (Mintzberg *et al.*, 1976). This phase model consists of three major phases: *identification*, *development*, and *selection*. Each phase is divided into a number of so-called *routines*. There is a strong similarity between these routines and the phases in the design process which have been described in chapter 2.

The identification phase is divided into two routines: *recognition* and *diagnosis*. The former is aimed at gathering information that may convince decision makers of the need to act on a perceived problem. In the latter, information is gathered that may clarify and define the real issues which are at stake in a specific problem situation.

The development phase is aimed at finding solutions to a problem. These may be either ready-made (*search*) or customer made (*design*).

The selection phase is aimed at evaluating and subsequently selecting one alternative solution. It comprises three routines: *screening*, *evaluation-choice*, and *authorization*. Screening involves the reduction of the number of (ready made) solutions. The evaluation-choice routine consists of three modes: *factual evaluation*, *individual judgement* and *bargaining*. Each mode (or combination of modes) is aimed at the identification of the "best" alternative solution. The authorization routine is required in case the individual who is involved in the evaluation choice routine, is not (fully) authorised to take the final decision.

Note that there is no unique path through the different phases and routines in the conceptual model presented in figure 6.3. In fact, a variety of paths through this model is possible. These are indicated by arrows and decision nodes. Furthermore, it is indicated that under some circumstances a routine may have to be repeated, i.e. iteration may be required. For example, this is the case if a new alternative solution is found after the initial decision making process.

The tool presented in this thesis has been developed to give support in the identification and evaluation of alternative production systems. In this respect, it may play an important role in the development phase and in the screening routine and the evaluation choice routine of the strategic decision making process.

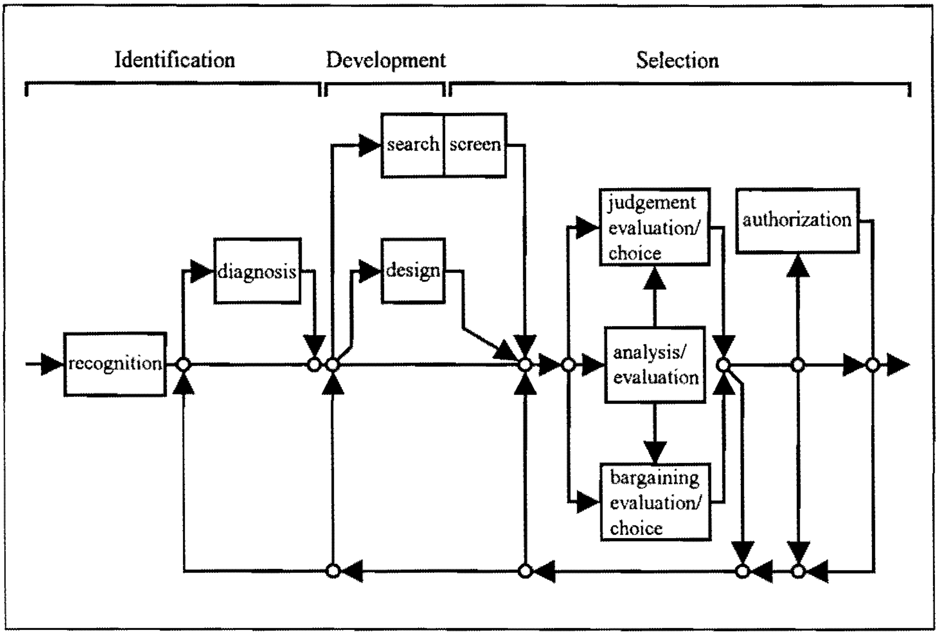

Figure 6.3: The phases and routines in the strategic decision making process (Mintzberg *et al.*, 1976).

6.3.2 The use in the policy formulating process

If a national government wants to pursue a sustainable development of economy and simultaneously intends to stimulate technological development, the question arises which technologies should be developed and which ones should not. In chapter 5 it has been demonstrated that by means of the tool described in this thesis it is possible to identify those technologies that are on the one hand worth to be developed and on the other hand more sustainable. This indicates that the tool may give support in the formulation of a technology policy.

Another application area of the tool is in the formulation of energy conservation and environmental policies which are aimed at industry. In this problem area, principal questions are what targets can be considered realistic, whether these targets can be achieved by means of the applied or intended policy instruments, and what the consequences for industry of achieving such targets are. By means of a study which analyses industrial production structures down to the level of unit operations, as has been done in this thesis, insight in the answers to these questions may be gained.

Yet another application area, which is more or less related to the former one and to the strategic decision making process described in subsection 6.3.1, is in the field of the negotiations on long-term agreements and convenants between a branch of industry and the national government. In these contracts industry commits itself to achieving a certain energy conservation target within a certain time-span. By applying the tool it can be studied whether such a target is realistic and what the consequences of achieving it are.

6.4 Recommendations for further research

As has already been mentioned in this chapter, the tool presented in this thesis is a step towards the development of sustainable industrial production structures. However, many important research questions are still unanswered. Among these questions, the following are considered to be most apparent:

- The tool presented in this thesis is focused on individual production systems. However, for the development of sustainable production chains, other chain-related subjects like reverse manufacturing and reverse logistics have to be studied in more detail. Especially the interaction between these subjects and the design of a production system should explored.

- After a production system has been designed and build, it has to be operated. In this field, a lot of research questions remain. These concern the problem of how to adjust the operational parameters of a production system in order to obtain the lowest specific energy consumption. To gain more insight into the answer to this problem, the relationship between the specific energy consumption and e.g. the machine-speed, the occupation level, and the quality targets, should be studied.

- In chapter 3 it has been discussed that the question which production system is more sustainable with respect to others, cannot be answered unambiguously since the answer depends on the environmental occupation space. Although this concept is used in many discussions, its quantification on micro-level is to a large extent still terra incognita. Considerable research efforts will be required to solve this problem.

- The tool that has been described in this thesis, gives insight in factors that are counteracting the introduction of more sustainable production systems. In practice however, there may be influences on the decision making process of which the decision makers are unaware, and that cannot be incorporated in the normative guidelines of this tool. It cannot be excluded that these influences (e.g. application of other criteria, other values of the weights, etc.) are of decisive importance to the introduction of more sustainable production systems. Therefore, they should be uncovered by analyzing actual decision making processes.

Chapter 7

Conclusions

7.1 Introduction

In this chapter the principal conclusions of this study are presented.

7.2 Conclusions

- For a sustainable development of economy, the use of fossil energy carriers has to be reduced in future. To achieve this, the energy intensity of industrial production has to be reduced drastically. A shift in applied technology will be indispensable for this, i.e. novel technological concepts have to be taken into account in designing production systems. (Chapter 1 + 2)

- In the literature much attention has been given to the systematic (re-)design of the heat recovery subsystem and the utility subsystem, in order to minimise the specific energy consumption of production systems. Given the objective of this study, these methods are applicable only to a limited extent, because:

    - No decision support in the identification of novel processes is given.
    - They are only applicable in existing (concepts of) production systems and are unable to take the application of alternative processes into consideration.
    - The influence of sequential decision making and of the periphery on the design of a total production system cannot be studied.
    - The evaluation of alternatives is mostly based on a single, cost related criterion. Other criteria, like technical and managerial ones, are not fully taken into account. (Chapter 1 + 2)

- The division of a production system into a transformation subsystem, a heat recovery subsystem and a utility subsystem, has been demonstrated to be a useful instrument to study all energy conservation options. To achieve the required shift in applied technology, the elements of all three subsystems have to be put for debate. Alternative elements for the transformation subsystem can be identified by dividing this subsystem into elementary tasks. (Chapter 3)

- By means of the presented mathematical formulation, the most energy efficient production system can be identified. By applying so-called design strategies, sequential decision making (i.e. sequentially selecting the elements of the subsystems) has been demonstrated to lead to production systems with a non-optimal specific energy consumption. Using an integral design strategy and the mathematical formulation leads to the application of those production unit operations which are most compatible from an energy point of view, but which individually do not necessarily have minimum energy use. (Chapter 3)

- The environmental occupation space and/or juridical restrictions may become constraints to the realisation of the production system with the lowest specific energy consumption. The influence of both can be taken into account in the mathematical formulation. (Chapter 3)

- Multiple criteria decision aid methods (viz. the Promethee methods), combined with extensive sensitivity analyses, are valuable tools in the process of selecting an alternative production system. By including the most energy efficient production system in the set of alternatives that is considered for evaluation, the pro's and con's of this alternative can be studied.
(Chapter 4 + 5)

- By means of the proposed weight sensitivity analysis, the number of viable alternatives can be reduced. This facilitates the selection problem. The obtained proximity ranking indicates which alternative is more likely to become ranked first. (Chapter 4)

- The tool presented in this thesis, has been demonstrated to be a valuable instrument in the strategic decision making process related to the introduction of more sustainable production systems. In the same problem area, it is also applicable in the policy formulating process. (Chapter 5 + 6)

- The characteristics of more sustainable production systems which are counteracting their introduction, can be determined by means of the tool presented in this thesis. By analyzing these characteristics, it can be indicated what (research) efforts are required to diminish them. (Chapter 5)

- The tool presented in this thesis is a step towards the design of sustainable production chains. Remaining research questions are in the field of other chain-related subjects (e.g. reverse manufacturing), the adjustment of the operational parameters of a production system, the quantification of the environmental occupation space on the micro-level, and the analysis of actual decision making processes. (Chapter 6)

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Appendix 1

The Promethee methods

In this appendix, a brief outline of the Promethee I & II methods is given (Brans, 1984, 1985, 1986). In subsection A1.1 the case in which no uncertainties are present in the data to be analysed (i.e. a deterministic case), is treated. Since a number of uncertainties may arise in practice, a stochastic extension to the methods (Mareschal, 1986) is described in subsection A1.2.

A1.1 Deterministic case

Consider a set A of n alternative actions a_i $(i = 1,..,n)$ that have to be ranked, and let $f_1,\dots,f_k$ be the set of selected criteria. Each alternative from A has to be evaluated through all criteria. The Promethee methods build an outranking relation on A which is used to obtain a partial (Promethee I) and a complete ranking (Promethee II).
The preference for action a over b $(a,b \in A)$ on criterion f_j is expressed through a preference function P_j, such that:

$$0 \leq P_j(a,b) \leq 1 \tag{A1.1}$$

In the case of no preference of a over b, or indifference between them, $P_j(a,b)$ equals 0. In the case of strict preference of a over b, it equals 1. $P_j(a,b)$ can be considered as the degree of preference of a over b, and is a function of the difference in the scores on criterion f_j of action a and b, i.e. $d = f_j(a) - f_j(b)$. In figure A1.1 the possible shapes (characterized by 0,1 or 2 parameters) for P_j are shown.

After preference functions P_j have been specified, weights w_j have to be assigned to the criteria. A weight w_j expresses the relative importance of criterion f_j with respect to all other criteria.
Subsequently a multi-criteria preference index π is defined as:

$$\pi(a,b) = \frac{\sum_{j=1}^{k} w_j \, P_j(a,b)}{\sum_{j=1}^{k} w_j}, \qquad \forall \; a,b \in A \tag{A1.2}$$

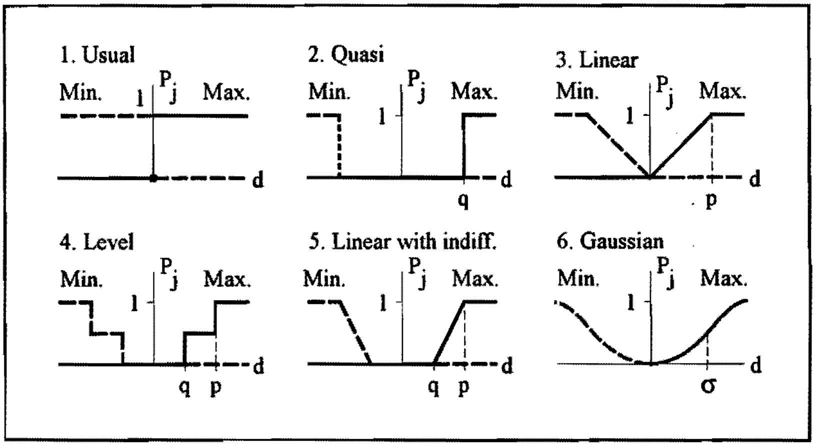

Figure A1.1: The six shapes for $P_j(a,b)$.

$\pi(a,b)$ represents the intensity of preference of a over b, taking all applied criteria into account simultaneously. It can be used to define a valued outranking relation on A. Promethee defines for each $a \in A$ its leaving flow $\phi^+(a)$, its entering flow $\phi^-(a)$, and its net flow $\phi(a)$. These are defined as follows:

$$\phi^+(a) = \sum_{b \in A} \pi(a,b) \tag{A1.3}$$

$$\phi^-(a) = \sum_{b \in A} \pi(b,a) \tag{A1.4}$$

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{A1.5}$$

Each flow induces a complete ranking on A. The higher $\phi^+(a)$, the better a. The higher $\phi^-(a)$, the weaker a. The intersection of the rankings resulting from ϕ^+ and ϕ^- defines the Promethee I partial ranking:

- $a\mathrm{P}_\mathrm{I}b$ (a preferred to b) if $\phi^+(a) \geq \phi^+(b)$ and $\phi^-(a) \leq \phi^-(b)$ (at least one inequality being strict)
- $a\mathrm{I}_\mathrm{I}b$ (a and b indifferent) if $\phi^+(a) = \phi^+(b)$ and $\phi^-(a) = \phi^-(b)$
- $a\mathrm{R}_\mathrm{I}b$ (a and b incomparable) otherwise

The Promethee II complete ranking is defined by the net flow:

- $a\mathrm{P}_\mathrm{II}b$ (a preferred to b) if $\phi(a) > \phi(b)$
- $a\mathrm{I}_\mathrm{II}b$ (a and b indifferent) if $\phi(a) = \phi(b)$

A1.2 Stochastic case

If uncertainties arise in the data to be analysed (for instance in the case of multiple experts evaluating the alternative actions), the methods described in the previous subsection are not applicable without due consideration. To cope with such uncertainties, a stochastic extension of outranking methods like Promethee is described briefly in this subsection, with a focus on the so-called experts-case (Mareschal, 1986).

In the deterministic case, each alternative a_i is evaluated through each criterion. If this evaluation is defined to be e_{ij}, then:

$$f_j\text{:}\ A \rightarrow \mathbb{R} \tag{A1.6}$$

$$e_{ij} = f_j(a_i)\ , \qquad \forall\ a_i \in A \tag{A1.7}$$

A matrix E of the evaluations e_{ij} may be defined such that:

$$E = (e_{ij}) \in \mathbb{R}^{n \times k} \tag{A1.8}$$

In (Mareschal, 1986) it is proposed to extend relations A1.6 and A1.7 in such a way that the evaluations e_{ij} become real random variables, i.e.:

$$f_j : A \rightarrow T \tag{A1.9}$$

where T is a set of real random variables. Let F_{ij} denote the distribution function of e_{ij}. E then becomes a real stochastic matrix with a joint distribution F:

$$F(E_0) = P(E \leq E_0), \quad E_0 \in \mathbb{R}^{n \times k} \tag{A1.10}$$

In the so-called experts-case, the joint distribution is discrete:

$$(E_l,\ p_l;\ l = 1,\ldots,m) \tag{A1.11}$$

where $E_l \in \mathbb{R}^{n \times k}$, $p_l = P(E{=}E_l) \neq 0$, $\sum_{l=1}^{m} p_l = 1$, and m is the number of experts with respective weights $p_1,\ldots p_m$. Since the evaluations of the m experts result in m values $E_1,\ldots,E_m$, m deterministic multi-criteria problems occur that can be solved as described in the preceding subsection. This results in a set of m binary preference relations S_l on A. Because the distribution on $\{E_1,\ldots..E_m\}$ is known, it is possible to aggregate the S_l's into a single valued preference relation S, which is defined by:

$$S(a,b) = \sum_{l \mid (a,b) \in S_l} p_l\ , \qquad \forall\ a,b \in A \tag{A1.12}$$

In case the S_l's are complete preorders, the following procedure may be used instead of relation A1.12. Let $r_l(a)$ denote the rank (averaged in case of ties) of alternative a in S_l and define $s(a)$ as:

$$s(a) = \sum_{l=1}^{m} p_l \, r_l(a) \, , \qquad \forall \; a \in A \tag{A1.13}$$

By ordering the alternatives from the smallest to the greatest value of s, an average complete preorder is obtained. An averaged partial preorder may obtained by defining:

$$S^{+}(a) = \sum_{b \in A} S(a,b) \tag{A1.14}$$

$$S^{-}(a) = \sum_{b \in A} S(b,a) \tag{A1.15}$$

$S^{+}(a)$ and $S^{-}(a)$ induce two preorders on A, the intersection of which defines a partial preorder.

Appendix 2

Energy analysis

In this appendix the concept of energy analysis is introduced. Energy analysis is defined as "the determination of the energy sequestered in the process of making a good or service within the framework of an agreed set of conventions or applying the information so obtained" (IFIAS, 1974). It is a technique for examining the way in which energy sources are harnessed to perform useful (economic) functions, and has a role to play at global, national and industrial branch/company level (Boustead and Hancock, 1979). In this thesis there is a focus on the latter level. Whenever an energy analysis is performed, the term and unit of account have to be defined. The Gross Energy Requirement (GER) and the Net Energy Requirement (NER) are the most important terms to the work presented in this thesis. They are defined as follows (IFIAS, 1974):

GER: The amount of energy source which is sequestered by the process of making a good or service.

NER: The Gross Energy Requirement less the gross enthalpy of combustion of the products of the process under study.

The unit of account of all these terms is Joules per unit of product. Which of these terms has to be used depends on the interests of the energy analyst and on the system boundary that is chosen. For example the NER may be useful in cases where the energy analyst wishes to discount the energy locked up in the product or wastes (e.g. recycling or burning). To simplify the task of the energy analyst, the scheme presented in figure A2.1 was proposed. By applying this scheme the energy analyst is able to control the accuracy of the information resulting from the analysis. The levels reflect the sequence in magnitude of the contributions to the total GER or NER. In general, level 1 and level 2 account for 90 to 95% of the total GER or NER (IFIAS, 1974; Boustead and Hancock, 1979). Therefore, this study is restricted mainly to these levels, although a few notes on level 3 and 4 are made as well.
The definition of the GER and the NER enables to define the concept of energy intensity of a product. This is essentially the same as the GER or NER and its unit of account is also Joules per unit of product. Therefore it is sometimes called technical energy intensity as opposed to economical energy intensity which is measured in for example Joules per unit of GNP. Within the framework of this study the concept of energy conservation may now be defined as the decrease in energy intensity of a certain commodity. Its unit of account is Joules/unit of product.

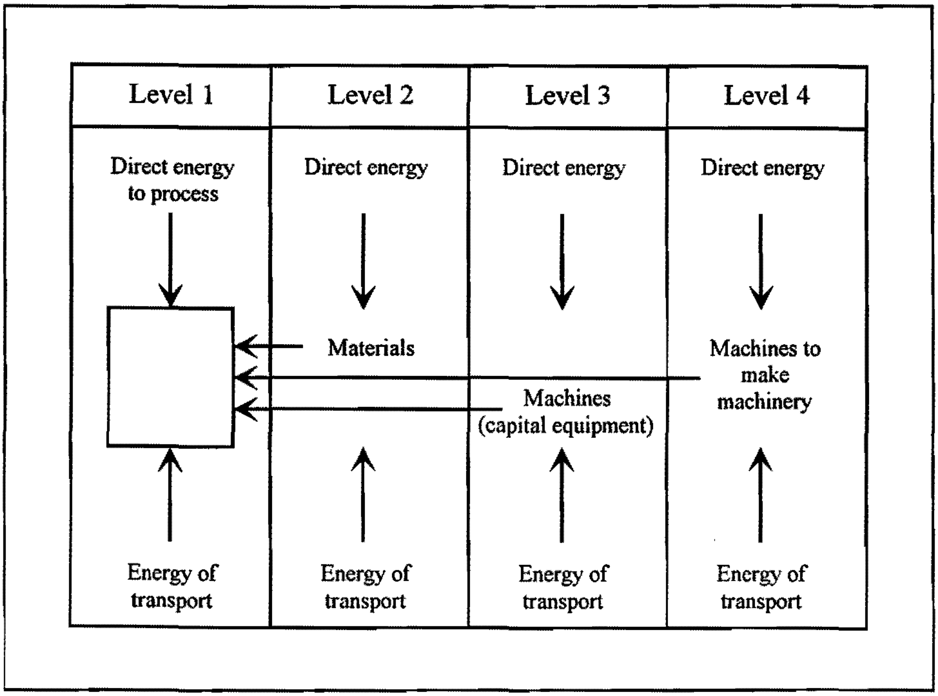

Figure A2.1: The levels in energy analysis.

Appendix 3

List of elementary tasks

In this appendix a list of so-called elementary tasks is presented. It should be noted that it is not claimed that this list is complete, nor that it can provide a unique analysis in every design situation. The list that is presented in this appendix is an extension of a similar list described elsewhere (Ayres, 1978).

1 Transformation of extrinsic parameters

1.1 Transformation in place
    1.1.1 Motorized
        1.1.1.1 Motor carried in transport
            - *Self-propelled vehicle*
        1.1.1.2 Motor not carried in transport
            - *Passive vehicle*
    1.1.2 Non-motorized
            - *Gravity flow*
            - *Pressure flow*
            - *Convective flow*
            - *Capillary flow*

1.2 Transformation in time
    1.2.1 Storage under controlled conditions
            - *Controlled temperature*
            - *Controlled pressure*
            - *Controlled humidity*
            - *Controlled illumination*
            - *Controlled contact with specific substances*
    1.2.2 Storage under un-controlled conditions
            - *No control of anything*

2 Transformation of intrinsic parameters

2.1 Mixing
  2.1.1 Physical integration
    - *Fusion or sintering*
    - *Adhesion*
    - *Mechanical joining (sew, rivet, screw, bolt, nail, weave)*
  2.1.2 Physical association
    - *Mechanical stirring or blending*
    - *Mixing by acoustic agitation*
    - *Entrainment and suspension by moving fluid stream*
    - *Solution*
    - *Absorption*
    - *Adsorption*
    - *Diffusion*
    - *Electrostatic deposition*

2.2 Separation
  2.2.1 Physical disintegration
    - *Shock (chopping, splitting, blasting, acoustic)*
    - *Cutting (sawing, slicing, drilling, milling)*
    - *Crushing*
    - *Tearing or picking*
  2.2.2 Physical dissociation
    - *Mechanical dismantling*
    - *Sifting and sorting*
    - *Filtration*
    - *Centrifugal separation*
    - *Flocculation*
    - *Precipitation*
    - *Settling*
    - *Draining*
    - *Crystallisation*
    - *Evaporation, melting or sublimation*
    - *Condensation or freezing*

2.3 Transformation of shape (total mass is constant)
        - *Pressure forming*
        - *Extension or expansion*
        - *Torsion*
        - *Shear*

2.4 Transformation of chemical properties
    2.4.1 Endothermic reactions
        2.4.1.1 Chemical association or synthesis
            - *With catalyst*
            - *Without catalyst*
        2.4.1.2 Chemical dissociation or decomposition
            - *With catalyst*
            - *Without catalyst*

        2.4.1.3 Biological digestion or synthesis
            - *Biotechnology*
    2.4.2 Exothermic reactions
        2.4.1.1 Chemical association or synthesis
            - *With catalyst*
            - *Without catalyst*
        2.4.1.2 Chemical dissociation or decomposition
            - *With catalyst*
            - *Without catalyst*
        2.4.1.3 Biological digestion or synthesis
            - *Biotechnology*

2.5 Transformation of physical properties
    2.5.1 Change in electron distribution
            - *Electrification*
            - *Magnetisation*
            - *Heating/cooling by: convection, irradiation, conduction pressure*
    2.5.2 Change of molecular structure
        2.5.2.1 With change of phase
            - *Heating/cooling by: convection, irradiation, conduction, pressure*
        2.5.2.2 Without change of phase
            - *Heating/cooling by: convection, irradiation, conduction, pressure*

- 2.5.3 Change of nuclear properties
    - 2.5.3.1 Spontaneous reaction
        - *Nuclear fission*
        - *Nuclear fusion*
        - *Isotope reaction*
    - 2.5.3.2 Forced reaction
        - *Nuclear fission*
        - *Nuclear fusion*
        - *Isotope reaction*

Appendix 4

The determination of the weights

In this appendix, a brief outline is given of the three methods that have been applied to determine the weights in the framework of the case study presented in chapter 5.

A4.1 The rank reciprocal weighting procedure

In the rank reciprocal weighting procedure, the decision makers are asked to rank the criteria in order of importance. Subsequently, these ranks are transformed into weights using relation A4.1.

$$w_i = \frac{1}{R_i \sum_{j=1}^{n} \frac{1}{R_j}} \qquad R_i, R_j = 1, 2, 3, \ldots, n \qquad \text{(A4.1)}$$

where w_i is the weight that is assigned to criterion i, R_j is the rank of criterion j, and n is the total number of criteria. Note that the set of weights that is obtained in this way is already normalised.

A4.2 The rank sum weighting procedure

If the rank sum weighting procedure is applied, the decision makers have to rank the criteria in the same way as for the rank reciprocal weighting procedure. However, this time the ranks are transformed into weights using relation A4.2.

$$w_i = \frac{n + 1 - R_i}{\sum_{j=1}^{n} R_j} \qquad R_i, R_j = 1, 2, 3, \ldots, n \qquad \text{(A4.2)}$$

w_i, R_j and n are defined in the same way as for the rank reciprocal weighting procedure.

A4.3 The direct rating weighting procedure

In the direct weighting procedure, the decision makers are asked to distribute 100 points over the criteria, in such a way that the number of points assigned to a criterion reflects its relative importance.

Appendix 5

Developments in the paper and board industry

In this appendix a brief overview is presented of the developments which are expected to take place in the paper and board industry in the long term (e.g. in 25 to 50 years. The presented data are based on a comprehensive study of relevant literature.

A5.1 The future volume of industrial production

In the Global Shift scenario, process industries (to which the paper and board industry belongs) are confronted with a number of conflicting forces. The competitiveness is deteriorated by the presence of trade barriers, as a result of which industry cannot benefit from economy of scale effects in its production systems. Furthermore, the demand for products from the process industries and consequently its production volume will not have grown very much.

In the Balanced Growth scenario the growth in production volume is mitigated by high environmental taxes on fossil energy carriers. Since these taxes will not be equal around the world, there will be a trend to transfer business to regions where environmental taxes are lower and where environmental legislation is not so strict. These regions can be found mostly in developing countries. However, the environmental tax on fossil energy carriers also stimulates the development and introduction of novel, more energy efficient and environmentally friendly technologies. This will compensate for the trend to transfer business to other regions. Consequently, the expectations for the dutch paper and board industry are not adverse.

In the European Renaissance scenario, the growth in production volume of the dutch process industries is between that of the Balanced Growth en Global Shift scenario. Within europe, the production of primary products will be concentrated in eastern europe. There they can benefit from the resources which are present in CIS countries.

A5.2 The future consumption of paper and board

Paper and board consumption is determined by amongst others:

- demographic factors (size of population, number of households etc.)
- the volume of industrial production
- the economical development

Furthermore, for each specific grade a number of other factors can influence the consumption. These factor like e.g. the reading habits, may vary from country to country. Consequently, the consumption of different grades may vary. These variations occur in the quantities of consumed paper as well as in the quality of that paper. Generally, quality standards for paper increase with growing welfare.
It is expected that the total paper and consumption in the world will grow. However, significant variations may occur per region. Taking into account the size of the population, the expected economic growth and the relatively low paper consumption per capita, it is expected that the strongest growth in paper and board consumption will occur in Asia (exclusive of Japan). In the european community there is also a considerable growth potential given the relatively low consumption in comparison with North-America. The least growth will occur in North-America. This is due to the already high consumption per capita, and to the moderate economic growth. In the very long term it is expected that eastern-europe and the CIS countries will become very important markets.

The expectations presented above are based on extrapolations of recent historical data. This implies that sudden shifts in e.g. the socio-economic structure are not taken into account. Such a shift could for example be the result of the introduction of a technology that would replace paper as an information carrier. In fact, such technologies are already penetrating in society or are being developed (e.g. Electronic Data Interchange, multi-media products, CD-ROM). Although normal reasoning would point out that such technologies would reduce the use of paper drastically and would cause changes in the pattern of paper usage, some studies from the paper industry itself indicate that these technologies will boost paper consumption (P&P Papermaking Report, 1991).

If it is assumed that a shift as mentioned above will not take place, the growth of paper and board consumption in the Netherlands will be closely related to the growth in Gross National Product (GNP). In table A5.1, an overview is given of the consumption level in the three scenarios. It is expected that the growth in consumption of printing and writing grades will be the highest. The lowest growth will occur for the newsprint grades. More important however will be the shift to the use of more recycled paper as raw material for all grades.

Table A5.1: The future paper consumption in the Netherlands (1990 = 100).

	Global Shift	Balanced Growth	European Renaissance
Consumption	148	215	190

A5.3 Future quality requirements

Changes in the applications of paper and board will lead to stricter and sometimes conflicting quality requirements (P&P Papermaking Report, 1991). Producers of printing and writing grades will be confronted with costumers that on the one hand demand paper with lower basic weight and on the other hand paper which is less translucent and has less show through. The application of faster printing-presses implicates that the strength of the paper will have to be improved. Furthermore, stricter requirements will have been set with respect to flexibility and to criteria which are related to the appearance of the paper (e.g. whiteness). Similar developments in quality requirements will have taken place for wrapping and packaging grades.

Summary

To achieve (more) sustainable production systems and chains, the energy intensity of industrial production has to be reduced. The application of other production technologies will be indispensable for this. The objective of the study presented in this thesis is to develop a tool that may support decision makers in identifying and evaluating intrinsically energy efficient production systems.

A review of literature on systematic methods for minimising the energy consumption of a production system, reveals that these seldom question the demand for energy. In this thesis it is argued that doing this is indispensable in order to arrive at more sustainable production systems and chains.

The demand for energy primarily results from the production unit operations which transform the raw materials into the desired commodity. Therefore, fundamental changes in the demand for energy can be achieved only by applying other production unit operations. Given the objective of this study and the literature review, five gaps in literature can be discerned. Based on these gaps, the following research questions have been formulated:

- How can alternative production unit operations be identified?
- Which unit operations should be selected in order to obtain the most energy efficient production system?
- What is the influence of sequential decision making on the design and, consequently, on the specific energy consumption of a production system?
- What is the influence of the periphery on the design and, consequently, on the specific energy consumption of a production system?
- How is the selection of energy efficient production systems influenced by other than energy or cost related criteria?

The first four research questions are related to the identification of energy efficient production systems. They are treated in chapter 3 of this thesis. For this purpose, it is proposed to decompose a production system into three subsystems: the *transformation subsystem* where energy is used to transform the raw materials into the desired commodity; the *utility subsystem* where energy is made available in the right quantity and quality; and the *heat recovery subsystem* where residual heat is recovered.

To answer the first research question, a qualitative method is proposed which can be used to identify alternative production unit operations and, consequently, alternative transformation subsystems. Generally, this results in a rather high number of alternatives, which hampers the identification of the most energy efficient production system. This stresses the importance of the second research question. To answer this question, mathematical building blocks are presented by means of which the production system (combination of elements) that is optimum from an energy point of view can be identified, via an optimisation step. By sequentially fixing the variables during the optimisation, the influence of sequential decision making can be studied. The influence of the periphery can be studied by means of sensitivity analyses and/or by adding additional constraints to the optimisation problem.
The theory developed in chapter 3, is illustrated by a simulation experiment. From the results it is concluded that sequential decision making has a significant influence on the design and, consequently, on the specific energy consumption of a production system. Furthermore, it is concluded that simply selecting those production unit operations with minimum energy use, not always results in the production system with the lowest specific energy consumption. Instead, those production unit operations should be selected that are most compatible from an energy point of view. This can be done by means of the mathematical formulation. Finally, it is concluded that the periphery has a significant influence on the energy performance and on the design of a production system.

The fifth research question is related to the evaluation of production systems. This subject is studied in chapter 4 of this thesis. By including the most energy efficient production system in the set of alternative production systems that is considered for evaluation, the advantages and disadvantages of this alternative become apparent. This is illustrated by means of two experiments. From the results it follows that if criteria like complexity, flexibility etc. are taken into account, the alternatives resulting from the methods described in chapter 2 may not meet the preferences of decision makers from practice.
Since sensitivity analyses play an important role in the evaluation of production systems, extra research efforts have been devoted to this. This has resulted in a method that enables decision makers to reduce the number of "feasible" alternatives, and thus to facilitate the selection process.

The practical applicability of the tool presented in this thesis has been tested by means of a case study in the Dutch paper and board industry. This case study was part of the project "Sustainable Industrial Production", which has been performed by TNO (Netherlands Organisation for Applied Scientific Research) in cooperation with Eindhoven University of Technology, on behalf of the Dutch Ministry of Economic

Affairs. From the results of this case study which are presented in chapter 5, it is concluded that the provided information is valuable to industrial decision makers who are thinking about switching to a more sustainable production system in the long term. Application of the tool gives them insight in the possibilities that exist for this, and in the advantages and disadvantages of each alternative. By means of a systematic analysis of the (physical) causes of the disadvantages, aimed (research) efforts can be initiated to diminish their influence.

Samenvatting (summary in Dutch)

Om te komen tot duurzame(-re) produktiesystemen en -ketens, zal in de komende jaren de energie-intensiteit van industriële produktie moeten worden gereduceerd. Toepassing van andere produktie-technologieën is hierbij noodzakelijk. Het doel van de studie die beschreven is in dit proefschrift, is het ontwikkelen van een instrument dat beslissers kan helpen bij het identificeren en evalueren van intrinsiek energiezuinige produktiesystemen.

Uit een overzicht van in de wetenschappelijke literatuur bekende methoden om het energiegebruik in industriële produktiesystemen te reduceren, blijkt dat hierin de energievraag zelden ter discussie wordt gesteld. In dit proefschrift wordt betoogd dat juist dit noodzakelijk is om duurzame(-re) produktiesystemen en -ketens te realiseren.
De energievraag is primair afkomstig van de produktie unit operations welke de grondstoffen daadwerkelijk transformeren tot het gewenste produkt. Fundamentele veranderingen in de energievraag kunnen dus alleen gerealiseerd worden door het toepassen van andere produktie unit operations. Gegeven het doel van deze studie, kunnen een vijftal tekortkomingen in de in de literatuur bekende methoden worden geconstateerd. Gebaseerd op deze tekortkomingen zijn de volgende onderzoeksvragen geformuleerd:

- Hoe kunnen alternatieve produktie unit operations worden geïdentificeerd?
- Welke unit operations moeten geselecteerd worden om het meest energiezuinige produktiesysteem te verkrijgen?
- Wat is de invloed van het sequentieel nemen van beslissingen op het ontwerp en daarmee op het specifiek energiegebruik van een produktiesysteem?
- Wat is de invloed van de omgeving op het ontwerp en daarmee op het specifiek energiegebruik van een produktiesysteem?
- Hoe beïnvloeden andere dan aan energie of kosten gerelateerde criteria de selectie van energiezuinige produktiesystemen?

De eerste vier onderzoeksvragen hebben betrekking op het identificeren van energiezuinige produktiesystemen. Deze vragen worden beantwoord in hoofdstuk 3 van dit proefschrift. Hierin wordt allereerst voorgesteld om een produktiesysteem op te delen in een drietal subsystemen: Het *transformatie subsysteem* waar energie wordt gebruikt om de grondstoffen te transformeren tot het gewenste produkt; het *utility subsysteem* waar energie beschikbaar wordt gemaakt in de juiste hoedanigheid en hoeveelheid; en het *warmte terugwinning subsysteem* waar restwarmte wordt teruggewonnen.

Ter beantwoording van de eerste onderzoeksvraag wordt een kwalitatieve methode voorgesteld waarmee alternatieve produktie unit operations en daarmee alternatieve transformatie subsystemen kunnen worden geïdentificeerd. Deze aanpak resulteert in een groot aantal alternatieven, hetgeen de identificatie van het meest energiezuinige produktiesysteem bemoeilijkt. Dit onderstreept het belang van de tweede onderzoeksvraag. Ter beantwoording van deze vraag, worden een aantal wiskundige bouwstenen gepresenteerd waarmee via een optimalisatie-stap het meest energiezuinige produktiesysteem (combinatie van elementen) kan worden geïdentificeerd. Door tijdens het optimaliseren de variabelen sequentieel vast te leggen, is het mogelijk de invloed op het ontwerp van een produktiesysteem van het op deze wijze nemen van beslissingen te bestuderen. De invloed van de omgeving kan worden bestudeerd door middel van het uitvoeren van een gevoeligheids-analyse en/of door het toevoegen van extra randvoorwaarden bij de optimalisatie.

De in hoofdstuk 3 ontwikkelde theorie wordt geïllustreerd met behulp van een simulatie experiment. Uit de resultaten hiervan blijkt dat het op sequentiële wijze nemen van beslissingen een grote invloed heeft op het ontwerp en dus op het specifiek energiegebruik van een produktiesysteem. Verder blijkt dat de combinatie van de meest energiezuinige produktie unit operations niet altijd leidt tot een produktiesysteem met een optimaal specifiek energiegebruik. Hiervoor moeten namelijk die produktie unit operations worden genomen welke energetisch het best compatibel met elkaar zijn. Deze kunnen met behulp van de wiskundige bouwstenen en de toepassing van een integrale ontwerp-aanpak worden geïdentificeerd. De omgeving blijkt eveneens van invloed te zijn op het ontwerp en dus op het specifiek energiegebruik van een produktiesysteem.

De vijfde onderzoeksvraag heeft betrekking op het evalueren van produktiesystemen. Dit is het onderwerp van hoofdstuk 4 van dit proefschrift. Door het meest energiezuinige produktiesysteem op te nemen in de set van alternatieven die nader geëvalueerd wordt, kunnen de voor- en nadelen van dit alternatief worden bestudeerd. Dit wordt geïllustreerd door middel van een tweetal experimenten. Uit de resultaten hiervan blijkt dat, indien criteria zoals complexiteit, flexibiliteit etc. in de beschouwing worden meegenomen, de alternatieven welke het resultaat zijn van de in hoofdstuk 2 beschreven methoden niet altijd aansluiten bij de wensen van beslissers uit de praktijk.

Daar gevoeligheids-analyses een belangrijke rol spelen bij het evalueren, is hier een extra onderzoek naar ingesteld. Het resultaat hiervan is een methode waarmee beslissers het aantal toelaatbare alternatieven kunnen reduceren, om op die manier het selectie-proces te vergemakkelijken.

De toepasbaarheid van het in dit proefschrift beschreven instrument is getoetst middels een case studie in de Nederlandse papierindustrie. Deze case studie was een onderdeel van het project "Duurzame Industriële Produktie" dat is uitgevoerd door TNO in samenwerking met de Technische Universiteit Eindhoven, in opdracht van het Ministerie van Economische Zaken. Uit de resultaten van de case studie, welke gepresenteerd zijn in hoofdstuk 5 van dit proefschrift, kan worden geconcludeerd dat de verschafte informatie waardevol is voor beslissers in bedrijven die overwegen op langere termijn over te schakelen op een duurzame(-re) wijze van produceren. Toepassing van het instrument verschaft hen inzicht in de mogelijkheden die hiervoor bestaan, en welke voor- en nadelen hieraan verbonden zijn. Verder kunnen door middel van een systematische analyse van de (fysische) oorzaken van de nadelen, gerichte (onderzoeks-)inspanningen worden geïnitieerd om effecten van deze nadelen te reduceren.

About the author

Wim T.M. Wolters was born in Montfort on July 8, 1966. In 1984 he finished secondary school (Gymnasium ß) at B.C. Schöndeln in Roermond, after which he studied physics at the Roman Catholic University of Nijmegen. In December 1988 he finished his study at the Masters level, after a research project on spin-polarized tunnelling in GaAs and $Al_xGa_{1-x}As$ semiconductors. Subsequently, he joined the Graduate School of Industrial Engineering and Management Science (Energy & Environment Section) of Eindhoven University of Technology, to perform a research project on sustainable industrial production. He acted as one of the project-leaders of the project "Sustainable Industrial Production" which was performed on behalf of the Dutch Ministry of Economic Affairs by TNO (Netherlands Organisation for Applied Scientific Research) and Eindhoven University of Technology. At the conference "Sustainable Development and Research", which was organised by the Dutch Ministry of Environmental Affairs, he received an award for the research described in this thesis.

STELLINGEN

behorende bij het proefschrift

Sustainable Industrial Production

an energy perspective

door

WILHELMUS THEODORUS MARIE WOLTERS

1. Het gebruik van het zogenaamde "onion model" bij het ontwerpen van het utility en het heat recovery subsysteem, leidt meestal tot een sub-optimaal resultaat. (Linnhoff *et al.*, 1982; dit proefschrift, hoofdstuk 3)

2. Voor een goed inzicht in de duurzaamheid van een technologisch alternatief, dient in het bijzonder de interactie tussen dit alternatief en de milieugebruiksruimte te worden bestudeerd. (dit proefschrift, hoofdstuk 3)

3. Het niet betrekken van de milieu-effecten in de economische evaluatie is één van de belangrijkste belemmeringen voor de introductie van duurzame(-re) produktiesystemen. (dit proefschrift, hoofdstuk 5)

4. Voor de ontwikkeling en introductie van duurzame technologie is een nauwe samenwerking tussen industriële gebruikers en ontwikkelaars van technologieën, onderzoeksinstellingen, en de overheid noodzakelijk.
   (dit proefschrift, hoofdstuk 6)

5. Natuurkunde wordt vaak aangeduid als een "exacte" wetenschap. Indien men zich realiseert dat natuurkundige theorieën grotendeels gebaseerd zijn op gepostuleerde relaties tussen fysische variabelen, dan wordt het exacte karakter van deze wetenschappelijke discipline gereduceerd tot het gebruik van complexe mathematische modellen.

6. Het gebruik van overdadig veel moeilijke woorden, indrukwekkende afkortingen en extreem lange zinnen in wetenschappelijke publikaties belemmert de toepassing van de resultaten.

7. Natuurwetenschappen en religie sluiten elkaar slechts uit indien de wetten en regels van het ene worden toegepast op het domein van het andere. Dit kan echter worden aangemerkt als oneigenlijk gebruik, daar deze wetten en regels buiten hun eigen domein niet gevalideerd kunnen worden.

8. Legalisatie van hard en soft drugs verplaatst de handel in deze goederen naar "keurige ondernemers", hetgeen in niet geringe mate zal bijdragen aan een verdere normvervaging in onze samenleving.

9. Alhoewel het definiëren en operationaliseren van bedrijfskundige begrippen vaak moeilijk is, betekent dit niet dat deze zaken achterwege gelaten kunnen worden.

10. Een essentiële fout in veel als wetenschappelijk bedoeld werk is het doen van harde uitspraken op basis van slecht gedefinieerde begrippen.

11. Zolang de overheid nog een zogenaamd "minderhedenbeleid" voert, is er van daadwerkelijke integratie geen sprake.

12. Wezenlijk voor een goed promotietraject is een voortdurende discussie tussen promotor en promovendus over de inhoud en richting van het onderzoek, op basis van wederzijds respect.

13. Daar wetenschappelijk onderzoek grotendeels gedragen wordt door promovendi, dienen hun professionele vaardigheden juist in de werkomgeving door iedereen te worden gerespecteerd. Bij de selectie van promovendi dient er daarom op gelet te worden of zij in staat zijn dit respect af te dwingen.

14. In de wetenschap dient men vooroordelen nooit voor oordelen te laten doorgaan.

15. Bij het schrijven van een proefschrift dient de uitspraak van Goethe "als je het leven al te ernstig neemt, wat is er dan nog aan?" ter harte te worden genomen.

16. Het feit dat sommige mensen slechts met geopend venster kunnen genieten van de "muziek" in hun auto, wijst op een onbewust beveiligingsmechanisme tegen overmatige geluidsdruk.