Priorities in energy conservation: a study on the interactive effects of energy conservation measures

Willeboer, W.

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PRIORITIES IN ENERGY CONSERVATION

A study on the interactive effects of energy conservation measures

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE TECHNISCHE WETENSCHAPPEN AAN DE TECHNISCHE HOGESCHOOL EINDHOVEN, OP GEZAG VAN DE RECTOR MAGNIFICUS, PROF. DR. F. N. HOOG, VOOR EEN COMMISSIE AANGEWZEZEN DOOR HET COLLEGE VAN DEKANEN IN HET OPENBAAR TE VERDEDIGEN OP DINSDAG 24 SEPTEMBER 1985 TE 16.00 UUR

DOOR

WILLEM WILLEBOER
geboren te Serooskerke (W)
Dit proefschrift is goedgekeurd door de promotoren:

Prof. ir. J. Claus en Prof. drs. C. van der Enden
PREFACE

On the subject of energy use and energy conservation, many investigations have been made and a lot has been published: sometimes in a more general sense, but very often on specific aspects or certain technologies. This thesis focusses on management decisions concerning energy conservation in existing industrial production systems. It is not limited to certain industrial sectors or certain processes but it is aimed at a general application.

Partly based on the results of a case-study in industry, a fundamental treatise is given on the interactions between different energy conservation measures in one system. The analysis of the consequences of these interactions leads to a practical, general procedure for determining priorities for conservation measures and making decisions in conservation projects.

This thesis could be accomplished thanks to the stimulating co-operation of several people at the Eindhoven University of Technology and in industry:
- At the factory of Océ Van der Grinten b.v. in Venlo we were enabled to perform a case-study in one of the production processes; moreover, Océ gave practical support.
- My colleague Mr. Maarten Splinter initiated the research. With his unflagging energy he kindled me with enthusiasm and was of great help during the whole research.
- Professor J. Claus spent many hours in studying my reports and proposals and discussing them with me. He and professor C. van der Ende have guided me during the completion of this thesis in a very pleasant way.
- In performing the case-study of the paper dryer, the support of Mr. Jan Coumans on the subject of physical transport phenomena was indispensable.
- Mrs. Leonie Van Winkel and Mrs. Stance Van Woensel did the typework spontaneously and with a lot of patience.
- Mr. Piet Doorakkers was responsible for the clear and uniform presentation of the numerous figures.
- Dr. Peter Attwood read the almost complete text and gave many useful suggestions with respect to the use of English.

I express my gratitude to them and to all others who have been helpful to me.

Wim Willeboer
July 1985
OUTLINE

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OUTLINE

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<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>A</td>
<td>area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>a</td>
<td>parameter</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>radiator</td>
<td>kJ.m$^{-2}.s^{-1}$</td>
</tr>
<tr>
<td>BC</td>
<td>burner constant</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>(general) constant factor</td>
<td>-</td>
</tr>
<tr>
<td>c</td>
<td>specific heat</td>
<td>kJ.kg$^{-1}.K^{-1}$</td>
</tr>
<tr>
<td>c&lt;sub&gt;p&lt;/sub&gt;</td>
<td>specific heat at constant pressure</td>
<td>kJ.kg$^{-1}.K^{-1}$</td>
</tr>
<tr>
<td>D</td>
<td>mass diffusion coefficient of water vapour in air</td>
<td>$m^2.s^{-1}$</td>
</tr>
<tr>
<td>DF</td>
<td>(general) driving force</td>
<td>-</td>
</tr>
<tr>
<td>DS</td>
<td>decrease of energy cost savings</td>
<td>$$</td>
</tr>
<tr>
<td>d</td>
<td>parameter of the general energy savings function</td>
<td>kJ</td>
</tr>
<tr>
<td>E</td>
<td>radiation flux</td>
<td>kJ.m$^{-2}.s^{-1}$</td>
</tr>
<tr>
<td>ES</td>
<td>energy savings</td>
<td>kJ</td>
</tr>
<tr>
<td>EU</td>
<td>energy use</td>
<td>$$</td>
</tr>
<tr>
<td>EXP</td>
<td>expenses</td>
<td>$$</td>
</tr>
<tr>
<td>En</td>
<td>energy flow</td>
<td>kJ.s$^{-1}$</td>
</tr>
<tr>
<td>Ex</td>
<td>exergy flow</td>
<td>kJ.s$^{-1}$</td>
</tr>
<tr>
<td>e</td>
<td>parameter of the general energy savings function</td>
<td>-</td>
</tr>
<tr>
<td>er</td>
<td>electrical resistance</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>F</td>
<td>view factor (for radiation calculations)</td>
<td>-</td>
</tr>
<tr>
<td>FC</td>
<td>natural gas consumption</td>
<td>m$^3.s^{-1}$</td>
</tr>
<tr>
<td>f</td>
<td>parameter for the capacity-independent expenses</td>
<td>$$</td>
</tr>
<tr>
<td>fn</td>
<td>general function-sign</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>molar density</td>
<td>kmol.m$^{-3}$</td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof number: $Gr=gr<em>P_{L}^3</em>R_{T_1}/(T_2*V^2)$ (ideal gas)</td>
<td>-</td>
</tr>
<tr>
<td>g</td>
<td>parameter for the capacity-dependent expenses</td>
<td>$$</td>
</tr>
<tr>
<td>gr</td>
<td>acceleration due to gravity</td>
<td>m.s$^{-2}$</td>
</tr>
<tr>
<td>H</td>
<td>incidental radiant flux</td>
<td>kJ.m$^{-2}.s^{-1}$</td>
</tr>
<tr>
<td>h</td>
<td>enthalpy</td>
<td>kJ.kg$^{-1}$</td>
</tr>
<tr>
<td>I</td>
<td>investments</td>
<td>$$</td>
</tr>
<tr>
<td>i</td>
<td>electric current</td>
<td>A</td>
</tr>
<tr>
<td>K</td>
<td>heat transmission coefficient</td>
<td>kJ.m$^{-2}.s^{-1}.K^{-1}$</td>
</tr>
<tr>
<td>k</td>
<td>mass transfer coefficient</td>
<td>m.s$^{-1}$</td>
</tr>
<tr>
<td>L</td>
<td>length</td>
<td>m</td>
</tr>
<tr>
<td>l</td>
<td>thickness</td>
<td>m</td>
</tr>
<tr>
<td>loss</td>
<td>energy losses</td>
<td>kJ</td>
</tr>
<tr>
<td>M</td>
<td>molecular weight</td>
<td>kg.kmol$^{-1}$</td>
</tr>
</tbody>
</table>
**Greek symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>heat transfer coefficient</td>
<td>kJ.m⁻².s⁻¹.K⁻¹</td>
</tr>
<tr>
<td>$\beta$</td>
<td>scalar coefficient for investments</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>exponent in general energy use function</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>exponent in general energy savings function</td>
<td>-</td>
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</table>

**Greek symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tr>
<td>$\kappa$</td>
<td>mass flow</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>molar flux</td>
<td></td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
<td>$$</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number: $Nu=\alpha^2L/\lambda$</td>
<td>kg.m⁻².s⁻¹</td>
</tr>
<tr>
<td>n</td>
<td>mass flux</td>
<td></td>
</tr>
<tr>
<td>nr</td>
<td>number of additional drying boxes</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number: $Pr=\nu\rho c/\lambda$</td>
<td>$$/kg⁻¹</td>
</tr>
<tr>
<td>$p_{\infty}$</td>
<td>energy price (weighted average present value)</td>
<td>kJ.s⁻¹</td>
</tr>
<tr>
<td>$Q$</td>
<td>heat flow</td>
<td>kJ.m⁻².s⁻¹</td>
</tr>
<tr>
<td>$q$</td>
<td>heat flux</td>
<td>kJ.kmol⁻¹.K⁻¹</td>
</tr>
<tr>
<td>$R$</td>
<td>gas constant ($= 8.3143$)</td>
<td></td>
</tr>
<tr>
<td>RAF</td>
<td>ratio</td>
<td></td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number: $Re=w^2L\rho/\eta$</td>
<td></td>
</tr>
<tr>
<td>$r$</td>
<td>(not indexed): heat of vaporization of water</td>
<td>kJ.kg⁻¹</td>
</tr>
<tr>
<td>$r$</td>
<td>(indexed): resistance (general indication)</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>Sc</td>
<td>Schmidt number: $Sc=w/\nu$</td>
<td></td>
</tr>
<tr>
<td>Sh</td>
<td>Sherwood number: $Sh=\nu^2c/\lambda$</td>
<td></td>
</tr>
<tr>
<td>$s$</td>
<td>(layer-) thickness</td>
<td>m</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>K</td>
</tr>
<tr>
<td>$t$</td>
<td>technology parameter (in Cost-Energy Dynamics)</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$u$</td>
<td>(general) technical variable</td>
<td>$v$</td>
</tr>
<tr>
<td>$V$</td>
<td>voltage</td>
<td>m³.s⁻¹</td>
</tr>
<tr>
<td>$V_{\nu}$</td>
<td>volume flow</td>
<td></td>
</tr>
<tr>
<td>$w$</td>
<td>dimensionless (general) technical variable</td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>rate of evaporation</td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>mass flow of water vapour</td>
<td>kg.s⁻¹</td>
</tr>
<tr>
<td>$W$</td>
<td>velocity</td>
<td>kg.s⁻¹</td>
</tr>
<tr>
<td>$X$</td>
<td>water vapour mole fraction</td>
<td>kJ.mol.kmol⁻¹</td>
</tr>
<tr>
<td>$X$</td>
<td>moisture content</td>
<td>kg.kg⁻¹</td>
</tr>
<tr>
<td>$Y$</td>
<td>function, indicating equipment dimensions or capacity</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$Z$</td>
<td>coordinate normal to interface</td>
<td>m</td>
</tr>
<tr>
<td>$z$</td>
<td>height</td>
<td>m</td>
</tr>
</tbody>
</table>
\( \Delta \) difference
\( \delta \) Kronecker delta (\( \pm 0 \) or \( 1 \))
\( s \) emission coefficient
\( \eta \) dynamic viscosity
\( \theta \) temperature
\( \Lambda \) complex factor in radiation calculations
\( \lambda \) thermal conductivity
\( \mu \) exponent of the conservation-investments function
\( \nu \) kinematic viscosity
\( \xi \) exponent in burner aeration correlation
\( \rho \) density
\( \sigma \) Stephan-Boltzmann constant (\( -5.77 \times 10^{-11} \))
\( \tau \) dimensionless temperature
\( \phi \) net radiant flux
\( \chi \) complex factor in radiation calculations
\( \omega \) rotational speed

difference

Subscripts

A concerning conservation measure A
a air
app approximate
av average
B concerning conservation measure B
b concerning burners
C concerning conservation measure C
c convective
D concerning conservation measure D
d conductive
dep dependent
e concerning energy
F concerning natural gas consumption
f resulting from mass flow
g concerning flue gas in burners
he concerning heat exchanger
at interface (between paper and surrounding gas)
l at surface i (in radiation calculations)
ic concerning interchangeable measures
in incoming
indep independent
Concerning insulation concerns radiation calculation at surface. Intermediate layer concerns flue gas mixture in drying box. Transient phenomenon concerns with energy losses. Concerning flue gas mixture in drying box concerns with energy losses.

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CHAPTER 1

INTRODUCTION

Since the Second World War, energy has been considered as a cheap and abundantly available factor in industrial production and private use. Under those conditions, "growth" was one of the key-words. A good ten years ago this image was changed drastically by the first so-called "energy crisis". From that moment on, it has become evident that we do not deal with an "energy problem" in the sense of a problem that can be solved [1.1, 1.2]. The energy crisis is a structural phenomenon, which we have to reckon with in the near and far future. It manifests itself in -at least- three main aspects:

1. Fuel price rises
2. Decreasing availability and reserves of fossil energy resources (especially of "clean" fuels). Closely related to this point is the political vulnerability of fuel exporting and fuel importing countries: fuel reserves have become a powerful political weapon.
3. Increasing environmental pollution, which implies a growing danger for the well-being of present and future generations.

The consequences of these facts, with respect to national and international politics, are:

1. Primary energy use has to be reduced, because present resources will run out more quickly than new resources can be found or new technologies introduced. Scorer [1.3] said it this way: "What we need, in simple terms, is the voice of posterity more fiercely represented in the marketplace".
2. National economies have to be made less vulnerable with respect to external fuel supplies, by diversification, improved flexibility of the various fuel consumer sectors and exploitation of renewable energy resources.
3. Attention has to be paid to the protection of people and animals, also, of the air, the water and the soil. Recent developments justify the expectation that, soon in the near future, environmental aspects will become the most important issue and, thus, the most important reason for reducing the overall energy use.

With respect to industrial -and other- enterprises, the consequence of the above view of the energy situation is that they will have to adapt themselves to the changed conditions and, what is more, that they have to be able to anticipate to possible future changes. This point can only be satisfied if there is know-how concerning the following questions:

1. How can the energy use of a production system be changed (be reduced)? This point requires an insight into the physical behaviour of the system.
2. What are the financial consequences (the expenses) of such changes (that are, in fact, energy conservation measures)? In more general
With respect to the first question, it can be seen in practice that in certain - mostly energy intensive - industrial sectors (e.g. electricity generation, chemical industries) there is a lot of know-how about the physical behaviour of the production processes. On the other hand, there are large groups of industrial production processes and systems for which there is hardly any insight into the question of how the physical process could be changed in order to reduce the energy used. Often, this concerns more or less traditional, less energy intensive production processes. In several cases in industry, it was found that, in the past, the energy used had hardly been significant; therefore, process research had been limited to the aspects of production rate and product quality. For the Danish situation, Togeby c.s. [1.4] remarked: "Most of the energy consumption in the Danish industry is still associated with capital installed in a period when the relative price of energy was 1/5 of its present value". Of course, this applies to other countries too. For the Dutch situation, Over [1.5] noticed that, in industry, there is still a great difference between the potential savings and the savings that have been realised. There are, of course, various barriers that impede energy conservation. But, especially in the last-mentioned group of industries, the lack of know-how of the physical aspects (and the related fear-for-the-unknown) is an important reason.

In recent years, many handbooks and papers on energy auditing, energy conservation and energy management have been published: e.g. [1.6]. In those publications, most attention was paid to the well-known solutions for energy conservation, like insulation, heat recovery, etc. Far less attention was paid to the fundamental measures for process improvement, for which a better understanding of the physical aspects of the process itself is required. Most handbooks gave a procedure for such analyses in general terms, but they hardly went into detail; nor did they give practical applications or real case studies which could show the real efforts and problems involved in such analyses. Taking this into account, we decided to make a detailed case study of a real production process, in order to analyse the potential energy conservation opportunities. A process was chosen from the more traditional production processes, so that the approach used in the case study could serve as an example for a larger group of industries and processes, for which there is little know-how of the physical behaviour of the processes. Moreover, this case study provides a detailed description of the physical behaviour of the process; this description can serve very well as a tool for further investigations.

With respect to the financial consequences of energy conservation measures, it can be seen in practice that economic criteria are simply applied to individual measures. However, it became evident from several cases in industry that, in general, there are interactions between different measures, which may affect the decisions to be made. This aspect is ignored completely in all handbooks and in almost all literature on the subject of energy conservation. No satisfactory analysis of the consequences of such interactions can be found in literature. Since the insight into these interactions and their effects was expected to provide an important contribution to the economic optimisation of energy conservation projects, it was decided to investigate these aspects in general terms, so that the results could be used in arbitrary energy conservation projects.

The scope of this thesis is indicated by the following points:

- The considerations are based upon the viewpoint of industrial enterprises and focussed on energy conservation in existing production processes and systems.
- Considerations of energy conservation opportunities are limited to changes (improvements) based upon the present technologies, in
principle. This point applies to the part concerning the physical analysis, especially.

- In the considerations concerning decision-making, only the financial reasons for energy conservation were taken into account. This means that other possible arguments (for instance, strategic reasons, reasons of goodwill, publicity) were left out of consideration.
- Most attention was paid to energy conservation in existing production processes and systems.

After this introduction, Chapter 2 gives a general view of recent developments and the state of the art of industrial energy conservation. A discussion on some methods of analysis gives an insight into the tools presently available for investigations in the field of industrial energy use. These methods are evaluated in the light of the considered field of interest: energy conservation in existing systems.

A case study of an energy conservation project is described in Chapter 3. It concerns a paper drying process for an existing coating machine. A physical analysis was made, resulting in an inventory of alternative opportunities for energy conservation. It was decided to investigate one case thoroughly, rather than considering a number of cases superficially, because a profound and fundamental basis was required in order to study the influence of physical aspects upon the economics of energy conservation projects.

A simulation model of the process was developed for analysing the static physical behaviour in order to derive possible ways for reducing the energy used. Attention was paid to the practical aspects of analysing an existing industrial process and developing a simulation model. It is noticed for decision-making in practice that an analysis of only one process in the complete production system provides insufficient information. In principle, the complete system should be considered, because a change in one process might cause changes in other parts of the system; these changes could affect the decisions, of course. However, as the investigations in this thesis were aimed at studying the effects and backgrounds of interactions of measures rather than obtaining actual results for this case, the approach chosen here, in which only a part of the complete production system was considered, is satisfactory for this purpose.

After treating the physical aspects of energy conservation in the case study, the relationship with the economic aspects comes into the picture. Chapter 4 gives a view and brief discussion of some methods and approaches found in literature, aimed at treating energy conservation options in economic calculations and decision-making. Special attention is paid to the way in which the physical aspects are taken into account in these methods. Although the interest of this thesis is on the micro economic level (the company), methods developed for macro economic analyses were considered too, in order to see if their principles could be applied to the micro level. From an evaluation of the various methods, it became clear what aspects needed further investigation; these aspects provide the starting point for Chapter 5.

In Chapter 5, the interactive effects of energy conservation measures are analysed in general terms, with respect to both their physical and economic aspects. In order to provide a general application for the results, the analysis was based upon general equations that describe the relevant effects of various conservation measures. The physical backgrounds of the interactions between conservation measures were studied, together with the related consequences for the financial benefits. The results of this study were evaluated with respect to their effects on decision-making in energy conservation projects.

Finally, Chapter 6 summarizes the conclusions that can be drawn from the research. More specifically, an evaluation is given of the contribution of this thesis to energy conservation theory.
CHAPTER 2

INDUSTRIAL ENERGY CONSERVATION - STATE OF THE ART.

2.1 INTRODUCTION

Today, energy is a subject that receives more or less special attention in almost every industrial enterprise. However, until the oil crisis of 1973, for most industries energy was just a cheap and abundantly available production factor, that nobody specially cared for. Due to the rapid price changes (price rises up to 300%) and the reduced availability of energy during the past ten years, many techniques and methods for managing energy use and utilizing it better had to be developed and introduced. Moreover, alternative energy sources and new applications of the existing sources became feasible and were exploited.

In order to gain an insight into what methods are presently available for investigating the physical opportunities of reducing the energy use (the question mentioned first in chapter 1), the literature in this field was studied. This chapter gives a view of the recent developments and the state of the art.

With respect to energy conservation, developments have been different in different sectors of the society; also, different industrial sectors reacted differently to the changed circumstances in the energy field. In sub-section 2.2, these differences will be considered in more detail. There have been developments in methods of analysis etc. that are of a general nature, such as energy analysis, energy analysis, energy accounting and energy management. These items will be discussed in section 2.3.

It is evident that, apart from the developments in the management aspects of the energy field, much research and development has been devoted to the technical aspects of equipment, processes, etc. Some of these developments, relevant to the present research, will be discussed in section 2.4.

Section 2.5 summarizes the conclusions with regard to the present research. Specific developments in the field of the economics of energy are not considered in this chapter; they will be discussed in Chapter 4.

2.2 INDUSTRIAL ENERGY CONSERVATION DURING THE PAST TEN YEARS

With respect to the developments in the industrial sector regarding changes in the energy situation during the past ten years, it is evident that this sector cannot be considered simply as one uniform group of fuel and electricity consumers. As an illustration, table 2.1 shows a breakdown of
the total Dutch energy use, with an indication of the energy used by various industrial sectors. There is a great difference between the energy-intensive industries (refineries, chemical industries, steel, paper) and the remaining industries which are in fact a very large group of industries of very divergent natures.

Table 2.1 Total Dutch energy use broken down for different sectors (situation 1980), according to [2.4].

<table>
<thead>
<tr>
<th>sector</th>
<th>energy use [PJ/a]</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>households</td>
<td>620</td>
<td>23</td>
</tr>
<tr>
<td>services</td>
<td>430</td>
<td>16</td>
</tr>
<tr>
<td>industries</td>
<td>1160</td>
<td>43</td>
</tr>
<tr>
<td>of which:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- foods and allied products</td>
<td>95</td>
<td>3.5</td>
</tr>
<tr>
<td>- textile</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>- paper</td>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>- chemicals</td>
<td>700</td>
<td>26.0</td>
</tr>
<tr>
<td>- building materials</td>
<td>55</td>
<td>2.0</td>
</tr>
<tr>
<td>- metals</td>
<td>215</td>
<td>8.0</td>
</tr>
<tr>
<td>- remaining industries</td>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>agriculture</td>
<td>140</td>
<td>5</td>
</tr>
<tr>
<td>transport</td>
<td>350</td>
<td>13</td>
</tr>
<tr>
<td>total</td>
<td>2700</td>
<td>100.0</td>
</tr>
</tbody>
</table>

The energy intensive industries

In the energy intensive industries, attention has always been paid to the energy use and the energy efficiency of production processes, because energy costs have always been an important part of the total production costs in those industries. In fact, the same applies to the electricity utilities. In general, the processes in these industries are known and understood fairly well with respect to their energy usage, due to the research work that has been done through the years.

Due to this, the reactions of these industries to changes in the energy situation during the past ten years were not limited to better housekeeping, economical behaviour, building insulation, heat recovery, etc. but also the production processes themselves have been improved and new processes developed and introduced.

Of course, the current research has been extended and intensified more directly for energy conservation. An example of a new approach that was developed in recent years is the method of efficient process integration of Linhoff c.s. [2.5] and Umeda c.s. [2.6]. This method is a powerful tool for optimizing all kinds of heat exchanger networks.

In the management field, methods like energy accounting and energy management (see subsection 2.3.1) have been applied more and more in all kinds of industries but, first of all, in the energy intensive ones.

The not-energy-intensive industries

If we consider the industries that are less energy intensive, we see a quite
different situation. Here, until 1973, hardly any attention was paid to the energy use: energy was just a cheap and abundantly available production factor. Other aspects like product quality and production rate were of more importance with respect to their contribution to the total production costs. In many of these industries a substantial part of their - limited - energy use is for lighting and space heating; however, the energy used in processes is still of the same importance.

As energy had been an unimportant production factor for a very long time, process research had never been focussed on energy efficiency as such. Management teams of many companies did not even have any idea of the energy used.

In these industries, the reaction to changes in the energy situation after 1973 consisted of the well-known solutions like insulation, good housekeeping, heat recovery and sometimes co-generation of power and heat. Changing the processes themselves was not so easy, because of the lack of know-how about the energy behaviour of the processes. Moreover, because of this lack of know-how, people often showed a certain resistance to the change of production systems, for product quality or safe and reliable process operation could possibly be affected unfavourably.

It is true that the industries that are less energy intensive have done quite a lot to reduce their energy use, but, due to the points mentioned above, the most fundamental part, the process itself, has received little attention in most cases.

Conclusions

In the foregoing, the energy intensive industries and the remaining industries are represented somewhat extremely, as two groups that are completely different, and consequently very easy to distinguish. However, in practice, there are many industries which are somewhere between these two extreme situations. Each industry has to do with very common forms of energy use: for lighting and heating of buildings, for cars, boilers, steam systems, etc. For these aspects, the chances of saving energy have been studied extensively and technical solutions are available.

However, apart from these aspects, industries have their own special and sometimes unique production processes and systems. In most cases (putting aside the energy intensive industries), there is insufficient know-how of the processes and of possible conservation options. Standardised technical conservation measures are not available. The only way of enlarging the insight into the process is making a detailed physical analysis. By means of that, the "fear for the unknown" can be overcome and conservation options can be derived. The state of the art of such process analysis methods will be discussed in section 2.4.

2.3 METHODS OF A GENERAL NATURE

In the field of (industrial) energy conservation, there are some - more or less recent - developments in methods that are of a general nature. They are discussed in this section: firstly, energy accounting and energy management, which are management tools (sub-section 2.3.1); after that, energy analysis, which highlights energy use and energy conservation in a wider context (sub-section 2.3.2) and finally, second law analysis, which is a method for physical analysis (sub-section 2.3.3).
2.3.1 Energy accounting and energy management

Energy accounting is an accounting system (in units of energy: kWh) for industrial plants etc. It involves collecting all kinds of data about total and specific energy use and the related costs incurred by different parts of the plant, see [2.1]. This data is collected and processed weekly or monthly. The breakdown highlights specific areas of the plant where responsibility can be clearly defined. Thus, the energy accounting system can be used for energy management in the plant. For instance, budgetary control of energy use can be introduced, with targets etc. Recent developments in the field of energy accounting and management can provide faster, cheaper and more detailed measurement data with the aid of microelectronics and sophisticated sensors. Such systematic and continuous control of the energy use is just one form of activity that is covered by the term "energy management". An other important form of energy management concerns the energy management programs which are executed more incidentally. In general, energy management programs consist of three phases: initiation, audit and analysis, and implementation [2.2], [2.3]:

- The initiation phase includes the organizational preparation of the program: assignment of an energy management coordinator, creation of an energy management committee, etc.

- The second phase of the program is auditing and analysing the energy used in a plant. It can start with a review of historical data and patterns of energy use. Preliminary analyses can be made on the basis of equipment specifications, drawings, data sheets and a rough survey of the plant. Then, a detailed energy audit of the different processes and plant equipment has to be performed. Based upon that, the analysis and simulation step is made to find and evaluate energy management opportunities. After that, the economic aspects of the selected options have to be analysed [2.2].

- The third phase in energy management programs is implementation. Selected measures are introduced and measurement and reporting procedures are established. Results have to be published in order to stimulate the awareness and involvement of personnel, etc.

It is obvious that our field of interest is especially in the second phase: finding - and evaluating - energy conservation opportunities. In this phase, process analysis is the most important issue (section 2.4).

2.3.2 Energy analysis

Historical background

When considering energy requirements for making a certain product, until about 1970, it was very unusual to include the related energy used outside the factory itself. The inputs of raw materials etc. to the processes were thought of only in terms of tons and money. However, due to the sudden rise of the price of oil in 1973, several people started to look at the total amount of energy utilised in making goods and services, taking into account the processes all the way from ores in the ground to the finished product. This led to the idea that energy is embodied in goods or services, so that one can talk about the energy requirement of products in terms of MJ per kg. [2.8], [2.9], [2.10] and [2.11].
Definitions and aims

The method of analysis meant here was baptised "Energy Analysis" (in 1974; [2.7]). 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". The purpose of energy analysis is to describe present industrial energy use. Such descriptions provide information needed to compare different practices and examine new designs.

An essential point in energy analysis is the distinction between direct and indirect energy use of production.

The direct energy use of a production system is the energy that enters the system as fuel, electricity, etc.

The indirect energy use is the energy that is embodied in the raw materials, semi-fabricated articles, production installations, etc.

Another important concept is gross energy requirement (GER) which is defined as the amount of energy source which is sequestered by the process of making a good or service. So it is evident that GER comprises both the direct and the indirect energy use. An analysis of the gross energy requirement of a certain product shows directly that the maximum theoretical energy efficiency of the production system is lower than the maximum thermodynamic efficiency which ignores the indirect energy use. Unlike the thermodynamic optimum, the maximum energy efficiency point considering gross energy requirement appears at finite values of the process parameters.

This is illustrated in fig. 2.1.

![Diagram showing energy use per unit of product vs. process variable](image)

**Fig.2.1** Derivation of the minimum gross energy requirements.

Applications

An energy analysis can be made for a complete industrial sector, a certain factory, one process, or a certain product.

Applications are found for each of these subjects ([2.8] to [2.22]).

Generally speaking, the advantages of energy analysis over conventional energy studies (which do not include indirect energy use) were limited as far as it concerned company level. However, at more aggregated levels like industrial sectors, national and international politics, interesting facts and trends were discovered which could be of great importance for medium and long term planning and decisions.
Discussion

The following conclusions can be drawn with respect to the relevance of energy analysis in the sense of the definition of IFTAS (2.7):

- Energy analysis provides an insight into the total energy required (Gross Energy Requirements) for producing goods or services. Therefore, in fact, it is the only basis for determining the real energy savings when changing the production system.

- For single processes or complete production systems, certain physical limits or boundary conditions can be determined like, for instance, maximum (theoretical) energy efficiency, minimum ore grade of uranium or minimum oil content in tar sands that yields a positive net fuel production, etc.

- However, in many cases the insight into these limits does not affect the decisions concerning possible changes to the existing situation, because in general these limits are far beyond present conditions or they are beyond the control of the decision-makers. The insight into physically determined limits and boundaries is important, especially, in technology assessment studies and long term forecasting and planning. In such cases, the physical limits provide a more reliable basis than economic data. In this sense, energy analysis is important for developing strategies at the level of national and international politics.

- The questions on energy conservation in companies are related to the direct energy use by production processes most of the time, especially, when just a part of the total production system is under the control of the company concerned. Process analysis is the most convenient method, then: it shows which parts of the production system are most important with regard to their energy use and what the efficiencies etc. are. In searching for possible energy conservation measures, these parts should get most attention. Starting from such an analysis, thorough investigations can be made afterwards in order to understand the behaviour of the process. Subsequently, the effects of conservation measures can be determined and evaluated.

2.3.3 SECOND LAW ANALYSIS

Background

The second law of thermodynamics implies that all real processes are irreversible; reversible processes are idealised boundary cases of real processes. The degree to which a certain energy conversion process is reversible is expressed in the quantity of exergy: the concept of availability or potential to do work.* Although this concept has been applied for at least a century [2.24], it is only in recent decades that it has received the real attention of scientists and engineers. Analytical techniques and methods were developed in order to facilitate the application of the principles of the second law, and to express the efficiency of energy conversion processes, not only in terms of quantity, but also in terms of quality. This field is called "second law analysis" or "exergy analysis".

*) In German literature: "Technische Arbeitsfähigkeit" [2.24]
The exergy concept

In the conventional thermodynamic analysis of processes, energy flows and energy conversion efficiencies, etc, are expressed only in terms of energy or enthalpy; in fact they are quantitative measures. No distinction is made between different kinds of energy flows. The exergy concept [2.23] was introduced in order to account with this distinction: exergy is a measure that takes into account the quantity as well as the quality of energy flows or systems. Exergy is the maximum useful work that can be extracted from a system in any process that brings it into equilibrium with its environment. For different forms of energy, the exergy can be determined as follows:

- Mechanical or electrical exergy is equal to the mechanical or electrical energy of the system

- Heat exergy must be expressed as a function of the environment temperature \( T_e \), by means of the Carnot-efficiency:

\[
Ex = Q \cdot \left( 1 - \frac{T_e}{T} \right)
\]

where: the amount of heat \( Q \) is transferred at temperature \( T \).

- The exergy of a fuel is mostly assumed to be equal to the heating value of the fuel. In fact, it may differ depending on the state of the environment [2.33]

with the help of the exergy concept, a measure of performance for a system is defined as the ratio of the exergy gained to the exergy expended by the system [2.25]. This ratio is denoted as effectiveness [2.34], exergetic efficiency [2.32,2.30], or second law efficiency [2.33].

Applications

Recently, quite a lot of papers appeared on the application of the exergy concept, in divergent industries and processes. Most of the applications concerned only the physical aspects, [2.26] to [2.32], [2.35], [2.36], [2.40] to [2.43], but some of them dealt with the relationship between exergy and economic analysis too, [2.37] to [2.38].

The applications show that exergy analysis gives a very clear picture of the performance of each section of the plant or the process, and that irreversibilities are allocated. Exergy can be interpreted as the value of energy, for instance, for making energy cost distributions in an integrated plant.

Discussion

The exergy concept is not very well known, not even in the engineer's world. In fact, what is meant by the word "energy" in common parlance corresponds very often with the exergy concept: frequently one speaks of energy only if it can be applied usefully.

The significance of second law analysis and the exergy concept in energy engineering is discussed now in four areas:

- exergy and irreversibility
- exergy and the potential for improvement
- exergy and the evaluation of processes and process improvements
- exergy and economic analysis
Exergy and irreversibility

The exergy concept is an excellent tool for identifying the location and the magnitude of irreversibilities in a process. These insights are not suitable for practical engineering, but they are of great importance for fundamental process research. Second law analysis applied to the existing processes can reveal the places where irreversibilities occur. The "built-in" irreversibilities can be identified, which is very helpful in research aimed at more efficient production technologies. Moreover, exergy and the way it affects irreversibilities is of great didactic value.

Exergy and the potential for improvement

Several authors (e.g. Moran [2.33], Steeman [2.43]) argued that the gap between the level of fuel consumption with current practices and the minimum theoretical requirement determined by second law analysis, is a measure of the potential improvement. This is true, but it must be remembered that this is only a theoretical measure. It is evident that exergetic efficiency provides an indication of the potential for improvement that is more fundamental than that shown by energetic efficiency. But an exergetic efficiency of 100% is an impossible goal, and second law analysis does not provide information on what can be achievable in a certain production method due to technical boundary conditions. Thus, the information obtained by second law analysis on the potential improvement is of limited importance still.

Exergy and the evaluation of processes and process improvements

As Baehr [2.23] stated, one of the advantages of the exergy concept is that, in order to evaluate a process with respect to the way energy is utilised, it is no longer necessary -like before- to design a comparable process that is completely reversible. An exergy analysis of the process under consideration yields the same information. However, this concerns a general and more theoretical evaluation of the process. In practice, the evaluation of processes and process improvement is aimed at showing the differences in fuel consumption for different alternatives. Efficiency numbers, as such, are less important then. In determining and comparing the fuel consumption of alternative processes, exergy analysis and conventional process analysis are equivalent. So, in studying and evaluating practical alternatives for energy conservation, second law analysis is no better than conventional process analysis.

Exergy and economic analysis

One of the definitions of "exergy" is: the "potential to do work". Therefore, exergy could be interpreted as the "value of energy". With this, only a very small step is needed to determine the economic value of energy flows on an exergy basis. This can be applied for internal accounting of energy flows easily, in chemical plants etc., e.g., with energy cascading [2.43], and in plants for co-generation of power and heat.

For the economic evaluation of processes, for instance in conservation projects, the exergy concept has little value. In such studies, it is only the fuel consumption that counts. In the foregoing, it has been explained that, for determining fuel consumption, second law analysis has no specific advantages.
From the discussion of these four points, it is clear that the benefits of the exergy concept and the advantages of second law analysis over conventional (first law) process analysis are found especially in the fields of theoretical considerations, process research and engineering education. In practical studies of process changes, conservation projects, comparisons between different alternatives, etc. the exergy concept has few specific advantages.

2.4 PROCESS ANALYSIS

Survey of practical methods

In the two preceding sections, two analysis methods in the energy field were discussed: energy analysis as an approach to determine and compare energy use in producing goods and services, and second law analysis as a method to take into account the quality of energy in thermodynamic calculations. However, both methods are of a very general nature and they cannot answer the question how to reduce the energy used by a certain process. Therefore, the process itself must be analysed. A process analysis with this objective must not only give qualitative, but also quantitative, answers to the question how the energy use can be changed.

In energy conservation projects, process analysis must highlight the technical possibilities of reducing the energy used and the amount of energy that is saved that way. So, in fact, process analysis is the most fundamental phase in energy conservation projects. However, in most energy management handbooks [2.3, 2.46, 2.47] and in most case studies on energy conservation in industry, little attention was paid to the process analysis phase. Smith [2.3] mentioned the importance of process analysis ("The process itself must be understood,..."), but he did not go into it any further.

On the other hand there are of course authors who discussed process analysis in more detail. For instance, Turner [2.48] listed a number of analytical techniques:
- mass and energy balancing
- inventory of energy inputs and rejections
- heat transfer calculations
- evaluations of electric load characteristics
- process and energy system modelling and simulation

It is evident that each of these techniques can lead to a different kind of result, each with its own specific limitations. Mass and energy balances are useful tools for analysing existing situations, as well as possible new ones, because they provide boundary conditions for the complete system and for all its sub-systems. An inventory of the energy inputs and losses will give an insight in the opportunities for heat recovery in the system. However, just like the balances mentioned above, it will provide no information on how to change the process itself in order to reduce the energy used.

Heat transfer calculations and evaluations of electric load characteristics (and calculations of other physical phenomena) can be used for investigating the possibility of reducing the energy used by changing certain process variables (and thus changing the process). However, as long as such calculations are limited to one phenomenon or one process part, the results give no more than an indication of the overall-effects, because the impact on other process parts is left out of consideration. Far more reliable results are obtained, when calculations of all process parts and phenomena are brought together in a simulation model of the complete process or
system. Then, by changing all relevant process variables systematically, the behaviour of the process or system under all possible conditions can be simulated. From these simulation results, energy conservation options and their effects can be derived easily.

Based upon the techniques mentioned above, their applications, and other approaches presented in literature, five different levels of process analysis for energy conservation in industry can be distinguished:

a. site (or plant) survey: energy input and output of the site are measured and checked by means of the site energy balance.

b. mass and energy balancing of the energy systems (steam, hot-water, compressed air) and of the production processes. One of the things that results from these balances, is an inventory of energy inputs and losses, for studying possible heat recovery options.

c. calculating the physical phenomena that determine important parts of the system, like heat and mass transfer, fluid flows and pressure losses. These results are used to analyze and to judge important process parts and to find conservation options.

d. modelling and simulating the process parts

e. modelling and simulating the complete production system

In practice it is seen that energy conservation measures are developed and evaluated at each of these levels. However, it will be clear that the quality and the reliability of the information obtained at these different levels, with respect to the effect of conservation measures, will be quite different. In fact, levels a and b only describe the existing situation. Conservation measures that are taken on the basis of the information obtained at these levels are mostly of a well-known (standard) type, like heat recovery, insulation, or co-generation of heat and power. The estimation of savings to be realised are often based on indications from handbooks etc. This is very rough, of course. A more principle disadvantage of conservation studies at these levels is the fact that the possibilities of fundamental process improvements are left out of consideration.

However, in many cases the information from levels a and b can be used for making calculations at level c. These calculations offer more accurate and better situation-related results than the above-mentioned estimates; however, since the different process parts and phenomena are considered independently, it will be clear that possible effects of the relationships among different process parts are neglected. Most of these disadvantages disappear if the process is simulated with a complete model of the process (level d), or even of the whole production system (level e). Moving from level a to level e, the system under consideration gets more complicated although less restricted with respect to its boundary conditions.

When evaluations are performed at level a or b, they usually start from well-known energy conservation options. Of course, at levels c, d and e, such starting points can also be used, but in principle a more systematic approach is possible then, especially at levels d and e. By simulation, all possible process changes can be studied, so that an insight is gained into all fundamental possibilities of energy use reduction.

In the next part, the state of the art of process analysis by means of simulation is treated.

Process simulation

Although chemical and physical processes have been simulated for many years, the term "simulation" has been used generally only when computers are involved and when it concerns a process or a system which includes a number of interrelated phenomena. Computer simulation gives the engineer the ability to evaluate more alternatives and in more detail than was possible with manual methods. Bobillié et al. [2.49] defined "simulation" as: "the technique of constructing and running a model of a real system in order to
study the behaviour of that system, without disrupting the environment of the real system. It is essential that the environment of the system under consideration is not disrupted; in fact, it means that simulation is the opposite to research by means of experiments in the real system itself. So, it is evident that simulation is applied in cases in which investigations cannot be performed by trial and error or by systematic experiments in the system itself. The reasons for that may be:

- the real system does not (yet) exist: then, simulation is used for designing and evaluating different alternatives, etc.
- if the real system is available:
  - experiments are simply not possible: for instance, for models of national economies, world models, etc.
  - experiments by trial and error are too risky, too costly, or would take too much time, for instance:
    * if certain process changes might cause unsafe conditions
    * if production must proceed anyway
    * if the number of available measuring instruments is far too few
    * if process changes might cause loss of production or poor quality products
    * if the system to be studied is very extensive with a large number of variables.

These general arguments can be recognized if we consider current applications of simulation models for investigating the behaviour of systems, which are found especially in the following fields:

- macro-economic studies at national or international levels, aimed at long term forecasting
- national utility systems, for instance, electricity or gas supplies
- studies in the field of operations research into divergent kinds of systems
- large process networks of chemical plants etc.
- special industrial processes or installations
- large power plants
- heating and ventilation systems of buildings and houses

Here, further considerations will be limited to industrial systems. Apart from the above-mentioned general arguments for applying simulation models, there are some more specific points by which the application is determined: what costs (and other factors) are involved in developing the model?; to what extent is there knowledge of the physical and chemical phenomena of concern?; how many potential applications of the model will there be? In fact each of these points can be brought back to economic criteria.

In section 2.2 it has become clear that a distinction can be made between two main groups of industrial processes:

- processes that have been designed by physicists, chemists, engineers etc., on a scientific basis
- processes that have evolved through the years starting from traditional forms that were once performed on a small scale

For the first mentioned group, in fact, simulation is the logical next step after former calculations (by hand or by machine) of the separate process parts or the underlying phenomena [2.50]. A certain knowledge and understanding of these separate phenomena is already available which is why most applications of simulation models in industry are found in this group: unit processes [2.51] or complete chemical plants (flowsheet simulation) [2.52], heat exchangers [2.53] and heat exchanger networks [2.54], electric
power plants [2.55], boilers, furnaces, etc. [2.56]. For many of these applications standard computer programs and program systems are available, e.g. [2.54].

Very few examples are available of simulation models for industrial processes in the second group mentioned above [2.57]. For simulation models of processes and process systems, an important general distinction is that between steady state and dynamic models [2.58].

A steady state model describes the process behaviour under the condition that the process has settled into a state of equilibrium. Dynamic models aim at investigating dynamic process behaviour in addition to the steady state, in order to design control diagrams and concepts. In most energy conservation studies the steady state behaviour is most important because the energy used by a process is almost completely determined by the static conditions. The dynamic behaviour is important for design and control.

Considering recent literature, it can be concluded that quite a few simulation models have been designed and used for energy conservation studies although, in general, most models could be used for investigating the energy aspects. In fact, simulation is an excellent tool for comparing and evaluating different alternatives (for energy conservation) in a given situation, with respect to both the technical and economic aspects. The effects of proposed or theoretical changes and designs of the system can be computed and, based upon these results, decisions can be made. However, only a few applications of simulation for project evaluation are found in literature [2.59]. Very often, simulation is applied only for the design and technical aspects and economic evaluation is performed afterwards, as a separate step.

2.5 CONCLUSIONS

- There is a fundamental difference between the ways in which energy-intensive and not-energy-intensive industries have reacted to the rapid changes of price and availability of energy, during the past ten years. Due to the fact that the energy-intensive industries have always had a certain knowledge of and done research into their production processes, they have been able to change processes and fit them to the new situation. On the contrary, most of the not-energy-intensive industries have always had little idea of how to change their production processes if energy circumstances change. In these industries, reactions to the "energy crisis" have been limited mainly to well-known conservation measures like insulation, heat recovery, etc., while the production processes themselves have been left unchanged in many cases. For such industries, the only way to make more fundamental improvements to their production systems is to perform a detailed physical analysis of the basic production processes.

- The resistance to change, which exists in many industrial companies is often caused by a lack of know-how of the process behaviour; it can only be overcome by a thorough analysis of those processes.

- Two methods of analysis have received great attention of late years: second law analysis and energy analysis. However, for most energy conservation projects in existing systems, these methods appear to be hardly interesting:

  - Second law analysis, which is often proposed as a way of physical analysis that is far better than conventional analysis on the basis of energy, has advantages only in some specific
fields: theoretical considerations, fundamental research, and engineering education. However, in practical studies of process changes, conservation projects, comparisons between different alternatives, etc., the exergy concept has few specific advantages. Therefore, in the physical analysis in this thesis (Chapter 3), no separate exergy analysis is made other than the calculations on the basis of energy.

- Including the indirect energy use which is involved in the production of commodities ("energy analysis"), in fact, is the only way to determine the real energy savings in conservation projects. However, for normal investment decisions at company level, possible changes in indirect energy use have little influence in most cases. Based upon this, it was decided to limit the energy conservation case-study in this thesis (Chapter 3) to a consideration of the direct (process) energy use.

- The present research, which, basically, deals with energy conservation aspects in industry at company level or even at process level, has to focus on process analysis rather than considering statistical or input-output methods, or investigating the field of data acquisition for the energy requirements of materials, commodities, or energy.

- In practice, process analyses for energy conservation projects are performed at quite different levels of complexity. The most reliable results can be obtained from simulation. For calculating energy savings, in general, it is enough to simulate the steady state process behaviour; dynamic modelling is not necessary then. Today, simulation is a fairly common practice in large chemical plants, power plants, etc. However, in a lot of smaller, more traditional and -- often -- less energy intensive production processes, simulation has never been taken into consideration. Developing simulation models for such processes is a special problem, for these processes are often more or less unique, and there is a lack of know-how on the underlying physical or chemical phenomena. Literature on process modelling discusses only the mathematical problems in formulating and programming; it starts from sufficient knowledge of the relevant phenomena in the process.

- Based upon these considerations, it was decided to prepare an energy conservation case study by means of process simulation, for an industrial process belonging to the last-mentioned group of traditional, rather unique production processes, of which the behaviour with respect to process changes had never been investigated. The aim of this case study, apart from the specific results for the process itself, was to formulate and illustrate a way -- a procedure -- for developing a simulation model in such situations, and to get an idea of the problems that might occur when doing so. This case study is described in the next chapter.
CHAPTER 3

CASE STUDY: DERIVING THE POSSIBILITIES OF ENERGY USE REDUCTION IN AN EXISTING DRYING PROCESS BY MEANS OF A SIMULATION MODEL

3.1 INTRODUCTION

The most important issue of this thesis is the influence of the physical aspects of energy conservation projects upon their economic results. It is evident that this research requires a profound and fundamental physical basis.

That is why it was decided to make a thorough physical investigation of one case, rather than considering a number of cases superficially.

The case under consideration concerns the drying section of an existing coating machine for making photocopy paper. An important reason for choosing a drying process was the fact that drying is a unit operation which is very energy intensive, and frequently used in industry. For instance, in the Netherlands 7 percent of the total industrial fuel consumption is for drying [3.1].

During the whole investigation we have considered only the present technology for drying the paper, that is, direct drying in gas-heated drying boxes. Quite different technologies, for instance, indirect steam-heated drying, infrared drying or vacuum drying have not been considered. The reasons for this decision were:

- This case study was intended to learn more about energy conservation projects in existing installations. Introducing another technology involves complete or partial replacement of the installation. In general, such decisions are based upon more factors than just energy utilisation.
- It was not an objective of this research to develop a better and more efficient drying process for the paper coating machine.
- Analysis of the present process can give an insight into essential improvements that are possible and the efficiency increase that can be reached depending on the relevant process variables.

The physical analysis considered here has led to the development of a simulation model of the paper drying process. By means of this model the static behaviour (including the energy use) of the process can be calculated as a function of the process variables and the geometrical data of the installation. In this way all alternatives for energy conservation can be derived systematically.

This chapter handles the physical and technical aspects of the case. Section 3.2 describes the paper coating machine, including the drying
section, and defines the system boundaries of the drying process under consideration. Moreover, it describes the measurements performed. Next, in section 3.3 the steps that have to be taken for developing a simulation model, the problems that can occur, and suchlike, are described. Section 3.4 deals with the complete simulation model starting with a qualitative analysis of the process. Mathematical equations for the different mass- and heat-transfer phenomena are derived and coupled, the flow diagram of the computer program for the model is explained and finally, the test results for the program are presented. Next, section 3.5 presents the simulated results of a systematic study on the influence of each of the process parameters on the energy use in the drying process. Then, based upon these simulated results, possible conservation measures are derived (section 3.6). Also, the possibility of combining different measures is considered. Finally, in section 3.7 some general conclusions are drawn after the development and the operation of the simulation model.

3.2 DESCRIPTION OF THE PAPER COATING PROCESS.

3.2.1 Overall coating process

The case study described in this chapter concerns a process for making photocopy paper. Most of the energy used directly in this process is for drying the paper, that is why the detailed analysis is concentrated on a drying section of the coating machine. The coating process starts with "normal" untreated paper with a basic weight of 0.04 - 0.08 kg/m². The objective of the process with respect to the photosensitive quality of the product is to fix a certain amount of coating material uniformly on one side of the paper sheet with a certain degree of penetration. This is performed by putting a solution of the coating material on one side of the paper sheet (the "front" side) and drying it. Other quality requirements of the final product (which is the photocopy) do provide the need to also coat the back side of the paper sheet with an aqueous solution.

Fig. 3.1 shows a diagram of the paper coating machine under consideration. The process runs as follows: At point A, the untreated paper which comes from a paper plant, is unrolled. By means of several cylinders, the paper sheet is led to point B; there, water is put on the back side of the paper sheet (which is face down) with help of a cylinder that rotates through a bath with water. After that, this water film is spread evenly. Then, between C and D, the paper sheet is dried in six drying boxes. At point E, the front side of the paper sheet (which is then face down) is wetted with the solution of coating material. After evenly spreading this solution, the front side of the paper sheet is dried between F and G in eight drying boxes so that a dry coating of photosensitive material remains. Finally, the paper sheet is cooled by means of cylinders containing cold water, and it is rolled up at point H. The product is then ready for selling or further processing.
Fig. 3.1  Side-view of the coating machine for the production of photocopy paper
3.2.2 Drying section

During the whole coating process, the moisture content of the paper sheet varies as follows: The starting material has a moisture content of about 3 - 5 % (weight basis); after wetting at point B, this increases to 18 - 20 % and, then, is brought down to 6 - 9 % by the first drying section (point D). After point E, the moisture content rises to about 22 %; the paper sheet leaves the second drying section (F - G) with an end-moisture content of 2 - 2.5 % . So, there are two drying processes which are very similar: the only significant difference being the extent to which the paper is dried. Therefore, in order to get a better understanding of these operations, it is sufficient for the present research to take just one of them into consideration.

The first drying section (C - D in fig. 3.1) offers more opportunities for measurements and simple experiments (if necessary) than the second one; therefore, the first drying section, in which the wetted back side of the product is dried, was chosen for this investigation.

From fig. 3.1 it can be seen that the first drying section consists of six drying boxes which are identical. Fig. 3.2 shows a drying box diagrammatically. At both ends of the box (left and right in the drawing), there is a slit opening right across the box. The paper sheet enters and leaves the drying box through the slits. The construction of the box consists of a steel frame and walls of asbestos board. The upper side of the paper is the wetted side. There are three natural gas burners in the box; the length of each burner is almost equal to the width of the drying box. The upper part of the burners comprises a cast iron grate (fig. 3.3) for improving radiation of heat to the paper.

In each box, there are four fans over the paper sheet. Their blades are mounted on a shaft across the box which are driven by an electric motor. The fans improve the convection of heat and the evaporation from the paper sheet; also, they provide gas mixing within the box.

The flue-gas mixture of the six boxes in the drying section under consideration are brought together into one collective flue gas duct. This duct leads to an extractor mounted on the roof of the building which removes the flue gases. There is a flue-gas valve in this collecting duct which can be set by hand, in order to give the operator control of the air used in the drying section. Moreover, the flue-gas duct of each individual drying box, which leads to the collecting duct, is provided with a valve. By means of these valves, the ratio of the air used in the different boxes can be controlled.

The natural gas supply for the whole drying section (six boxes) is centrally controlled by a single gas control valve that is operated continuously and automatically by a controller according to the paper sheet temperature at the end of the drying section. This temperature is measured by a pyrometer at the end of the sixth drying box. In fact, the whole control function is based upon an empirical relationship between the moisture content and the temperature of the paper sheet at that point. So, it is not possible to control each drying box separately; however, small gas valves on each burner can preset the gas supply to the different burners, by hand.

From the description given above it will be clear that this drying process is not very sophisticated. Although much product research has been performed on the photocopy paper, the established process has never been reinvestigated fundamentally resulting in an eventual revision. Furthermore, any change in the process might lead to variations in quality of the final product, which have not been taken into consideration so far. However, this is not exceptional in industry: many industrial processes are still based on experience or tradition. Very often they are quite unique processes, just like the one considered here.
Fig. 3.2 Diagram of a drying box used in the paper coating machine.

Fig. 3.3 Cross-section of a burner
3.2.3 *Measurements in the drying section*

In different stages of the investigations in this drying process measurements were performed in the dryer, in operating condition. The objective of these measurements was different in the different stages:

- Firstly, measurements were performed in order to get an insight in the overall-process and the participating phenomena. Based upon these measurement results a process flow scheme was drafted and an overall mass and energy balance was drawn up.

- In a later stage, when mathematical descriptions of the different process parts had to be made in order to develop a model of the process, measurements were aimed at a detailed analysis of individual parts of the process. These measurement results confirmed the a priori supposed analytical expressions or they were used to determine empirical equations.

- Finally, measurements were performed to test the process model, in various operating conditions.

Measurement results were obtained from two paper dryers with different dimensions and different operating conditions. Most measurements had to be performed in the normal production situation, in order to prevent disturbances and production losses. However, in the final stage special runs were made for testing the model. During these runs several process variables were changed, so that the behaviour of the model could be tested under varying conditions.

Measurements in the different stages mentioned above concerned the following data:

- For the paper sheet:
  - width, velocity and basic weight
  - moisture content before the wetting section and after the last drying box (the moisture content could not be measured between the boxes)
  - temperature before and after each box

- Utilities: natural gas consumption, and water supply to the wetting section

- For each drying box:
  - Geometrical data
  - Inner and outer wall surface temperature of different parts of the box
  - Burner temperature
  - Temperature and dew point of the flue-gas removed from the box
  - Rotational speed of the air fans
  - (natural gas consumption could not be measured for each individual box)

- For the complete drying section:
  - Temperature and dew point of the flue-gases
  - Flue-gas volume flow

Measurements were performed by means of the following instruments:

- Natural gas and water supply were measured by ordinary gas and water meters
- Flue-gas temperatures were measured by thermo-couples
- Flue-gas dew point measurements were performed by means of a suck-off mirror dew point meter
- Surface temperatures of paper sheet and drying boxes were measured by pyrometers.
- The paper sheet moisture content measurements were performed by means of an infrared moisture meter, gauged with help of an off-line microwave moisture content meter.
- Flue-gas flow (in fact: velocity) was measured by an anemometer.

Results of these measurements are presented and used in different parts of this chapter:
- Results of the overall measurements in the first stage were used in the general process analysis (subsection 3.4.1).
- Results of detailed measurements were used to determine empirical expressions for radiative heat transfer (subsection 3.4.4 and appendices III and IV) and for drying box heat losses (subsection 3.4.5).
- Results of the measurements for testing the model are given in subsection 3.4.9.

3.3 DEVELOPING A MODEL FOR PROCESS SIMULATION

3.3.1 Procedure for developing a model

When investigating the possibilities of saving energy in an industrial process, a simulation model is an excellent tool. However, for most processes such a model is not simply available. A procedure for developing a model for simulating a static process is proposed now, based upon the experiences of this case-study. In this procedure, the following steps can be distinguished:

a. Firstly, get a general insight into the process. This may be obtained by observing the process and reading about it. In most cases, measurements must be taken in order to determine the mass and energy balances of the process. With the help of these measurements, efficiency and other characteristics can be calculated. It is evident that system boundaries must be chosen before balances can be determined.

b. After that, a detailed qualitative analysis of the process has to be made; from that analysis results an inventory of the physical phenomena that take place. This analysis may be supported by additional detailed measurements in order to remove possible doubts concerning the process' behaviour or to neglect certain minor influences.

c. Next, mathematical expressions have to be developed to describe these phenomena. When performing this step, it is very important to notice some general points:
- A model can be no more than an approximation of reality.
- The form and the contents of a model are determined by its aims. For instance, consider the paper drying process described in section 3.2.2: If one is not interested in using different paper qualities, it is not necessary to consider the material data for the paper and its drying characteristics as
process parameters within the model. On the other hand, if the relationship between the production speed and the dryer efficiency is to be determined, the model has to be developed for variable paper sheet velocity and related variable residence time for the paper in the drying section, and so on. The accuracy required for the simulation results determines the degree of refinement of the process description within the model.

In order to describe the process by means of analytical expressions, or at least to describe the trends analytically, it is necessary to make simplifying assumptions. This last statement may imply that a (constant) empirical factor is required to make the expression fit the real phenomenon. The magnitude of this factor is determined by comparing the measurement results with the outcomes of the calculations.

Then, the expressions have to be tested by comparing their numerical outcomes with the results of measurements for each individual phenomenon:

- The purely analytical expressions are tested by comparing the absolute values of the results as such.
- For the cases in which an empirical constant is introduced, the assumption of a linear relationship is tested.

When the tests show little agreement between the two kinds of results, the expressions have to be reconsidered. The number of assumptions has to be reduced, or less rough assumptions have to be made. The improved expressions have to be tested again.

In this way, all phenomena that play a role in the process are described separately.

d. Now, from the expressions for the separate phenomena, a model of the overall process has to be prepared. Therefore, the relationships between the different phenomena have to be developed. In general, these relationships are determined by mass and energy balances: the physical conditions of the process flows and the installation itself relate the phenomena distinguished to each other. When these relationships have been developed and have been translated into mathematical expressions for use in combination with the expressions derived previously, the simulation model of the process is complete. This integrated model has to be tested by comparing its simulated outcomes with the results of overall measurements of the actual process.

This whole procedure for developing a process model is represented diagrammatically in figure 3.4. Steps a to d above are contained in several "blocks":

- step a: blocks 10 and 20
- step b: block 30
- step c: blocks 40 to 110
- step d: blocks 120 to 170
Fig. 3.4 Procedure for developing a process simulation model
3.3.2 Problems arising

The procedure described above has been applied to the drying process of the paper coating machine under consideration. Performing this procedure, a number of difficulties arose, especially in steps c and d. The first problems to be faced concerned the measurements. Because of the fact that the coating machine under consideration is a normal production machine, measuring the process conditions had to be performed during production runs. Due to the construction of the machine it appeared to be impossible to measure all the detailed process conditions of each drying box which would be necessary for a complete analysis of the drying process. A solution to this problem was found by making some assumptions (for instance on the distribution of the total natural gas consumption over the drying boxes) and checking the consequences of these assumptions by means of a sensitivity analysis.

It is evident that the accuracy of measurements in a production machine is lower than the accuracy that can be obtained for laboratory apparatus. But an additional measuring problem was caused by the fact that during production runs the process conditions cannot be kept constant, because there are always some external disturbances. By means of equipment for continuous registration of temperatures, dew points and moisture contents, and frequent observation of the other measuring points, this problem could be overcome fairly well.

There was another difficulty related to measuring a production situation: one important goal for taking measurements of the process was to get an insight into its behaviour. Therefore, it would be necessary to change all the process variables systematically over a wide range. However, this is impossible because during production the process conditions have to be checked in order to see if the required product standards are reached. For this problem, a compromise was made. A number of well-prepared runs were made during which a number of variables were changed one by one. Some extreme situations occurred in which product standards could not be reached and the product was rejected. Moreover, measurements were taken for another coating machine, which was similar to the first, but had quite different geometry data etc. In this way, indications were obtained with respect to the process behaviour as a function of several variables.

Some difficulties of a different nature occurred during the numerical operations and programming.

With respect to programming the model, one aspect should be mentioned, which concerns step d of the procedure (subsection 3.3.1). When all the heat and mass transfer phenomena in the process had been described and programmed separately, a procedure had to be programmed by which these expressions are coupled and the equilibrium conditions are determined. As most of these phenomena are described by non-linear expressions, the equilibrium has to be found by means of an iterative procedure. It is the convergence of this procedure that required much effort, especially, because of the very strong non-linearity of the relation between the evaporation rate and the paper temperature. By numerically analysing this relation, and determining an approximating expression for its behaviour in a small range around a given point, an iterative procedure was found, which shows convergence over the whole range of process conditions to be considered.

Another problem of a general nature was judging the accuracy obtained by a certain version of the model. When a model has been developed, there is always the question whether this model can be improved by developing more detailed descriptions for the phenomena and whether such an improvement would be relevant. This question arose in the case considered here: At a certain stage of the research, a model of the drying process was available in which the radiative heat transfer within the drying boxes was described by two independent, rather simple, empirical expressions. After some
discussion, it was decided to improve this description by applying radiation theory far more in detail. Although the resulting description of the radiative heat transfer phenomena (sub-section 3.4.4 and appendix III) had a far more reliable theoretical basis than the former version, it was discovered that the overall simulation results were almost the same. This illustrates the fact that it is hard to judge whether more effort has to be put into refining a certain simulation model or not, in view of the objectives of the model *). It must be concluded that, usually, this question cannot be answered until a more refined version of the model has been developed and its results can be compared with those of the preceding, less detailed version. Generally speaking, the only procedure that can be suggested with respect to this point is: refine the model step by step until it is discovered that the last step has not yielded a significant improvement.

3.3.3 Concluding remarks

A simulation model developed according to the procedure described here, provides a tool for systematic analysis of the consequences of arbitrary changes in a process. It can be applied in investigations of energy conservation; also it can be used to get to know more about the process behaviour in general. Within energy conservation projects, the model can be used for:
- General studies of the influence of every variation to process variables on the energy used by the process.
- Optimizing process control,
- Calculating the effects of proposed or possible changes to the process. Then, based upon these results, decisions can be made with respect to these proposals and possibilities.

3.4 SIMULATION MODEL OF THE PAPER DRYING PROCESS

3.4.1 General process analysis

3.4.1.1 Drying behaviour of paper

Paper is a hygroscopic material. This means that paper, when in equilibrium with the surrounding air, will always contain moisture unless the moisture content of the air is zero. When a hygroscopic material is dried by means of warm air, in the course of this drying process two important periods can be distinguished. During the first period, water is evaporated from the surface of the material (the paper); the surface stays wet because the water evaporated at the surface is replaced by water from the mass of the wet paper. The movement of water to the surface is performed by capillary action.

*)Answering this question is even more difficult when the accuracy and the number of available measurement data is limited, due to practical circumstances.

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The resistance to this water movement in the material is so small that it does not limit evaporation. This part of the drying process is called the constant rate period. Since the material surface stays wet, the paper sheet behaves like a free water surface with respect to its temperature and the rate of evaporation. This means that the paper attains the wet bulb temperature (provided heat is transferred to the paper by convection only) and that the air at the paper surface is saturated with water vapour. As a consequence of this the drying rate will be constant (assuming constant drying air conditions and constant paper temperature); this explains the name "constant rate period".

As drying proceeds, the internal resistance to moisture movement increases due to the reduction of the moisture content of the paper. A condition will be reached in which this resistance has increased so much that the amount of water moved to the surface is insufficient to keep it wet. The moisture content of the paper at this point is called the "critical moisture content". This is the end of the constant rate period.

From then onwards, (partial) drying-up takes place at the surface; the drying front gradually spreads to the body of the paper sheet. During this second drying period, evaporation continues either, from the surface (that is no longer completely wet) or, from the interior of the sheet. Water evaporated from the interior has to diffuse through the dry layer to the paper surface before it can be removed by convection. In the dry layer, resistance to water movement is much greater than in wet paper. This second drying stage is called "the falling rate period": the rate of evaporation is continually decreasing due the fact that on one hand, the area of wetted surface decreases and on the other hand, the dry layer through which the water vapour has to diffuse becomes thicker. Meanwhile, the paper sheet temperature rises. Eventually, when the equilibrium moisture content has been reached, this temperature will equal the dry bulb temperature of the drying air.

Fig. 3.5 suggests the drying rate as a function of the paper moisture.
content, assuming a situation of constant drying air conditions ([3.2] and [3.3]).

3.4.1.2 Heat transfer phenomena

In the drying process under consideration, convective, as well as radiative heat transfer, plays an important part. Within the drying boxes, heat transfer to the paper sheet is performed partly by forced convection, because the paper sheet is moved through these boxes with a certain velocity. Moreover, in boxes where the fans are operating, this convection is improved further. Between each two drying boxes, there is an open space where heat is transferred from the — relatively warm — paper sheet to the surrounding air by convection.

Further, there is convective heat transfer between the gas mixture in the drying box and the inner walls. This heat transfer depends on whether or not the fans are operating, of course.

Besides convection, radiative heat transfer is very important within the drying boxes. In the natural gas burners, heat is transmitted from the flames and flue-gases to the burner walls and the grate (fig. 3.3) by means of radiation and convection. So, the body of this burner gets rather hot and it radiates heat to the paper as well as to the inner walls of the box. Of course there is also convective heat transfer from the burners to the gas mixture in the boxes. As a result of the temperature difference between the paper sheet and the inner walls, radiative heat exchange will take place between these two bodies. Besides this, there will be some radiation from the gas mixture in the box to the paper and the walls, due to the presence of CO₂ and H₂O. These are the only gas components that make a perceptible contribution to radiation of the flue gas. However, the concentration of these components is very low due to the large amounts of excess air used in these boxes. Moreover, the temperature differences between this gas mixture and the paper sheet on one side and the inner walls of the drying box on the other side are relatively low. So, the radiation of this gas mixture plays only a small part in the total heat exchange within the drying boxes.

From the drying process, heat is lost to the flue-gas mixture which is removed up the chimney; further, heat losses occur from the drying boxes. Heat is transferred by conduction from the inner to the outer walls and, then, it is lost to the surroundings by natural convection or radiation. Fig. 3.6 shows a diagram of the heat flows in the drying section of the coating machine. This figure gives an insight into the interdependence between the different heat transfer phenomena.

3.4.1.3 Mass transfer

Removal of water from the paper takes place by convective mass transfer (i.e. water vapour transfer) from the boundary layer of the paper sheet into the surrounding gas mixture. Because the paper is wet on one side only — i.e. the upper side — this mass transfer takes place at that side only. Mass transfer within the drying boxes and in the open spaces between them is just like heat transfer — forced by the paper sheet velocity. When operating, the air fans in the boxes increase the mass transfer on the upper side of the paper sheet. The driving force for the transfer of water vapour is the difference in partial water vapour pressure between the boundary layer and the bulk of the gas mixture (inside the boxes) or the surrounding air (between the boxes).
3.4.2 Restrictions of the system considered

3.4.2.1 System boundaries

The investigations were limited to the drying process in which the back side of the paper, wetted with pure water, was dried. This process takes place in the section between points C and D in fig. 3.1. The diagram given in fig. 3.7 shows the boundaries of the system considered, which are defined as follows:

- The paper sheet was examined from right behind the point where the water film was applied (point C, fig. 3.1) up to where it left the last drying box (point D).
- The complete drying boxes were taken into consideration. Here, the system boundary coincided with the outer walls of the boxes. At this boundary, air and natural gas entered the system, and heat left it (heat was lost from the outer wall surfaces by radiation and convection). Electricity consumption for transporting the paper sheet and driving the air fans was neglected with respect to the energy balance of the system. This was done because the full impact of electricity on the energy balance was less than one percent even when all the fans were in operation. Additionally, it was clear that only a part of the electricity consumed was dissipated within the drying boxes; the other part was absorbed into the mechanical transmission system.
- The ducts for the flue-gas mixture were considered up to the point where they are joined into one duct. Heat losses from these ducts were neglected, because the ducts were well insulated, and their surface area was small compared with the surface area of the drying boxes.
- Between every two drying boxes and in front of the first one, only the paper sheet was considered which meant that there, the system boundaries coincided with the upper and lower paper surfaces. At these boundaries, heat and water vapour was lost to the environment.

The fact that the considerations were limited to this system had several implications:

- The energy flows leaving the system at the boundaries were implicitly assumed to be useless. This assumption is acceptable in view of the aim of this case study, but in practice, the effects of these energy flows should be implemented in a consideration of the complete production system (including buildings etc.). For instance, the heat lost from the drying boxes to the environment may have a positive (in winter) or a negative (in summer) value.
- Of course, recovery of flue-gas heat can be studied as additional equipment to be installed in the flue-gas duct, before the chimney.
- The question whether the heat leaving the system boundary in the paper-sheet - at an elevated temperature - is of any interest, depends on the second part of the machine.
- Although in the existing situation the electricity consumption was negligible, it might perhaps reach a significant level, due to possible process changes. In such cases the assumption needs to be re-checked.
Explanation:

$Q =$ heat flow

*first index*: 
- $c =$ convective
- $d =$ conductive
- $r =$ radiative
- $t =$ total

*second and third index*: 
- $b =$ burners
- $g =$ flue gas in burners
- $m =$ flue gas mixture (outside burners)
- $p =$ paper sheet
- $s =$ surrounding air
- $w =$ box walls

*Fig. 3.6 Diagram of the direct heat flows in a drying box*
Fig. 3.7 System boundaries of the process.

Explanation of symbols: see fig. 3.10.

Of, in

Of, out
3.4.2.2 Boundary conditions -

At the process system boundaries there were interactions with the surrounding system. These interactions were determined by the boundary conditions. For the drying process under consideration these boundary conditions were as follows:

- Incoming paper sheet: wet on the upper side. Temperature and moisture content were arbitrary, in principle. Paper sheet velocity was arbitrary too.
- Outgoing paper sheet: moisture content must not be far below the usual values of 7–9%, see also section 3.4.2.3. Temperature was not restricted.
- Surrounding air: temperature and humidity were arbitrary. In normal situations the same conditions were used for the inlet air too. It is assumed that there was no forced air stream along the outside of the drying boxes, so there would be only natural convection. Further, the inner wall temperature of the hall in which the machine was placed is assumed to be equal to the temperature of the surrounding air. The wall temperature of the hall determined the radiation heat losses of the drying boxes.
- Flue-gas mixture: it was assumed that an underpressure existed in the flue-gas duct so that all flue-gases are removed through this duct.
- Natural gas supply: fuel was supplied to the burners as a mixture of natural gas and air. Complete combustion of this mixture was assumed.

3.4.2.3 Approximations And Assumptions -

Based upon observations of the process, calculations and measurement results the following approximations were made:

- With respect to the rate of evaporation, it was assumed that drying occurred in the "constant rate period" during the whole process.
- The excess sorption enthalpy of water to paper was neglected.
- Radiation of the flue-gas mixture in the drying boxes was included in the considerations for burner radiation.
- In the drying boxes, ideal mixing of the gas was assumed.
- In the calculations for each drying box, average values have been used for several process conditions.

Each of these points will be described now.

Drying rate:
In the two drying stages mentioned before - constant rate period and falling rate period - the drying rate depends upon essentially different process variables. During the constant rate period, the vapour pressure of water in the boundary layer along the paper sheet equals the saturation vapour pressure at the material temperature. The rate of drying then depends on the water vapour transfer from the boundary layer to the surrounding air, which is determined by, among other things, the vapour pressure difference between boundary layer and surroundings.
During the falling rate period, the water vapour pressure in the boundary layer is lower than the saturation vapour pressure at material temperature. Moreover, as drying proceeds, the rate decreases continuously. The drying rate is determined by two phenomena: moisture movement to the surface followed by evaporation at the surface as well as evaporation in the interior followed by vapour diffusion onto the surface. These two phenomena depend upon, among other things, [3.6, 3.7]:

- the moisture gradient in the material
- the diffusion resistance in the material
- the sorption isotherm
- the liquid diffusivity which, in general, depends on the material temperature and moisture content.

It is evident that, during the constant rate period, the drying rate is determined fully by the external conditions and, during the falling rate period, by the properties and conditions of the drying material in particular. When describing a drying process mathematically with a model, these two drying stages require quite different formulae. However, in the drying process considered here it was obvious from measurement results that only the first stage occurs, which is the constant rate period.

This conclusion was based on the following indications:

- Measurements were made of the temperature and dew point of the air right above the paper sheet. The results showed that the air layer on the paper sheet is saturated.
- The paper sheet temperature, measured before and after each drying box, gave the most important indication. From these paper temperatures, taking into account gas conditions etc. in the boxes, the rate of vaporization was calculated for the complete drying section, assuming saturation vapour pressure in the boundary layer at the measured paper temperatures. These results showed fair agreement with the measured drying rate: deviations were smaller than 20%. This accuracy is satisfactory, because a change of 20% in the drying rate means a change of only 3-5 degrees in the average paper sheet temperature.

From this it was concluded that the paper surface had been fully wetted and thus behaved like a free water surface all along the drying boxes. So, it is evident that it is sufficient to consider the constant rate period which represented the whole drying process under consideration. A condition that must be satisfied then, when applying the model, is that the drying rate may not be higher and the final moisture content may not be lower than the original figures.

Considering the whole coating process, the fact that the constant rate period continued for the whole drying process can be explained by several points:

- The water was brought to the paper surface and had very little time (less than half a second) to penetrate into the body of the paper sheet.
- Penetration of water into the paper was hindered by the fact that the paper had a certain degree of impermeability.
- For the drying process under consideration the final moisture content was still rather high in comparison with the moisture content at the entrance (8 versus 18% approximately). Moreover, it was higher than the moisture content before the paper was wetted.
Excess sorption enthalpy
For each stage of the process, the energy balance of the material to be dried (the paper) can be written as follows:

\[ \phi = n_x \cdot \left( r(\theta) + h_s(x_p) \right) + n_p \cdot c_{p,p} \cdot \frac{dT}{dt} \quad (3.1) \]

where:

- \( \phi \) = heat flux to the paper \([kJ.s^{-1}]\)
- \( n_x \) = mass flux of the evaporated water \([kg.s^{-1}]\)
- \( r(\theta) \) = heat of vaporization of water at temperature \( \theta \) \([kJ.kg^{-1}]\)
- \( n_p \) = specific mass of the paper sheet \([kg.m^{-2}]\)
- \( c_{p,p} \) = specific heat of the paper \([kJ.kg^{-1}.K^{-1}]\)
- \( \frac{dT}{dt} \) = temperature change of the paper \([K.s^{-1}]\)
- \( h_s(x_p) \) = excess sorption enthalpy of water to paper at moisture content \( x_p \) \([kJ.kg^{-1}]\)

For most drying processes, the excess sorption enthalpy of water can be neglected compared to the heat of vaporization \(3.2\). Information about the excess sorption enthalpy for the paper dried in this process was not available; however in \(3.5\) a curve is given for the excess sorption enthalpy of water to wood. Assuming that the behaviour of paper equals to that of wood, the excess sorption enthalpy should be about 100 kJ per kg of water evaporated. This is the mean value for the range of \( \theta \) to 18 percent moisture content, found in this drying process.

However, taking into account the fact that the paper used was treated in order to make it impermeable to water, it can be expected that the excess sorption enthalpy for this paper would be much lower than 100 kJ per kg of water. Based upon this, it was decided to neglect the excess sorption enthalpy in all further considerations. So, in the energy balance of the material (equation 3.1), the term \( h_s(x_p) \cdot n_x \) has been ignored.

Gas mixing in the drying box:
Gas entered the drying box at different points: flue-gases from the burners entered the box above the burners, and air entered at various places. Most air entered through the slits for the paper sheet; also, there were holes in the burner ends, at the ends of the fan shafts and so on. The gas flow and gas temperature distribution etc. were difficult to establish; moreover gas flows were influenced by the moving paper sheet. Experimental determination of the gas flow conditions in the boxes would have been outside the scope of this thesis. Considering all these points, it was decided to assume an ideal mixing of the gases in the drying box. Consequently, the gas conditions in the box are the same as those at the exit. In particular, when the fans are operating, this assumption seems realistic; however, even when there is a (horizontal) dismixing of the gases this assumption will produce only minor errors in the heat and mass transfer calculations, as long as the average gas conditions over the paper surface area are the same as the exhaust gas conditions.

Radiation from the gas mixture:
Measurements in normal production situations indicated that partial pressures in the gas mixture within the drying boxes were no higher than about 7000 Pa for the water vapour and about 800 Pa for the carbon dioxide (mean values for the six drying boxes). Estimation of the heat radiation from the gas mixture to the paper sheet based upon these values made it clear that the contribution of this transfer phenomenon was no more than about 5 percent of the total heat transferred to the paper sheet. The radiation from the gas mixture to the inner walls of the drying box was even smaller, due to the smaller temperature difference. On account of these results it was decided to ignore the specific behaviour of this radiative
phenomenon and to include its effects in the considerations for the radiation from the burners (section 3.4.4).

**Average process conditions per drying box**

For each drying box, also, for each open space between boxes, average values have been used for several conditions when calculating heat and mass transfer. For each drying box these are: average paper sheet temperature in the box, average inner box wall temperature and average outer wall temperature.

In each sub-section between two boxes an average paper sheet temperature has been used.

The average paper sheet temperature was used only in respect of the heat transferred; for mass transfer, the weighted average saturation water vapour content was used (appendix VI). The difference between the paper temperature at the beginning and at the end of a box was no more than about 20 K. The differences between the inner wall temperatures in one box amounted to about 50 K at most, according to measurements.

The temperature of the inner walls was about 400-500 K, and the differences between the outer wall temperatures in one box were much smaller than 50 K, of course.

Considering the convection from the paper sheet and box walls, it was assumed that the average temperature caused little inaccuracy, as long as ideal gas-mixing in the box was realistic. With respect to radiation, the differences mentioned may lead to percentage deviations compared with the results of calculations on the basis of the averages of temperatures to the fourth power. These deviations were acceptable.

3.4.3 **Description of the convective heat transfer phenomena**

3.4.3.1 **Convective heat transfer to the paper**

The simulation model describes the convective heat transfer to the paper sheet in the drying box by the simple analytical expression which can be found in every handbook on heat transfer (see for instance [3.8] to [3.11]):

\[
Q_{c,mp} = A_p \cdot \alpha_p \cdot \Delta T_{mp}
\]  

(3.2)

In which

- \(Q_{c,mp}\) = convective heat transfer from gas mixture to paper sheet \([kJ.s^{-1}]\)
- \(A_p\) = area of the paper sheet through which heat is transmitted \([m^2]\)
- \(\alpha_p\) = heat transfer coefficient \([kJ.m^{-2}.s^{-1}.K^{-1}]\)
- \(\Delta T_{mp}\) = temperature difference between gas mixture and paper \([K]\)

In fact, this equation applies to pure heat transfer only. For heat transfer in presence of mass transfer, the heat transfer coefficient has to be corrected because heat transfer is affected by mass transfer too [3.12]. Its influence is proportional to the mass flux at the surface.

So this influence applies to the wet side of the paper only. Estimation of this influence shows that it is below 5% for most boxes; at the point with the highest paper temperature it is about 10%. On the average, deviations are below 5% for the wet paper side, which means that it is below 3% on the basis of total convection to the paper. Taking into account the fact that convection concerns only \(1/3\) of the total heat transfer to the paper, this influence has been neglected in the formulae for the simulation model.
A distinction had to be drawn between the upper and lower sides of the paper sheet, because fans are present only in the upper part of the drying box. When the fans operate the heat transferred on the upper side will be quite different from that on the lower side, because of the difference in relative gas velocity along the paper.

Applying equation 3.2 for the heat transfer to the paper in a drying box, the total paper surface area (upper plus lower side) equals:

\[ A_p = 2 \times L_b \times b_p \]  

where:
\[ L_b \] = length of the drying box [m]
\[ b_p \] = width of the paper sheet [m]

Further, the heat transfer coefficient \( \alpha \) has been determined according to appendix I which describes correlations for this coefficient, based upon [3.12]. Some of the factors on which this heat transfer coefficient depends are the material properties of the gas, the dimensions of the geometry and the flow along the surface.

The material properties of the gas have to be determined for the conditions (temperature, humidity) in the transition zone between the boundary layer and the body of the surrounding gas.

According to [3.12] this temperature \( T_{m,av} \) and water content \( x_{m,av} \) are determined as follows:

\[ T_{m,av} = T_m - (T_m - T_{p,av}^\sigma) - \frac{0.1 \times Pr + 40}{Pr + 72} \]  

(3.4)

where:
\[ T_m \] = gas mixture temperature [K]
\[ T_{p,av} \] = average paper sheet temperature in the drying box [K]
\[ Pr \] = Prandtl number [-]

and:
\[ x_{m,av} = \frac{x_m + x_1}{2} \]  

(3.5)

in which:
\[ x_m \] = humidity of the gas mixture [kgH_2O/kg dry gas]
\[ x_1 \] = humidity in the boundary layer along the paper sheet [kgH_2O/kg dry gas]
\[ x_{m,av} \] = average humidity of the gas in the transition zone [kgH_2O/kg dry gas]

In appendix II, the formulae for calculating the material properties and conditions are summarized. According to [3.5], the length of the drying box was taken to be the characteristic dimension in the Grashof, Nusselt, Reynolds and Sherwood numbers as used in the correlations for the transfer coefficient.

The velocity difference between the gas mixture and the paper sheet improving convection was taken to be equal to the paper sheet velocity for the lower side of the sheet as well as for the upper side, if the fans stand still. This was assumed, because the velocity of the gas mixture was negligible with respect to that of the paper sheet. If the fans are rotating, the velocity difference between the gas and paper-sheet can be estimated from the sum of the sheet velocity and the vane tip velocity of the fans.

For calculating the heat transfer from the paper sheet to the ambient air in the open spaces between the drying boxes, eq. 3.2 applied is in the same way. The characteristic dimension to be used for the dimensionless numbers of Reynolds etc. is then equal to the distance between two boxes. Further, the gas mixture conditions \( T_m \) and \( x_m \) in eqs. 3.4 and 3.5 are the same as
3.4.3.2 Convective heat transfer from the inner walls of the drying boxes

The equation for heat transfer between the inner box walls and the gas mixture is analogous to equation 3.2:

\[ Q_{c,wm} = A_w \cdot \alpha_w \cdot \Delta T_{wm} \]  

(3.6)

where:
- \( Q_{c,wm} \) = heat transferred from the walls of the drying box to the gas mixture within that box [kJ/s]
- \( A_w \) = surface area of the inner walls [m²]
- \( \alpha_w \) = heat transfer coefficient of the inner walls [kJ/s·m²·K⁻¹]
- \( \Delta T_{wm} \) = temperature difference between the inner walls of a box and gas mixture in it [K]

Again, the heat transfer coefficient has been determined according to appendix I. The gas velocity with respect to the inner walls of the box has been estimated as follows:
- If the fans stood still, it was formed by dividing the total gas volume flow through the drying box by the area of a cross-section of the box perpendicular to the flow direction of the paper sheet. This velocity is very low compared to e.g. the paper sheet velocity (see previous sub-section).
- If the fans were rotating, the gas velocity in the upper half of the drying box was taken to equal the vane tip velocity of the fans.

The length of the drying box was chosen as the characteristic dimension when calculating the Reynolds number (appendix I). In normal situations, \( \Delta T_{wm} \) was rather small, so \( Q_{c,wm} \) had limited influence to the whole process.

3.4.4 Description of the radiative heat transfer in the drying boxes

3.4.4.1 Radiative heat exchange between the burners, the paper sheet - And The Inner Drying Box Walls -

In a drying box, heat was exchanged by radiation between the burners, the paper sheet and the inner walls of the box. In fact, the gas mixture in the box and the air fans played a part in the radiative exchange too, but their influences were neglected because of their minor contributions (see section 3.4.2.3). If we assume the three burners in a drying box are equally loaded, which is realistic, and if we further assume each burner to be isothermal, the drying box can be considered as an enclosure consisting of three isothermal "gray" bodies (surfaces). Then the three burners are taken together to form one "surface"; the other surfaces are the inner box walls and the paper sheet. For calculating the radiative interchange in such enclosures, analytic computational methods are available, see for instance [3.13] to [3.16]. These methods postulate a number of assumptions which are
not applicable here. For instance, there is the assumption that the
distribution of the emitted radiation as well as that of the reflected
radiation is diffuse. However, for one method, similar to the one given in
[3.13], the application to our drying boxes was investigated. It was found
that its results showed a fair agreement with the actual results for very
divergent process conditions.
In appendix III, this method is derived and the results of the applicability
study are presented.
Based upon these results, it was concluded that this computational method
could be used to describe the radiant interchange in the drying boxes.
As a result of appendix III the method can be summarized in a set of linear
equations whose number is equal to the number of surfaces (bodies) involved.
As mentioned before, three surfaces are distinguished within a drying box:
the burners, the paper sheet and the inner walls of the box. The unknowns
in the set of equations are the net absorptions of radiant heat by the three
surfaces: \( Q_{\text{net},b} \), \( Q_{\text{net},p} \), and \( Q_{\text{net},w} \). Comparing these net absorptions
with fig. 3.6 produces the following relationships:

\[
Q_{\text{net},b} = -Q_{r,bp} - Q_{r,bw} \\
Q_{\text{net},p} = Q_{r,bp} + Q_{r,wp} \\
Q_{\text{net},w} = Q_{r,bw} - Q_{r,wp}
\]

From these expressions, it will be clear that in normal cases, \( Q_{\text{net},b} \) will
be negative, and further that:

\[
Q_{\text{net},b} + Q_{\text{net},p} + Q_{\text{net},w} = 0
\]  

Eq. 3.10 can be understood easily, if we remember that a drying box is
assumed to be an enclosure.
Now, according to appendix III, the set of linear equations describing the
radiant interchange is given in eqs. 3.11 to 3.13:

\[
\frac{1}{\varepsilon_b} Q_{\text{net},b} + \frac{1}{\varepsilon_p} Q_{\text{net},p} + \frac{1}{\varepsilon_w} Q_{\text{net},w} = 0
\]

\[
= A_b \sigma T_b^4 F_{bb} + A_p \sigma T_p^4 F_{bp} + A_w \sigma T_w^4 F_{bw}
\]

\[
= A_b \sigma T_b^4 F_{bb} + A_p \sigma T_p^4 F_{bp} + A_w \sigma T_w^4 F_{bw} - 39
\]

\[
= A_b \sigma T_b^4 F_{bb} + A_p \sigma T_p^4 F_{bp} + A_w \sigma T_w^4 F_{bw} - 39
\]
in which:

- $A_i$ = surface area $[m^2]$
- $F_{ij}$ = view factor for radiation from surface $i$ to surface $j$, which designates the fraction of the radiation leaving $i$ that arrives at $j$.
- $e_i$ = emission coefficient $[-]
- T_i$ = surface temperature $[K]$
- $o$ = Stephan-Boltzmann constant: $5.77 \times 10^{-11} [kJ \cdot m^{-2} \cdot s^{-1} \cdot K^{-4}]$

Index: $b$ = burners
- $p$ = paper
- $w$ = drying box (inner) wall

From eqs. 3.11 to 3.13, $Q_{net, b}$, $Q_{net, p}$ and $Q_{net, w}$ are determined by applying a Gauss elimination procedure (see for instance [3.7]) and assuming the temperatures $T_b$, $T_p$ and $T_w$ to be known.

The view factors, $F_{ij}$, are fully determined by the geometry of the drying box. Many handbooks on heat transfer deal with this subject, for example [3.8], [3.11], [3.13]. Moreover, in [3.17], formulae are given for calculating the viewfactors, for parallel and perpendicular surfaces.

An enclosure consisting of $N$ surfaces has $N^2$ viewfactors. However, most of these factors are not independent. In general, for an enclosure, the following relationships can be derived:

$$A_i \cdot F_{ij} = A_j \cdot F_{ji} \quad \text{for each combination } i,j \quad (3.14)$$

and:

$$\sum_{j=1}^{N} F_{ij} = 1 \quad \text{for each } i \quad (3.15)$$

These general eqs. 3.14 and 3.15 together yield $(N^2 + N)/2$ independent equations between viewfactors, this means that only $(N^2 - N)/2$ independent viewfactors have to be determined directly from the geometrical data. In the case of the drying box with $N=3$ this means that three independent viewfactors have to be determined that way. For reasons of simplicity, the viewfactors $F_{bp}$, $F_{bb}$ and $F_{pp}$ (see eqs. 3.11 to 3.13) were chosen for this.

With respect to the emission coefficients of the surface materials, according to [3.5] the following numbers were used:

$$e_b = 0.6 \quad (\text{steel})$$

$$e_p = 0.92 \quad (\text{asbestos board})$$

$e_b = 0.6$ is only a rough estimation, because it depends on the exact condition of the steel. In fact, from the literature, we can infer no more than that $e_b$ must be between about 0.5 and 0.7.

However, in section 3.4.4.2 it will be shown that this inaccuracy had no effect on the simulation results, because an empirical correlation would be used in burner calculations.

It has been mentioned that the temperatures $T_b$, $T_p$ and $T_w$ were assumed to be known when applying eqs. 3.11 to 3.13. However, these temperatures themselves depended on the radiant interchange. So, the equations 3.11 to 3.13 had to be applied within an iterative procedure in which heat exchange and the temperatures were determined simultaneously (section 3.4.7).
from the radiant interchange, the following factors played a role: for the paper sheet: the convective heat exchange (section 3.4.3.1) and the evaporation of water (section 3.4.6) and for the box walls: the heat losses (section 3.4.5) and the convective heat transfer on the inner side (section 3.4.3.2). The burner temperature was determined by the equilibrium between the heat transfer from the flue-gases to the burner on the inside and the net radiation to the paper sheet and the inner box walls on the outside of the burner.

The phenomena that determined the heat transfer from the flue-gases to the burner body on the inside of the burner will be treated in the next section.

3.4.4.2 Burners: relationship between fuel supply, temperature and -

Radiative Heat Exchange -

In fig. 3.3, a diagrammatic section of the burner is given. From this figure it will be clear that when in operation, the rectangular burner body is filled with flames and flue-gases, which exit on the upper side, through the grate. Now, in order to describe the heat transfer from these gases to the burner body, the following assumptions were made:

- heat transfer to the burner is by radiation as well as by convection
- with respect to the radiative transfer, the burner is considered as an enclosure
- with respect to the convective heat transfer from the flue-gases to the burner it is assumed that this transfer takes place only at the grate when the gases leave the burner
- the influence of the fuel supply pipe on the heat transfer phenomena in the burner is neglected
- the flue-gases in the burner are assumed to be isothermal. Moreover, the concentrations of H2O and CO2 are assumed to be uniformly distributed
- in heat transfer calculations, the flue-gas temperature in the burner is taken to be equal to the average of the initial flame temperature (based upon primary plus secondary aeration) and the flue-gas temperature at the burner exit (the grate)
- it is assumed that combustion is completed before the gases leave the burner body (through the grate)

Then, radiative and convective heat transfer from the flue-gases to the burner are calculated as follows:

Radiation: The only gas molecules that contribute appreciably to radiative transfer are CO2 and H2O. In [3.18] and [3.19], expressions are given for the radiation of these molecules in a gas cloud which apply to the considered situation:

\[
E_{CO_2} = 10.35 \times (P_{\text{gas}})^{0.4} \times \left(\frac{T}{100}\right)^{3.2} \times 10^{-5} \\
E_{H_2O} = (47.85 \times 10^{-3} \times P_{\text{gas}}) \times (P_{\text{gas}})^{0.6} \times 10^{-6} \times \left(\frac{T}{100}\right)^{\text{exp}}
\]

where: \(\text{exp} = 2.32 + 0.3(P_{\text{gas}})^{0.33}\)

where:
- \(E\) = radiation flux on an adjacent black wall with a temperature of 0 K [\(\text{W} \cdot \text{m}^{-2}\)]
- \(P\) = vapour pressure of the relevant gas [\(\text{Pa}\)]
- \(s\) = (layer-) thickness of the gas cloud [\(\text{m}\)]
- \(T\) = gas temperature [\(\text{K}\)]
Further, in (3.18) it can be shown that:
\[ E_{H_2O+CO_2} = 0.95 \times (E_{H_2O} + E_{CO_2}) \]  
(3.18)

Based upon the recommendations given in (3.18), the value of \( s \) that is used in eqs. 3.16 and 3.17 is determined as:
\[ s = \left( \frac{b_b}{z_b} \right)^{1/2} \]  
(3.19)

where:
- \( b_b \) = width of the burner body [m]
- \( z_b \) = height of the burner body [m]

Now, we change from the radiation intensity \( E(H_2O+CO_2) \) to the emission coefficient \( \varepsilon_g \) of the gas cloud. This coefficient is given by:
\[ \varepsilon_g = \frac{E_g}{\sigma T_g^4} = \frac{E(H_2O+CO_2)}{\sigma T_g^4} \]  
(3.20)

where \( \sigma \) = Stephan-Boltzmann constant

In (3.5), the analogy between this case of a gas cloud surrounded by solid walls and the case of two solid bodies in which one is surrounded by the other, is considered. Based upon this analogy, the following approximation is given for the net radiant heat transfer from the gas to the burner (walls):
\[ Q_{r,gb} = \frac{A_b \varepsilon_b (T_b^4 - T_g^4)}{1/\varepsilon_g + (1/\varepsilon_g^\infty)^* (1/\varepsilon_b - 1)} \]  
(3.21)

with
- \( A_b \) = total inner wall surface of the burner \([m^2]\)
- \( \varepsilon_g^\infty \) = emission coefficient of the gas with the same temperature, assuming an infinitely large gas layer thickness \([-]\)

\( \varepsilon_g^\infty \) is not known precisely, but can be found from figures given in (3.5) in combination with eq. 3.18; it can be concluded that \( \varepsilon_g^\infty \) will be very close to unity. Thus, eq. 3.21 can be replaced easily by:
\[ Q_{r,gb} = \frac{A_b \varepsilon_b (T_b^4 - T_g^4)}{1/\varepsilon_g + 1/\varepsilon_b - 1} \]  
(3.22)

Convection: The convective heat transfer from the flue-gases to the grate of the burner (fig. 3.3) can be expressed as follows:
\[ Q_{c,gb} = \alpha_b \varepsilon_{\text{grate}} (T_g - T_b) \]  
(3.23)

where:
- \( \alpha_b \) = heat transfer coefficient on the grate \([\text{kJ} \cdot \text{s}^{-1} \cdot \text{m}^{-2} \cdot \text{K}^{-1}]\)
- \( \varepsilon_{\text{grate}} \) = the surface area on which the gas is in contact with the grate \([\text{m}^2]\)

As in the former convection calculations, the heat transfer coefficient can
be determined according to appendix I. The relevant gas velocity is
determined by the flue-gas volume flow and the total flow-through area in
the grate.

Now, by means of eqs. 3.22 and 3.23, the total heat transfer from the
flue-gas to the burner body will be described. Except for the geometrical
data and burner temperature (which is determined by iteration, see section
3.4.4.1), the natural gas consumption of the burner has to be known, as well
as the total aeration. These two quantities together determine the initial
flame temperature, the emission coefficient of the flue-gases and the
flue-gas volume flow. The natural gas consumption of the burners is
considered to be one of the input data in the simulation calculations, just
like the total air used in the drying boxes. However, the total aeration of
the burners (primary plus secondary) was no more than a fraction of the
total air used in the box. It has been mentioned before that due to the
fact that the flue-gas mixture is extracted from the drying box, much air
directly enters the box at different places. Of course, this air does not
play a role in the heat transfer process within the burners.

The total aeration of the burner is determined by its geometry. Moreover,
aeration will generally depend on the burner load (the natural gas
consumption). Due to the fact that no characteristics were available for
the burners under consideration, an empirical correlation had to be derived
for the total aeration as a function of the natural gas consumption. The
derivation of this correlation is described in appendix IV. The resulting
expression for describing the relationship between the fuel consumption and
the aeration reads as follows:

\[
{\text{RAT}_b} = 24.25 \times \left( \frac{\text{FC}}{\text{FC}_{\text{ref}}} \right)^{0.4}
\]

(3.24)

where:

- \( \text{RAT}_b \) = ratio of air volume flow and
  - natural gas volume flow \([\text{m}^3, \text{m}^{-3}]\)
  - natural gas volume flow \([\text{m}^3, \text{s}^{-1}]\)
  - reference natural gas volume flow per burner = 448 \times 10^{-6} \([\text{m}^3, \text{s}^{-1}]\)

Expression 3.24 applies to the burners of the coating machine under
consideration, with the limitation that \( c_b \) is taken to be equal to 0.6.

Now, starting from a given natural gas supply, the flue-gas flow in the
burners can be determined with eq. 3.24. Afterwards, eqs. 3.22 and 3.23
can be applied in combination with eqs. 3.11 to 3.13 in order to calculate
the total radiant interchange within the drying box.
3.4.5 Description of the heat losses from the drying boxes

3.4.5.1 Analytical description for the idealised situation

Heat is lost from the drying boxes into the surroundings, that is: into the machine hall. The heat losses can be sub-divided into two kinds: convective and radiative losses. If some simplifying assumptions are made, analytical expressions can easily be derived for these two loss terms, starting from ideal conditions. The following assumptions are made:
- Each drying box is sited horizontally and free in an empty hall
- The outer wall of the drying box is isothermal
- The temperature of the walls of the hall is equal to that of the air in the hall
- Natural convection can take place from all sides of the box without hindrance

Now, the expressions for convection and radiation become as follows:

**Convective heat losses**: The heat lost by convection is described as:

\[ Q_{c,wo} = A_w \alpha_{wo} (T_{wo} - T_s) \]  (3.25)

where:
- Index \( wo \) = outer wall of the drying box
- \( w \) = surrounding air (and machine hall)

The heat transfer coefficient \( \alpha_{wo} \) is determined by natural convection. The intensity of natural convection depends, among other things, on how the relative surface is situated. Because of this, the heat losses from the upper surface of the box, the vertical walls and the under-surface are calculated separately and summarized afterwards. In Appendix V, correlations for calculating the heat transfer coefficients for natural convection are presented, according to (3.8) and (3.10).

**Radiative heat losses**: Starting from the aforementioned assumptions, the heat lost by radiation is calculated as follows [3.8]:

\[ Q_{r,wo} = A_w \sigma \epsilon_{wo} (T_{wo}^4 - T_s^4) \]  (3.26)

Implicitly, this expression assumes a constant emission coefficient \( \epsilon_0 \) in the temperature range from \( T_s \) to \( T_{wo} \), which is quite realistic.

3.4.5.2 Measured heat losses

Under various process conditions, the surface temperatures of the inner and outer walls of the drying boxes of the coating machine were measured. From the temperature difference between inner and outer wall the heat flow through the wall can be calculated easily. It is evident that the heat losses from the wall to the environment equal the heat flow through the wall.
So the heat losses are calculated from the measurement results as follows:

\[ Q_{ws} = A_w \cdot (T_{w1} - T_{wo}) \cdot \frac{\lambda_w}{l_w} \]  
(3.27)

where: 

- \( \lambda_w \) = thermal conductivity of the wall material [kJ.m\(^{-1}\).s\(^{-1}\).K\(^{-1}\)]
- \( l_w \) = wall thickness [m]

The drying box walls consist of asbestos board; the thermal conductivity of this material is: \( \lambda_w = 0.15 \times 10^{-3} \) kJ.m\(^{-1}\).s\(^{-1}\).K\(^{-1}\) ([3.20] and 3.21]).

Deriving the heat losses from the temperature difference between inner and outer wall is a very direct and reliable method, because the phenomenon which it is based upon (thermal conduction) is not affected by external factors.

In figure 3.8 the drying box heat losses measured this way are presented as a function of the outer wall temperature.

### 3.4.5.3 Description of the heat losses in practice

Analytical calculations of heat losses according to eqs. 3.25 and 3.26 (idealised conditions) have been made for the cases that were used for fig. 3.8. These analytical calculations start from the measured outer wall temperature and the temperature of the ambient air. Now, in fig. 3.9 these results \( (Q_{c,ws} + Q_{r,ws}) \) are presented as a function of the measured heat losses. From this fig. 3.9 it is evident that there is a rather close linear correlation between the measured heat losses and the results of the analytical calculations. By means of the method of least squares, this correlation is determined as follows:

\[ Q_{ws} = (Q_{c,ws} + Q_{r,ws}) \times 1.1 - \Delta Q_{\text{fixed}} \]  
(3.28)

where:

- \( Q_{ws} \) = total heat losses of the drying box [kJ.s\(^{-1}\)]
- \( Q_{c,ws} \) = analytically determined convective heat transfer (eq.3.25 and 3.26) [kJ.s\(^{-1}\)]
- \( Q_{r,ws} \) = and radiative heat transfer [kJ.s\(^{-1}\)]
- \( \Delta Q_{\text{fixed}} \) = constant (corrective) heat transfer term [kJ.s\(^{-1}\)]

In this expression the constant term \( \Delta Q_{\text{fixed}} \) appears which is caused by the fact that eqs. 3.25 and 3.26 start from the ambient air temperature \( T_a \) in the hall. However, in fact, the air temperature in the close surroundings of the machine was much higher. Moreover, with respect to radiation, a drying box does not "see" only the walls of the machine hall, but the boxes are in each others "field of view". Fig. 3.8 has already shown that heat losses become equal to zero, not at an air temperature equal to \( T_a \) (which is about 300 K), but at a temperature which is considerably higher.

Now, realising this, it will be evident that the "constant" term \( \Delta Q_{\text{fixed}} \) in eq. 3.28 depends on the general temperature distribution in and around the drying section of the machine.
measured heat losses $Q_{t,ws}$

$kJ.s^{-1}$

per drying box

outer wall temperature

Fig. 3.8 Measured heat losses of the drying boxes.
analytically determined
heat losses $Q_{c, ws} + Q_{r, ws}$

Fig. 3.9 Heat losses: correlation between measurements and analytical calculations
So, although the constant term is of minor influence it is better to introduce the influence of the average outer wall temperatures of the boxes of the machine, combined with the surface area of the boxes:

\[ Q_{ws} = (Q_{c,ws} + Q_{r,ws}) \times 1.1 - 0.002 \times A_w \times (T_{w0,av} - T_s) \] (3.29)

where \( T_{w0,av} \) the average outer wall temperature of all boxes of the drying section [K]

3.4.6 Description of the mass transfer process

During the drying process in and between the boxes, water vapour is transferred from the wet side of the paper sheet to the surrounding gas mixture or the surrounding air.

Generally speaking, the rate of water removal from a drying material depends on the resistance to heat and mass transfer within and outside the material. During the first stage of the drying process (the constant rate period) to which the process under consideration is limited (see section 3.4.2.3), the resistance to transfer phenomena within the material can be neglected in comparison with the resistance outside the material (in the boundary layer in the surrounding gas at the surface). Therefore, the paper temperature is assumed to be constant over the thickness of the sheet. With respect to mass transfer, the wet side of the paper sheet behaves like a free water surface.

According to (3.8) the molar water vapour flux relative to the paper sheet is given by:

\[ N_x = X \times (N_x + N_m) = G \times D \times \frac{\partial X}{\partial z} \] (3.30)

where:

- \( N_x \) = molar water vapour flux leaving the paper sheet surface [kmol.m\(^{-2}\).s\(^{-1}\)]
- \( X \) = mole fraction of water vapour [-]
- \( N_x + N_m \) = convective molar flux of the total gas mixture leaving the paper surface [kmol.m\(^{-2}\).s\(^{-1}\)]
- \( G \) = molar density of the gas mixture [kmol.m\(^{-3}\)]
- \( D \) = mass diffusivity of water vapour in air \([m^2.s^{-1}]\)
- \( z \) = coordinate normal to the interface (the paper sheet surface) \([m]\)

This equation shows that the diffusion flux \( N_m \) is the resultant of two factors: the term \( X \times (N_x + N_m) \) which is the molar water vapour flux resulting from the bulk motion of the gas mixture, and the term \((-G \times D \times \frac{\partial X}{\partial z})\), which is the molar water vapour flux resulting from the diffusion with respect to the bulk flow. In the case considered here, which concerns evaporation of water from a free water surface, it will be clear that \( N_m \) equals zero at the interface. Thus, eq. 3.30 can be reduced to:

\[ N_x \times \frac{\partial z}{D} = -G \times \frac{\partial X}{1-X} = G \times 3(\ln(1-X)) \] (3.31)
Now, eq. 3.31 is integrated over the thickness of the boundary layer (z = 0 to z = z_l; z_l being the boundary layer thickness). The mass transfer coefficient k is defined as [3.8, 3.12]:

\[ k = \frac{D}{z} \]  

(3.32)

This leads to:

\[ N_x = k \ast G \ast M_x \ln \left( \frac{1 - P_{x,m}/P_{tot}}{1 - P_{x,1}/P_{tot}} \right) \]  

(3.33)

where:
- \( k \) = mass transfer coefficient \([\text{m.s}^{-1}]\)
- \( P_{x,m} \) = partial water vapour pressure \([\text{Pa}]\)
- \( P_{tot} \) = total pressure of the gas mixture \([\text{Pa}]\)
- \( P_{x,1} \) = partial water vapour pressure in the gas mixture at the interface (z = 0) \([\text{Pa}]\)

In [3.12] correlations were given for determining the mass transfer coefficient, similar to the correlations for the heat transfer coefficient. Appendix I summarizes these correlations.

Because an expression for the mass flux is wanted and not one for the molar flux, eq. 3.32 is rewritten using the following expression:

\[ N_x = \frac{n_x}{M_x} \]  

(3.34)

where:
- \( n_x \) = water vapour mass flux \([\text{kg.m}^{-2} \cdot \text{s}^{-1}]\)
- \( M_x \) = molar weight of water \([\text{kg.kmol}^{-1}]\)

Now, the expression for the water vapour mass flux becomes:

\[ n_x = k \ast G \ast M_x \ast \frac{A_p}{2} \ast \ln \left( \frac{1 - P_{x,m}/P_{tot}}{1 - P_{x,1}/P_{tot}} \right) \]  

(3.35)

Introducing the paper surface area within a drying box: \( A_p \) (eq. 3.3) and remembering the assumption of one-sided evaporation, the rate of evaporation in a drying box is given by:

\[ W = k \ast G \ast M_x \ast \frac{A_p}{2} \ast \ln \left( \frac{1 - P_{x,m}/P_{tot}}{1 - P_{x,1}/P_{tot}} \right) \]  

(3.36)

where:
- \( W \) = rate of evaporation of water \([\text{kg.s}^{-1}]\)

Eq. 3.36 is used in the simulation model. A similar equation is used for calculating the rate of evaporation in the open spaces between the drying boxes.
In applying eq. 3.36, the molar density \( G \) has to be determined with the following expression (according to [3.12]):

\[
G = G_m - \left( G_m - G_i \right) \cdot \frac{40 + 0.1 \cdot \text{Sc}}{72 \cdot \text{Sc}} \quad (3.37)
\]

where:
- \( G_m \) = molar density of the bulk of the gas mixture [kmol.m\(^{-3}\)]
- \( G_i \) = molar density of the gas mixture at the interface [kmol.m\(^{-3}\)]
- \( \text{Sc} \) = Schmidt-number (*), determined at temperature \( T_m \) [-]

Eq. 3.4 which is analogous to eq. 3.37 is used for calculating the temperature at which the material properties in the boundary layer have to be determined, for application to the correlations for the mass transfer coefficient (appendix I).

As a result of the fact that the paper sheet surface behaves like a free water surface, the partial water vapour pressure at the interface \( P_{X,i} \) equals the saturation vapour pressure at the paper sheet temperature. This saturation vapour pressure is determined according to [3.22], see Appendix II. Because, in general, the paper temperature is not constant within a drying box, \( P_{X,i} \) has to be determined as the average weighting along the drying box length. This procedure has been explained in appendix VI.

The partial water vapour pressure in the bulk of the gas mixture \( P_{X,m} \) is derived from the water vapour mass fraction of the gas (appendix II). This mass fraction is calculated from the water balance in the drying box (see section 3.4.7).

Although a small under-pressure prevails in the drying boxes, caused by the flue-gas extractor, the whole drying process is assumed to operate under atmospheric pressure. Thus, the total pressure \( P_{\text{tot}} \) is taken to be equal to \( 10^5 \) Pa.

3.4.7 Determining the equilibrium process conditions

In the preceding sections, all relevant heat and mass transfer phenomena have been described as functions of the temperatures or humidities of the related bodies or flows: paper sheet, gas mixture, drying box, etc. Most of these factors are closely interrelated because they depend partly on the same material and flow conditions. The equilibrium conditions of the process are determined by the transfer phenomena between the various bodies and flows and the energy and mass balances of each of these. Simulating the process, basically, means determining these equilibrium conditions under arbitrary circumstances. Therefore, within the simulation model, the transfer phenomena are interrelated by applying the energy and mass balances of the paper sheet, the gas mixture and the drying box walls. Figure 3.10 shows all relevant heat flows, including those resulting from mass flows.

\*) \( \text{Sc} = \frac{\nu}{D} \), in which \( \nu \) = kinematic viscosity \( [m^2.s^{-1}] \)

\( D \) = diffusivity \( [m^2.s^{-1}] \)
Energy flows relevant to the drying process. (Numbers refer to numbers of equations describing the particular transfer phenomena, sections 3.43 to 3.45).
Now, the energy balances of the different bodies and flows can easily be derived from this figure.

For the flue-gases within the burner bodies the energy balance reads:

\[ Q_{f,\text{in}} = Q_{f,\text{gb}} + Q_{c,\text{gb}} + Q_{f,\text{gm}} \]  

(3.35)

The indices used here have been explained in fig. 3.10. Whenever heat flows resulting from mass flows are mentioned in this section, the sum of the sensible heat plus the latent heat is meant.

\( Q_{f,\text{pin}} \) represents the (higher) heating value of the natural gas that is supplied to the burners. \( Q_{f,\text{pin}} \) is the heat content of the air supplied to the burners. Further, \( Q_{f,\text{gm}} \) is the heat content of the flue-gases leaving the burners through the grate on the upper side.

The energy balance of the gas mixture in the drying box is:

\[ Q_{r,\text{gm}} + Q_{r,\text{in}} = Q_{r,\text{mp}} - Q_{f,\text{pm}} - Q_{c,\text{wm}} + Q_{f,\text{out}} - Q_{c,\text{bm}} \]  

(3.39)

Here, \( Q_{r,\text{in}} \) is the heat content of the air that is sucked in directly from the surroundings, consequent to the under-pressure in the drying box. \( Q_{f,\text{pm}} \) represents the heat content of the water vapour that comes from the paper. The heat flow \( Q_{f,\text{out}} \) represents the heat content of the gas mixture that is removed up the chimney.

The energy balance of the burner bodies in the drying box reads:

\[ Q_{c,\text{gb}} + Q_{r,\text{gb}} - Q_{r,\text{bp}} + Q_{r,\text{bw}} + Q_{c,\text{bm}} \]  

(3.40)

These heat flows are all treated in section 3.4.4. The convective heat exchange between the outside of the burner bodies and the gas mixture (\( Q_{c,\text{bm}} \)) in the drying box is neglected in comparison with the radiative exchange of the burner bodies. This concerns only the side walls and the bottom of the burner bodies, as convection at the upper side (the grade) is considered in subsection 3.4.4.2. The neglected convective heat exchange from the burners is in the order of about 2% of the radiative heat exchange. The energy balance of the paper sheet is given by:

\[ Q_{f,\text{pin}} + Q_{r,\text{mp}} + Q_{r,\text{bp}} + Q_{r,\text{wp}} - Q_{f,\text{pout}} + Q_{f,\text{pm}} \]  

(3.41)

Of course the heat flows \( Q_{f,\text{pin}} \) and \( Q_{f,\text{pout}} \) include the heat content of the water contained in the paper sheet. \( Q_{f,\text{pm}} \) is the (total) heat content of the water evaporated on the paper.

Finally, the energy balance of the drying box walls reads:

\[ Q_{r,\text{bw}} = Q_{c,\text{wm}} + Q_{r,\text{wp}} + Q_{c,\text{wa}} + Q_{r,\text{ws}} \]  

(3.42)

For the box walls themselves, the relationship between heat losses and inner and outer wall temperatures is given by eq. 3.27.

In addition to these energy balances, mass balances of the flue-gases in the burners, the gas mixture in the drying box and the paper sheet provide information about the relationships between different transfer phenomena. The mass balances of the dry gas components and of the dry paper are
irrelevant. However, it is important to consider the mass balance of the water in the drying box because of the interdependence of the water vapour content of the gas mixture in the drying box and the rate of evaporation of water from the paper sheet.

The mass balance of the water contained by the paper sheet reads:

\[ W_{\text{in}} = W_{\text{out}} + W_{\text{pm}} \]  \hspace{1cm} (3.43)

where \( W_{\text{in}} \) is the mass flow of evaporated water.

The mass balance of the water vapour in the gas mixture is given by:

\[ W_{\text{in}} + W_{\text{pm}} + W_{\text{pm}} = W_{\text{ms}} \]  \hspace{1cm} (3.44)

where \( W_{\text{pm}} \) consists of two components: the water vapour from the air drawn in by the burners and the water vapour that is liberated by burning the natural gas.

Now, all process conditions (temperatures, drying rate, heat losses, etc.) have to be determined so that the balances 3.38 to 3.44 are fulfilled simultaneously, where all heat and mass flows are calculated according to equations given in sections 3.4.3 to 3.4.6. This task is performed with the simulation model by means of an iterative procedure.

3.4.8 Programming aspects of the simulation model

In the preceding sections 3.4.3 to 3.4.7 expressions were formulated for describing all the relevant relationships between process flows, transfer phenomena and process conditions. These relationships form the basis of the simulation model of the drying process under consideration. This model consists of a computer program written in FORTRAN-V. It has been fed into the DEC-20 system at Eindhoven University of Technology. In the present section, the most important programming aspects of the model will be discussed.

In the drying section of the paper coating machine under consideration the paper passes through six drying boxes. Moreover, after being wetted, the paper sheet passes through an open space before it enters the first drying box, and five more open spaces between the drying boxes. In these open spaces the evaporation of water goes on due to the fact that the paper sheet is in contact with the surrounding air, which is relatively dry. So the whole drying process can be subdivided into twelve steps corresponding to twelve subsections through which the paper sheet passes. Each of these subsections can be considered as an individual drying process; the only interrelationships between the different subsections are the paper sheet conditions (temperature and moisture content) at the beginning and at the end of the subsections. With respect to gas and air flows the different subsections are fully independent of each other. Therefore, simulation of the whole drying process can be performed in twelve successive steps, starting with the open space in front of the first drying box. The paper sheet conditions at the end of this open space, which are determined by simulation, will be used as the starting points for the next subsection, which is the first drying box; and so on.
The drying process, as a whole, is simulated starting from the following "input data":

- temperature and moisture content of the paper sheet at the beginning of the drying section
- natural gas consumption of each drying box
- inlet air flow through each drying box, and the air conditions (temperature and humidity).
- rotational speed of the air fans in the drying boxes.
- geometry of the drying section and the paper sheet, including paper sheet velocity.

So, these same items are the starting points for the calculations for each individual dryer "subsection".

For determining the equilibrium conditions of the process, an iterative procedure has been applied. This procedure begins by assuming the starting values for several process variables, of which the average paper sheet temperature is the most important. Based upon these assumptions and, of course, the above mentioned input data, the heat and mass flows in this subsection are determined (eqs. 3.2 to 3.36), where balance equations are used in order to calculate process conditions, etc. Finally, the energy balance for the paper sheet within the subsection (eq. 3.41) is checked. If the deviation is too large, the assumptions are revised and the procedure starts again from the beginning. When the equilibrium conditions for a certain dryer subsection have been determined in this way, the paper sheet conditions (temperature and water content) at the end of this subsection can be calculated. Then, these conditions are used as the starting points for the next subsection.

For each subsection of the dryer the simulation calculations are performed using average temperatures of the paper sheet, the gas mixture, the inner and outer drying box walls (if present) etc. and an average value for the water vapour content of the gas mixture.

An overall flow diagram of the simulation program is presented in fig. 3.11.

In fact, the outcomes of the program contain all process conditions of the dryer, like for instance:
- paper sheet conditions at the end of the drying section and at the end of each subsection
- flue-gas conditions of each drying box and in the composite flue-gas duct to the chimney
- temperature and heat losses of the drying box walls.

From these process conditions, all kinds of data can be derived: efficiency of the drying process, evaporation rate (in total and for each drying box), heat transfer to the paper sheet, etc.
read the input data

take the first dryer subsection

choose starting values for iteration parameters

take the next dryer subsection

revise iteration parameters

calculate:
- drying box wall temperatures
- heat losses
- flue gas temperature
- evaporation rate
- etc.

calculate the total heat transfer to the paper sheet

check the energy balance (deviation = DEV)

? DEV < DEV_max

no

yes

calculate paper conditions at the end of the subsection

put out the results

all subsections completed?

no

yes

STOP

calculated end paper conditions are the starting conditions for the next subsection

Fig. 3.11 Flow diagram of the simulation program
### 3.4.9 Testing the model

#### 3.4.9.1 Review of the basic elements of the model

Before the simulation model could be used, it had to be tested with respect to its suitability and accuracy. When performing these tests it is important to realise how the model had been built up: which parts were based upon empirical data, which parts had an analytical background and what assumptions were made.

The basic elements of the model are the equations which describe the heat and mass transfer phenomena and their interrelationships. Also, the applied computational methods and procedures are an important part of the model.

Now, with respect to the above-mentioned questions, from sections 3.4.3 to 3.4.6 the following conclusions can be drawn:

- Heat transfer to the paper sheet comprises a convection and a radiation component. Convection has been described by analytical expressions, using well-known correlations for the heat transfer coefficients. Radiative transfer is calculated partly analytically (appendix III) and partly, on the basis of empirical data (appendix IV).
- Heat transfer to the drying box walls (inner side) is also performed by convection and radiation. The remarks mentioned above apply to this case too: convection has been described analytically and for radiation, analytical as well as empirical expressions have been used.
- The heat losses from the drying boxes (by natural convection and radiation) have been described by analytical expressions with respect to their behaviour. However, an empirical constant ratio was introduced in order to fit the results to the real situation.
- Evaporation of water from the paper is the most important phenomenon in the drying process, in fact. For this mass transfer process an analytical description has been used in the model. The mass transfer coefficients are calculated according to well-known correlations.

Summarizing these remarks, it can be seen that most of the physical phenomena have been described analytically in the model. At two points, empirical data have been used: in the expressions for the radiative heat transfer from the burners (appendix IV) and in the description of the heat losses of the drying boxes (section 3.4.5.3). The assumptions and approximations that have been made and the inaccuracies that have been included in the descriptions are the most important aspects in testing the model.

#### 3.4.9.2 Test results

In order to test the model, measurements were performed in two different production machines: DP3 and DP4 of the Océ-plant in Venlo (see subsection 3.2.3). The basic principles of these two machines are identical. The most important differences apply to the number of drying boxes (DP3: 6, DP4: 4), the width of the paper sheet (DP3: 1.5 m.; DP4: 1 m.) and the geometry of the drying boxes (DP3: flat boxes; DP4: high boxes). Moreover, there are minor differences at several points like, for instance, the usual paper sheet velocity (DP3: 2.67 m.s⁻¹; DP4: 2.33 m.s⁻¹). In the DP3-machine, measurements were performed in sixteen different situations. Their results have been presented in [3.23]. During these measurements, the following process parameters were varied systematically:
specific air used in the drying boxes, rotation of the air fans in the boxes, and paper sheet velocity. Measurements in the DP4-machine were performed in six different situations. During these runs the air used in the boxes was varied as far as possible. Systematic variation of other process parameters could not be performed. The measurement data for eleven situations of the DP3-machine have been used for deriving empirical correlations. The other data, including those of the DP4-machine, could not be used for these correlations, because during those runs insufficient details had been measured.

For all situations mentioned, a comparison between measured results and simulated results is presented in Table 3.1, showing the most important process data, namely:
- rate of evaporation (drying rate)
- end-temperature of the paper sheet (after the last drying box)
- temperature of the composite flue-gases in the central flue-gas duct
- temperature of the outside walls of the drying boxes (averaged)

Moreover, this table gives some characteristic data for each situation:
- number of drying boxes
- paper sheet velocity
- specific air use of all boxes together
- air velocity with respect to the paper sheet in the drying boxes (averaged over all boxes).

With respect to the accuracy of the measurement results, it is evident that, as measurements were performed in the factory in normal production conditions, the accuracy of the results was not very high. The accuracy of the results given in Table 3.1 was estimated as follows:
- paper sheet velocity: 3 % (inaccuracy of 5 m/min at a velocity of 150 m/min)
- specific air use: 10 % (anemometer: 1.5 %; averaging the flue-gas velocity in the duct: 5 %; paper sheet velocity: 3 %
- see above)
- velocity difference gas mixture/paper sheet:
  - when the fans are not operating: 5 % (paper sheet velocity: 3 %; gas-mixture velocity in the box (neglected): 2 %)
  - when the fans are in operation: 20 % (paper sheet velocity: 3 %; gas-mixture velocity: 2 %; inaccuracy of the rotational speed of the fans and deviation between fan tip velocity and gas velocity: 15 %)
- rate of evaporation: 15 % (inaccuracies of moisture content measurements: at the beginning: 0.1 % moisture, at the end: 1 % moisture; water supply: 0.5 %; paper sheet velocity: 3 %)
- temperatures of paper sheet and box walls: 5 % (pyrometer: 1 %; averaging: 4 %)
- temperature of flue-gases: 3 % (thermo-couple: 0.5 %; averaging: 2.5 %)

Evaluating the comparison between measurement results and results of simulations performed with help of the model, the following points should be taken into account:
- The limited accuracy of the measurement results.
- The limited number of measurement data: the measurements performed did not provide any information for how the natural gas consumption and the air used was spread over the different drying boxes. Therefore, assumptions were made with respect to these facts. It will be clear that these assumptions may give rise to deviations between measurement data and simulation results.
Finally, figs. 3.12 and 3.13 show the simulated and the measured process behaviour as functions of two process parameters. In fig. 3.12, the parameter is the specific air use in the drying boxes, and in fig. 3.13, it is the air velocity with respect to the paper sheet. These figures have been derived from certain conditions given in table 3.1: fig. 3.12 from situations 1 to 5 and fig. 3.13 from situations 12 to 14. As in these figures only the behaviour of process conditions was important, all conditions are presented as ratios or variations. The point (1,1) in the upper figures represents the usual situation.
Table 3.1: Comparison of simulation results with measurement results, for divergent situations, in two different production machines. \((m = \text{measurement data, } s = \text{simulated data})\)

<table>
<thead>
<tr>
<th>Situation</th>
<th>Number of drying boxes</th>
<th>Paper sheet velocity ([\text{m/s}])</th>
<th>Specific air use (\left[\text{m}^2/\text{kg paper}\right])</th>
<th>Velocity difference air/paper (\left[\text{m/s}\right])</th>
<th>Rate of evaporation (\left[10^{-3}\text{kg/s} \right])</th>
<th>End-temperature paper sheet ([\degree C])</th>
<th>Temperature composite flue-gases ([\degree C])</th>
<th>Temperature outer box walls ([\degree C])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>2.7</td>
<td>4.1</td>
<td>5</td>
<td>28.0</td>
<td>33.7</td>
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</tr>
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<td>2</td>
<td>6</td>
<td>2.7</td>
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<td>5</td>
<td>28.0</td>
<td>33.8</td>
<td>58</td>
<td>49</td>
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<tr>
<td>3</td>
<td>6</td>
<td>2.7</td>
<td>2.4</td>
<td>5</td>
<td>29.0</td>
<td>31.1</td>
<td>56</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>2.7</td>
<td>2.0</td>
<td>5</td>
<td>27.8</td>
<td>29.8</td>
<td>56</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>2.7</td>
<td>1.9</td>
<td>5</td>
<td>25.3</td>
<td>28.1</td>
<td>56</td>
<td>53</td>
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<td>6</td>
<td>2.7</td>
<td>2.0</td>
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<td>26.7</td>
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<td>16.8</td>
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<td>7.3</td>
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<td>2.8</td>
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<td>19.3</td>
<td>19.4</td>
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<td>11</td>
<td>6</td>
<td>2.7</td>
<td>2.7</td>
<td>5</td>
<td>26.6</td>
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<td>4</td>
<td>2.3</td>
<td>3.5</td>
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<td>19.3</td>
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<td>2.3</td>
<td>3.1</td>
<td>8</td>
<td>18.8</td>
<td>18.1</td>
<td>62</td>
<td>63</td>
</tr>
<tr>
<td>19</td>
<td>4</td>
<td>2.3</td>
<td>2.8</td>
<td>8</td>
<td>18.3</td>
<td>15.8</td>
<td>66</td>
<td>62</td>
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<td>8</td>
<td>19.6</td>
<td>17.5</td>
<td>64</td>
<td>63</td>
</tr>
</tbody>
</table>

\* Measurement data used for deriving correlations for burner fuel/air-ratio and for heat losses of the boxes.
Comparison between results of measurements and of simulation: variations of the specific air use.

Fig. 3.12

- specific natural gas consumption (10=reference base)

- variation of flue gas temperature (0=reference base)

- variation of end temperature of paper (0=reference base)

- = measurement results
- = simulation results
Comparison between results of measurements and of simulation: variations of the velocity difference between gas mixture and paper sheet.
3.4.9.3 Conclusions -

In order to simplify the assessment of the model's accuracy, the deviations between measurement and simulation results have been summarized in table 3.2. For each of the process quantities that were compared in table 3.1, the standard deviation, the average deviation and the average of the absolute values of the deviations, were determined. From the average deviation, conclusions can be drawn with respect to a possible systematic deviation. In table 3.2, proportional deviations are presented with respect to the rate of evaporation; absolute deviations are used for the temperatures.

Table 3.2: Summary of the deviations between simulation and measurement results according to table 3.1.

<table>
<thead>
<tr>
<th>Rate of evaporation [%]</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>end paper sheet</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>10</td>
</tr>
<tr>
<td>Average deviation</td>
<td>3</td>
</tr>
<tr>
<td>Average absolute value</td>
<td>8</td>
</tr>
</tbody>
</table>

Considering table 3.2, and comparing the deviations with the accuracy of the measurement results, it can be concluded that the process has been simulated with a satisfactory accuracy. Moreover, from figs. 3.12 and 3.13, it is seen that the behaviour of the process due to changing the variables "specific air use" and "velocity difference air/paper sheet" has been described quite well too: results of measurements and of simulations show similar trends. One exception is found: in the lower curve in fig. 3.12 the simulation results show a decreasing trend and the measurement results are almost constant; however, the differences are within the accuracy of the measurements.

3.4.10 Simulating variations of process conditions

The simulation model described in the preceding sections offers the opportunity of simulating the paper drying process starting from given input data. One input figure is the quantity of natural gas supplied. Consequently, if the change of the natural gas consumption due to a change of certain process variables has to be calculated, an iterative procedure will have to be applied. For that purpose a variation program has been written in which the simulation program has been embodied in an iterative procedure.

This variation program starts by simulating a "basic case", for instance, the situation in which measurement data were obtained. In this simulation run, among other things, the end-moisture content of the paper sheet is computed. This end-moisture content of the basic case is the criterion to be used for determining the effects of changes of process variables.

Then, for each desired variation, complete simulations have to be performed again. Within an iterative procedure, these simulations are repeated until the computed end-moisture content of the paper sheet equals the end-moisture content that was calculated for the basic case. In addition to the natural gas consumption for the changed situation, in principle, all other process
Fig. 3.14: Overall flow diagram for the variation program
quantities are calculated too; for instance, flue-gas temperatures, drying box heat losses, etc. Fig. 3.14 shows the flow diagram of the variation program.

In the variation program the following process variables can be changed:
- specific air use
- supply air (=surrounding air) temperature
- supply air humidity
- paper sheet velocity
- air fan rotational speed in the drying boxes (causing velocity differences between air and paper sheet)
- initial paper sheet temperature
- drying box length
- number of drying boxes
- length of the open space between each two boxes
- degree of insulation of the drying boxes

Most of these variations apply to all boxes to the same extent. The air fan rotational speed has to be given for each individual box. Further, when the specific air used is varied, the air used in each box is changed proportionally.

By means of this variation program a systematic analysis of the behaviour of the process can be made easily. The natural gas consumption can be determined as a function of the above mentioned variables. These results give an insight into the ways in which the energy used by the process can be reduced. Based upon this knowledge, energy conservation measures can be derived.

3.5 SIMULATION RESULTS

In order to get a complete view of the parameters that may affect the energy used by the process, simulations have been performed for all variables. Each variable is changed independently of all others. The results of these simulations (as far as natural gas consumption is concerned) are presented in figs. 3.15 to 3.24;*) they will be discussed as follows:

- Varying the specific air use of the drying boxes greatly affects the natural gas consumption of the drying section (fig. 3.15). Reduction of the air used is favourable; in fact there are two physical effects. The gas mixture temperature in the boxes increases, so that heat transmission to the paper is improved; on the other hand the moisture content of the gas mixture increases, which reduces evaporation. The optimum is found at about 20 % of the present air use. At that point, the consumption of natural gas is 70 % of the present consumption. Other consequences of reducing the air used are: increased flue-gas temperatures and water vapour content, a small increase of the paper sheet temperatures and drying box heat losses (due to increased box wall temperatures).

*)In each of these figures the specific natural gas consumption is on the vertical axis; the point 1.0 at this axis represents the natural gas consumption per m$^2$ of paper in the usual situation, which is considered as the reference situation.

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- From fig. 3.16 it can be seen that the temperature of the surrounding and supplied air has a great influence on the energy used. This effect is caused by two factors: a rise in temperature of the air supply means, in fact, an additional energy input to the drying box and a rise in temperature of the surrounding air causes a decrease of the heat losses from the boxes.

- Changes in the supply air humidity (fig. 3.17) have little influence on natural gas consumption. For variations of the air humidity between completely dry and completely saturated (temperature 25°C), the natural gas consumption varies from 99 to 102 % of the present level.

- With respect to the effects of changes to the paper sheet velocity, fig. 3.18 shows two different cases. In one case (A), the sheet velocity is changed with constant specific air use (air used per kg paper) which means that the total air used in the drying boxes is varied proportionally to the paper sheet velocity. On the other hand, case B shows the results for a constant total air usage in the drying boxes. The figure shows a big difference between cases A and B: when the specific air use is kept constant, the efficiency of the drying process increases with decreasing sheet velocity. The main reason for this, in fact, the increase of the time that the paper remains in the drying section. In case B this effect is completely eliminated by the effect of the increased specific air usage which is caused by the fact that the air used itself is kept constant and the paper sheet velocity (thus, the quantity of paper per unit of time) decreases. The last-mentioned effect is a very important one: the paper sheet velocity is directly related to the production rate. Therefore changes in the sheet velocity will be considerably restricted by the desired production rate.

- Figure 3.19 shows the effect of changes of the velocity difference between the air and the paper sheet in the drying boxes, caused by variations in the rotational speed of the air fans in the boxes. The energy used by the drying-section decreases with increasing velocity difference, because convective heat and mass transfer improves. Of course, an increased rotational speed for the air fans causes an increase in the energy used by the electric motors that drive the fans. However, this effect is neglected because it is very small compared to the changes in natural gas consumption (see subsection 3.4.2.1).

- Variations of the initial paper sheet temperature cause important changes in natural gas consumption (fig. 3.20). This can easily be understood from the fact that an increased initial paper temperature means an additional energy input to the drying section.

- In principle, the length of the drying boxes is a variable that affects the energy used by the drying section (fig. 3.21). However, substantial reductions of the energy used can only be reached by increasing this length by a factor of 2 or more. The main cause of the reduction of energy used is the fact that the time that the paper remains in the boxes is increased by enlarging the drying boxes.

- If the specific air usage of the whole drying section is constant, variations in the number of drying boxes (fig. 3.22) can have the same effect as increasing the length of the boxes. Again,
substantial reduction in the energy usage is obtained only with a large number of drying boxes.

- From fig. 3.23, it is clear that varying the length of the open spaces between the boxes has hardly any influence on the energy used. It is true that, in these open spaces, a considerable amount of water is evaporated; however, the heat that is necessary for this evaporation is transferred to the paper sheet inside the drying boxes. Consequently, changing the length of the open spaces does not really change the heat transfer process, although paper temperatures etc. may change.

- Thermal insulation of the drying boxes (fig. 3.24) reduces the energy used, up to 10% of the present use. The most important effect of improving the thermal insulation of the boxes is an increase of the temperature of the inner box walls, giving an improvement of the radiative heat transfer to the paper. The flue-gas temperature increases little in this case.

It has been mentioned before that these results only apply to changes of one process variable at a time. It will be clear that combinations of changes of different variables can be simulated as well. However, it is impossible to present the possible combinations systematically, because their number is infinitely large. To give some indication of the effects of combining variable changes, a few results are shown in figs. 3.25 and 3.26. The figure first mentioned shows the results of situations in which the specific air use is reduced to 20% of the present use and the supply (surrounding) air temperature varies from 20 to 120°C. Fig. 3.26 shows the effect of variations in air used when the air fans are rotating in all drying boxes. The difference between the effect of changes of one single process variable and that of a combination of variables can be seen for these cases by comparing fig. 3.25 with fig. 3.16 and fig. 3.26 with fig. 3.15. It is seen that the effect of changes of one variable with respect to the energy used decreases if the energy used had been reduced before by changing another variable. Although only two examples have been given here, it can be shown that this effect is of a general nature.
Simulations results: varying specific natural gas consumption with initial paper sheet temperature

Fig. 3.19 Simulation results: varying velocity difference between paper sheet and gas mixture

Simulations results: varying specific natural gas consumption with drying box length

Fig. 3.21 Simulation results: varying drying box length

Simulations results: varying specific natural gas consumption with the number of drying boxes

Fig. 3.22 Simulation results: varying the number of drying boxes
Specific natural gas consumption

**Fig. 3.23** Simulation results: varying the length of the open space between each two boxes.

**Fig. 3.24** Simulation results: varying the degree of insulation of the boxes (λ = 0.06 W/m·K)

Specific natural gas consumption

**Fig. 3.25** Simulation results: varying supply air temperature with reduced air use.

**Fig. 3.26** Simulation results: varying specific air use with increased air fan speed.

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3.6 DERIVING POSSIBLE ENERGY CONSERVATION MEASURES

3.6.1 Possible conservation measures

From the simulated results presented in the preceding section it is clear which process parameters can be used for reducing the energy use. In principle the following parameter changes offer opportunities of conserving energy:

- reducing the specific air use
- raising the supply air temperature
- reducing the paper sheet velocity
- increasing the velocity difference between air and paper sheet
- raising the initial paper sheet temperature
- enlarging the drying box length
- enlarging the number of drying boxes
- improving thermal insulation of the boxes

The application of each of these measures will depend on the chances of introducing the changes into the real situation. In the following, the opportunities of each of the above-mentioned measures in the existing installation for making photocopy paper will be discussed:

- Reducing the specific air use

  A certain reduction of the air used in the drying boxes can be realised by adjusting the flue-gas valves. In the installation under consideration, the reduction attained this way will be about 40% of the present air use. Further reduction is possible only if the air supply to the boxes is limited by sealing unnecessary openings (holes etc.) in the box walls. The slits for the paper sheet must be sealed as far as possible. A total reduction of 80% of the present air use is assumed to be possible then.

  In fig. 3.27 the energy use reduction is presented as a function of the reduction in the specific air use of the drying section.

- Raising the supply air temperature

  Performing the drying process with higher supply air temperatures has two prospects in practice: preheating the air and supplying the preheated air to the drying boxes. Supply air*) at higher temperatures can be obtained in the following ways:

  * heat recovery: preheating the supply air with heat from the flue-gases, by means of a heat exchanger. The practical solution for this comprises:
    - a heat exchanger
    - supply air ducts between the heat exchanger and the two points where the preheated air is supplied to the boxes (i.e. at the front of the first box and at the back of the last one.
    - the drying boxes themselves, as well as the open spaces between them, have to be sealed in order to prevent that air from the surroundings enters the boxes.
    - the flue gas ducts of all boxes except the two in the middle (fig. 3.1) have to be closed and fully sealed.

*) In any case the primary combustion air is extracted directly from the surroundings. However, this is only about 5% of the total present air use.
flue gas recycling: recycling a part of the flue-gases to the drying boxes, thereby substituting a part of the supply air. The practical solution is as above, however, with a recycling valve instead of a heat exchanger.

re-use of flue gases (from four boxes) as a secondary air supply to other boxes. Practical solution:
- the drying boxes and the open spaces have to be sealed
- four flue gas ducts have to be closed and scaled

It is seen that due to the construction, recycling flue-gases always involves re-use of flue-gases from certain boxes to other ones (the last-mentioned possibility). However, due to this re-use, the flue-gases in the central flue-gas duct have a rather high water vapour content, which means that recycling these gases will hardly be worthwhile. Thus, only two methods with raised supply air temperature remain: heat recovery by means of a heat exchanger, and re-use of flue-gases from certain boxes for other ones.

With respect to heat recovery, fig. 3.28 shows the energy reduction as a function of the heat transfer surface area of the heat exchanger.

In fig. 3.29, energy conservation due to re-use of flue-gases of four drying boxes is presented as a function of the percentage of air re-used.

Reducing the paper sheet velocity
The possibility of conserving energy by reducing the paper sheet velocity is left out of consideration here, because of the fact that the paper sheet velocity is directly related to the production rate. This production rate has to be chosen by taking into account a number of factors, of which the energy use is of minor importance.

Increasing the velocity difference between air and paper sheet in the drying boxes
In the usual situation, the air fans operate in just two of the six drying boxes. This means that the first increase in the average velocity difference can be realised simply by switching on the fans in the other boxes. After that, in principle, an additional increase is possible by increasing the rotational speed of the fans.

In any case, increasing the average velocity difference between air and paper sheet involves an increase in the electricity consumption. However, this is small compared with the decrease in natural gas consumption (5% at maximum).

Fig. 3.30 (derived from fig. 3.19) shows the net energy savings as a function of the rotational speed of the air fans.

Raising the initial paper sheet temperature
The initial temperature of the paper sheet could be raised simply by preheating the water that is used for wetting the paper. However, due to the fact that the contribution of the added water to the total heat capacity of the wetted paper sheet is no more than about 30%, and taking into account the maximum temperature (80-90°C) to which the water can be heated, the effect of this measure will be very small. Other methods of raising the initial paper sheet temperature would always mean heating the paper sheet directly, which is, in fact, an extra drying step.

Based upon these points it was decided to leave the method of
raising the initial paper temperature out of further considerations.

- **Enlarging the drying box length**
  Enlarging the drying box length is equivalent to increasing the number of boxes and that is why only this last measure is taken into account.

- **Increasing the number of drying boxes**
  In the existing installation, an increased number of drying boxes is hard to imagine. Nevertheless, this measure can be taken into account as a suggestion in further considerations. Fig. 3.31 shows the energy savings as a function of the number of added drying boxes.

- **Improving thermal insulation of the drying boxes**
  The drying box walls are made of asbestos board which is heat resistant; moreover it provides a certain degree of thermal insulation. However, this insulation can be greatly improved by covering the outside of the boxes with glass wool for instance. This layer of insulating material can be covered with metal plate. In fig. 3.32, the energy use reduction is given as a function of the thickness of the layer of insulating material (based upon the thermal conductivity of glass wool: 0.05 J.m⁻¹.s⁻¹.K⁻¹).

---

<table>
<thead>
<tr>
<th>Energy saved by reducing the air use in the boxes.</th>
<th>Energy saved by recovering heat from the flue gases in a heat exchanger.</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="specific energy savings" /></td>
<td><img src="#" alt="specific energy savings" /></td>
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<tr>
<td><img src="#" alt="specific air use reduction" /></td>
<td><img src="#" alt="heat transfer surface area" /></td>
</tr>
<tr>
<td><img src="#" alt="Fig.327" /></td>
<td><img src="#" alt="Fig.328" /></td>
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</tbody>
</table>
specific energy savings

% 60 50 40 30 20 10

re-used flue gases

Energy saved by re-using the flue gas mixture from four boxes

Fig. 3.29

specific energy savings

% 60 50 40 30 20 10

increase of air fan rotational speed

Energy saved by increasing the rotational speed of the air fans in the boxes

Fig. 3.30

specific energy savings

% 60 50 40 30 20 10

additional number of boxes

Energy saved by increasing the number of drying boxes

Fig. 3.31

specific energy savings

% 60 50 40 30 20 10

thickness of insulating layer

Energy saved by insulating the drying box walls ($\lambda = 0.06 \, \text{W} / \text{m} \cdot \text{k}$)

Fig. 3.32
3.6.2 General remarks

In the preceding sub-section, possible energy conservation measures were derived on the basis of the results of systematically simulated changes of all process variables. Most of these measures simply involved a change in a certain process variable (specific air use, number of drying boxes, etc.), which does not primarily change the incoming and outgoing process flows. Such energy conservation measures are very specifically related to the kind of process considered. On the other hand there are conservation measures that are based upon processing the ins and outs. Examples of this group of measures are: raising temperatures of supply air and wet paper, recovering heat from flue-gases. These measures and their practical solutions are not specifically related to this process, but they are of a more general nature. Other methods of this group are: heat pumps, combined power and heat generation, and all kinds of heat recovery equipment. So we see that, for this group of measures, a lot of well-known solutions are available.

3.7 SUMMARY AND CONCLUSIONS

- In this chapter a case study has been described in which a paper drying process was analysed in order to find all relevant methods for reducing its energy usage.
- A simulation model describing the stationary behaviour of the process was developed to allow for possible conservation measures to be derived systematically. A general procedure for developing such a model was proposed, and the problems that may arise during these steps were discussed.
- Developing a simulation model of an existing industrial process is a question of both performing measurements and deriving the mathematical formulae. Obtaining the right measurement data can be a big problem, because in an industrial system the number of measuring instruments is limited, and, mostly, production may not be disturbed by additional measurements etc. Consequently, the number of empirical data will be limited, which will make the derivation of reliable mathematical formulae for the process more difficult.
- The proposed procedure for developing a simulation model is an iterative one: Starting from a small amount of empirical data, a simplified description of the process is made. Based upon the questions and the inaccuracies resulting from this description, additional measurements must be performed, and the description can be extended in more detail. These steps must be repeated until the reliability and the accuracy of the model obtained is satisfactory for the intended application. As development costs of the model will rise progressively with increasing refining of the descriptions, one should be aware of the fact that there will be a certain optimum degree of model refining. In fact this optimum could be defined as the 'optimum ratio of information (knowledge of the process) and energy use'.
- The simulation model is based upon formulae that give a quantitative description of the physical phenomena (heat and mass transfer) that take place in the drying process, and the relationships between these phenomena. In this process most of the heat is transferred by convection and radiation. Most of the formulae for these phenomena are of an analytical nature; at some
points empirical factors have been introduced. Mass transfer (of water vapour) is described by an analytical formula.

- In developing the model, special attention was paid to the radiative heat transfer in the drying boxes. For this phenomenon each box was modelled as an enclosure consisting of three isothermal surfaces; for this situation general equations are available. In this way the radiant heat transfer calculations could be implemented relatively simple, with satisfactory results.

- The accuracy of the model is in the range of 10 %, which is considered to be satisfactory for evaluating energy conservation measures and combinations of measures.

- By systematic simulation of changes in all process variables, the energy conservation measures in principle were derived. After that, the energy savings due to these measures were determined as functions of the process variables in concern, by means of simulation.

The most important conservation opportunities and related savings are:

- reducing specific air use: up to 30 % saving
- recovering flue-gas heat: up to 50 % saving
- re-using flue-gases: up to 35 % saving
- increasing air fan rotational speed: up to 20 % saving
- insulating drying boxes: up to 10 % saving
- increasing the number of boxes: up to 15 % saving

The real savings depend on the extent to which the measures are performed.

- Of course, in principle, all conservation measures can be combined arbitrarily. The effects of such combinations and the resulting energy savings can easily be determined with the simulation model.

- From simulation results it can be concluded that the considered drying process is not by far ideal. The applied specific air use is much too high; besides, the efficiency of the process can be improved a lot by recovering heat or re-using flue-gases, and by improving convection in the drying boxes.

- This case study is in fact no more than an example. However, as such it shows that also for more traditional and less-energy-intensive industries or production systems it can be very interesting and very profitable to perform simulations of the processes in concern. The profit of such an approach is not limited to the fact that energy conservation opportunities can be derived very directly, but above that the general insight into the process and the understanding of its behaviour is improved. By that, the intuitive barriers for changing the process are reduced because the consequences of process changes can be quantified.
CHAPTER 4

ENERGY AND ECONOMICS - RECENT DEVELOPMENTS.

4.1 INTRODUCTION

A physical analysis (for instance the case-study in the previous chapter) shows the alternative opportunities for energy conservation. Then, the economic aspects have to be taken into consideration in order to choose from alternatives and to make decisions on the implementation. In Chapter 1 it was mentioned that, with respect to the economic aspects, this thesis is aimed at investigating the consequences of the interactions of conservation measures. This subject can be formulated more specifically by means of the following practical question: "In a certain production system, if a number of alternative energy conservation measures are possible, which measures have to be implemented and in what sequence in order to obtain maximum financial benefits for the total conservation project?"

Just like for other investment decisions, the well-known economic calculation methods and decision criteria are available for decisions on energy conservation measures. The most comprehensive of these methods is the capital value method, of which the net present value method is a special form.

Energy use and energy conservation have become of ever growing importance in decision-making for companies and governments. That is why the role that energy plays, both in the economic theory for decision-making at macro economic and micro economic levels, has been studied more and more since 1973 when it became obvious that inexpensive oil and other resources were no longer available. Van Gool [4.1] stated that "Some economic models cannot be used for situations completely different from what happened in the past, since economic theory alone cannot derive causal relationships between technical parameters. Besides economic factors, other factors like the environment suggest the need for integrating technical, social and economic knowledge". Several authors have discussed the analogy between physical phenomena and economics [e.g. 4.2] in order to obtain a better understanding of the consequences of thermodynamic limits, and for the long term of the limitation of resources with respect to the way energy and resources are treated in the economic theory. Those studies were of a very theoretical nature, [4.2, 4.3, 4.4]. Studies aimed at getting more practical results are those that consider the specific nature and the effects of energy conservation projects and measures, or those concerning methods for better energy use control in industry etc. Recent developments in these fields have taken place at macro level [e.g. 4.10] as well as at micro level [e.g. 4.13]. One of the aspects that is found behind many of these analyses is the implementation of indirect energy use for production systems. Only a very limited view of the "recent developments in energy and economics" can be given here. The considered subjects were chosen after taking into account the question of priority for measures, as was mentioned above.

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With respect to macro economics, investigation of the role of energy resulted in an improved understanding of the effects of energy conservation grants, special tax structures etc. These insights were used to support national energy programs and middle and long-term national energy plans. Section 4.2 discusses some of these developments in macro economics.

Developments in micro economics (especially at the level of industrial companies) ran partly in parallel with those mentioned above, although resulting in tools for decision-making in investment allocation instead contributing to national policy-making. Some of these approaches were based on pure economic considerations; others started from considerations of the interrelationships between those alternatives. A discussion of some of these developments is given in section 4.3.

Finally, in section 4.4 the relevance of these developments with respect to the present research is discussed. From the preceding chapters, it is evident that this research in the first place focuses on aspects of energy conservation as far as they concern decision-making at company level. Most attention has been paid to methods for allocating investments and the determination of the priority for different alternatives. This discussion leads to conclusions with respect to the applications and limitations of the available methods and, based upon them, to examination of the aspects that have to be investigated further. This need for further investigations will serve as the starting point for the remainder of this thesis, in the next chapter.

4.2 ENERGY AND MACRO ECONOMICS.

In many countries, energy conservation is considered as an issue of national concern at least. That is why many national governments during the last decade started to develop an energy policy aimed at reducing the total energy use of the country, as an important goal. Another goal was reducing the dependence on other countries with respect to energy supplies. For the main objective (national energy conservation) certain programmes have started which are aimed at either, stimulating the introduction of certain energy conservation techniques (e.g. cogeneration of power and heat, insulation, heat recovery), or at reducing the risks of energy conservation investments by certain consumer groups (e.g. private households, certain industrial sectors). The tools available to governments are tax structures, capital subsidy, energy price structures, etc. The question of how to use these tools most efficiently has been subject of many studies. In its most elementary form, this question reduces to an investment allocation problem. This allocation problem may be considered as a "simple" financial optimization problem (e.g. [4.5]), or as a multi-objective optimization problem when it concerns more than one aspect (e.g. money, energy, environment), see for instance [4.1].

Three approaches to the problem will be treated briefly now; they are all applicable at the national level or at the level of industrial sectors. The first is called "Cost-Energy Dynamics"; the second is derived from production function theory adapted to engineering production functions and the third, concerning "Conservation-Investments-curves", is aimed at ranking industrial sectors in respect of their attractiveness for investment in energy conservation.

* Cost-Energy Dynamics

The method called cost-energy dynamics was developed by Phung and Van Gool [4.6, 4.7]. It combines cost analysis and process analysis in order to form
a single framework for analyzing and rationalizing energy conservation decisions. It can be used in the public sector as well as for private-sector decisions.

Basically, the cost-energy dynamics method starts from the assumption (on the grounds of thermodynamic considerations) that for a given technology and a fixed production capacity the energy use decreases with increasing system size and/or complexity. On the other hand, it is evident that the system cost per unit of product increases with increasing size and/or complexity. These relationships can be expressed most simply by the following very common power functions:

\[ EU = a_1 + a_2 Y^{-t} \]  

(4.1)

and

\[ I = a_3 + a_4 Y^e \]  

(4.2)

These relationships can be combined as follows:

\[ I = a_3 + a_4 \left( \frac{-a_2}{a_2} \right)^{-t} \]  

(4.3)

in which:

- \( EU \) = energy use  
- \( I \) = investments  
- \( a_1, a_2 \) = parameters  
- \( Y \) = dimensionless indication of the size and/or complexity of the installation  
- \( a_3, a_4 \) = parameters  
- \( e, t \) = exponents characterizing the savings curve and the investments curve  
- \( t \) = technology parameter  

(4.3)

Based upon these equations, the expressions can be expanded into expressions for life-cycle energy use (including the indirect energy use of the production system) and life-cycle cost (including all cost components) on a present value basis. Fig. 4.1 illustrates these functions, with the life-cycle process energy use \( C_p \), direct energy use \( EU \) on the horizontal axis. Note that the indirect energy use is related to the investments for the production system. The "investment-related cost" is assumed to be proportional to the investments (eq. 4.3): \( C_t \).

The cost optimum in fig. 4.1 moves to the right, due to changes, caused for instance by shortage of capital. When the energy policy is aimed at reducing national energy use, policy makers will be interested in moving the optimum to the left, for instance by price regulations or investment grants. The area to the left of the energy optimum is in no way attractive and should be ignored.

Designing a system in the area to the left of the cost optimum is called "overdesign" and to the right: "underdesign". If a government wants to stimulate energy saving, it can use its policy tools (regulations, tax incentives, price regulations, etc.) in order to force or to stimulate firms towards "overdesign" of new systems. From fig. 4.1, the (extra) cost that is required to save a certain amount of energy can be obtained. It can be seen that under certain conditions (see \([4,7]\)), the percentage increase of
The cost optimum and energy optimum design, as indicated by the basic functions of cost-energy dynamics, life-cycle basis.

- Energy use
- Total energy use
- Investment-related cost
- Direct energy cost
- Total cost
- Process energy use (kJ)
- Cost
- $J/
- kJ
- $/th

Fig. 4.1: Cost optimum and energy optimum design, as indicated by the basic functions of cost-energy dynamics, life-cycle basis.
capital cost for every 1 percent change of energy-saving will be given by
the above mentioned technology parameter "t". This "t" is the ratio of the
exponents β and γ , which can be obtained either, from handbooks, or from
simple principles [4.7]. When parameter "t" is known for different systems
or areas under consideration, the optimum allocation of grants etc. can be
determined on the grounds of their "t"-values. In [4.7], this was done for a
number of unit processes in the U.S. industry, at an aggregated level.
It can be concluded that the method of cost-energy dynamics has some
interesting characteristics. Cost analysis and energy analysis are combined
into one framework which permits a homogeneous cost evaluation of all types
of conservation efforts. An analysis of energy savings and the cost of
conservation can be performed either, on an elementary basis, or at national
level. Cost-Energy Dynamics establish a direct relationship between the
price elasticity of demand and the technology parameter of the process, for
certain unit processes at an aggregated level, or even for a whole industry.
Moreover, it provides a basis for analysing quantitatively public-sector
measures in order to encourage or to subsidise certain fuel-saving
programmes.

* Engineering production functions.

Production functions are widely used tools in the theory of macroeconomics
in order to express the relationship between production system inputs and
prices, usually, applied with aggregate capital and labour as inputs to the
economy. Based upon these production functions, substitutabilities among
production factors can be derived. However, these substitutabilities can
thereby be translated to the micro-economic level, because, if single
processes or systems are considered, the assumptions under which the
production functions are defined hold no longer. Therefore, in the last
decade, production functions in terms of physical quantities at the
(somewhat aggregated) process level have been introduced. Chochoy [4.8]
introduced the term "engineering production function", which describes the
relationship between quantities and qualities of inputs (materials, capital
goods, labour and energy) and outputs. As energy appears explicitly in these
functions, they can be used for analysing the substitutability of energy by
each of the other production factors. De Vries and others [4.5, 4.9, 4.10]
worked out an engineering production function theory and used it to develop
a framework for studying the energy (in fact: exergy) requirements for
processes, by considering energy conservation as a substitution problem.
They have applied it to different unit processes, at a somewhat aggregated
level. More recently, Van den Hauvel [4.11] started research in this field,
beginning at the most fundamental level: the production process itself.
Because the approach of De Vries et al. has been worked out furthest, it
will be discussed here in some detail. De Vries defines engineering
production functions and analyses them for a certain unit process or a
certain kind of unit equipment. Examples are: boilers, evaporators,
compressors, or a complete electricity generating plant. The engineering
production function of a certain kind of unit equipment can be determined on
the basis of process analysis, but for well-defined equipment, it can be
based on empirical engineering data too. The "non-exergy" factors in this
function have to be translated into capital investment by means of empirical
equipment cost functions. Combining these two functions yields a
relationship between the exergy and the capital inputs, for a certain
output. A useful representation of this relationship is obtained when the
exergy input is converted into a specific exergy input (per unit of product
output) and capital investment is converted into relative specific capital
input (initial capital investment per unit of product output, relative to
that of a certain reference installation). Due to the use of specific
quantities, it is possible to compare equipment with different outputs, so
that the effects of scaling can also be taken into consideration.
An illustration of the relationship between specific exergy input and relative specific capital input is given in Fig. 4.2. For fictitious equipment based upon two different technologies - A and B - two isoquants (curves for installations with the same output capacity) and two "pure scaling" curves are given. The points with the vertical coordinate being equal to one, refer to reference installations. Moving from the right to the left along an isoquant means improving the energetic efficiency of an installation with a fixed production capacity, and based upon the same technology. Moving from the right to the left along a pure scaling curve implies up-scaling of the installation, based on the same technology and the same state of the art.

In general, there will be a certain theoretical minimum for the specific exergy input (the thermodynamic limit). In Fig. 4.2 this limit can simply be indicated by a vertical line.

By means of representations like Fig. 4.2, several aspects of production dynamics can be analyzed with respect to their impact on energy consumption: scaling, innovation and scarcity. Innovation is considered if the isoquants are built up from the data of installations representing different degrees of innovation. Scarcity (of a certain fuel) can be considered by comparing the curves for installations that use different fuels: e.g. the scarcity of natural gas for electricity generation can be analyzed by considering the effects of a change from gas turbines to coal-fired plants. Although isoquants and scaling curves have been mentioned separately, it is evident that, in practice, a certain change will very often consist of a combination of both qualitative changes and a change of scale.

It is evident that on the basis of these relationships conclusions can be drawn concerning the optimum allocation of investments for energy conservation. In the isoquants of Fig. 4.2, the slope of the curve at the
point representing the present situation is the criterion for that optimization. Optimizing the allocation of a finite amount of investment for energy conservation over several unit processes results in an aggregate cost-energy function (4.10). That function shows, starting from the present situation, which unit process has to be improved first, to what extent; then, which unit process has to be improved after that, etc. This approach is based upon the assumption that all unit processes considered are independent; possible interactions amongst them are ignored. In (4.10), it was mentioned, that including integration effects by a simple extension of the method is not possible. "The analysis becomes increasingly more complex then" (p.123).

* Generalised Conservations-Investments curves.

The generalised conservations-investments curve, proposed by Valero (4.12), is a tool, aimed at defining the conditions for optimising single conservation measures and ranking different groups of measures in order to obtain maximum profit from the total investment. It is based on statistical data aggregated at the industrial sector level. An analysis of several examples led to the idea that there must be an empirical law that describes the relationship between energy savings that can be achieved with a certain measure, and related investments. This relationship has the following form:

\[
ES = ES_{\text{max}} \times (1 - e^{-\mu I})
\]

in which:

\[
\begin{align*}
ES & = \text{realised energy savings} \quad \text{[kJ]} \\
ES_{\text{max}} & = \text{maximum energy savings that} \\
& \text{can be achieved by this} \\
I & = \text{investments} \quad \text{[$]} \\
\mu & = \text{elasticity or flexibility of} \\
& \text{the conservation measure} \quad \text{[$^{-1}]} \\
e & = \text{(only in this equation:) the} \\
& \text{base of the natural logarithm} \\
& (-2.71828...) \quad [-]
\end{align*}
\]

**Fig 43** Conservation-investments curves according to eq. (4.4)
Fig. 4.3 shows the graphic representation of this conservations-investments curve.

This relationship (4.4) was consolidated empirically with the aggregated results of energy conservation in 18 industrial sectors in Spain. Based upon this relationship an expression can be given for the optimum savings of the measure, depending on the criterion that is applied (e.g., maximum net present value). Moreover, the effect of combining different measures is considered. The consequences of some general trends in the behaviour of and the interactions among conservation measures have been analysed, at an aggregated level. That analysis led to the formulation of a criterion for ranking different conservation measures in order to obtain the highest possible overall financial benefits. This criterion says that the measures have to be ranked, from highest to lowest values of ES/I, where the values of ES (the amount of energy saved) and I (the related investments) refer to the optimum point of each individual measure, or group of measures if the analysis is performed at an aggregated level.

4.3 ENERGY AND ECONOMICS AT MICRO LEVEL.

4.3.1 General remarks

Decision-making at the company level, or at the level of individual consumers, deals with less criteria and factors of significance than decision-making at the macro level. Within the boundary conditions and regulations created by the government, decisions at the micro level have only one important criterion in fact: the financial one. This means that here, energy conservation projects are used ultimately as tools for improving financial results.

The first developments in the field of energy and macro economics discussed in the preceding section have a somewhat broader objective: besides cost and investment aspects, they cover the field of multi-factor trade-offs too, and of substitutability of all possible combinations of production factors. Of course, the principles of cost-energy dynamics and engineering production functions apply at the micro economic level, but quite different conditions must be satisfied with respect to the kind of data to be used, and their accuracy.

Subsection 4.3.2 will discuss the application and kind of outcomes for these methods from the viewpoint of the decision-maker at company level. Also, the method of LeGoff [4.13 to 4.15] will be discussed there: he used an approach that is somewhat similar to cost-energy dynamics, however, completely adapted to the micro level.

With respect to the second field that is of interest to the present research, viz: ranking and setting priorities for conservation measures, two developments are important for decision-making at company level. The first one is the method of the conservations-investments curves, which was already handled in the preceding section for the macro economic level. The second development is that of "supply curves of conserved energy", as proposed by Meier [4.16, 4.17]. These subjects will be discussed in subsection 4.3.3.

4.3.2 Investment allocation for energy conservation.

For decision-making in concrete energy conservation projects at the company level (for instance, in the case study of Chapter 3), the methods of cost-energy dynamics and of engineering production functions could be used in principle. However, as these methods were developed for the macro level, they are not very attractive in such cases:
Adapting the data of the conservation measures considered to the general forms that are used in these methods requires a lot of time and trouble which is not necessary in fact. Because there is no aggregation effect, the required accuracy of those applications is much higher than of the applications at macro level. From these points, it can be concluded that applying the cost-energy dynamics method or engineering production functions for investment allocation problems at the company level is not very efficient. The results obtained can be derived more easily by conventional process analysis and cost analysis of the conservation measures considered.

Another method that combines process analysis and cost engineering is the approach of Le Coff [4.13]. This approach was developed from elementary analyses at the process level and is aimed firstly at considerations and decisions of the micro level. Le Coff considered an energy conservation measure as a change of one or more technical variables of the process (or system). In the most simple case, there is only one variable. Then, the following quantities can be presented as functions of this variable:

- direct energy use of the production process
- indirect energy use of the production system
- total energy use which is the sum of these two
- total non-fuel costs of the measure, which are in fact the total costs of changing the variable in concern
- fuel costs of the process
- total production costs.

Fig. 4.4 presents these functions. Based upon those functions, Le Coff derived the CAREC-diagram ("characteristics energy-costs") which shows the total production cost (per unit of product) as a function of the total energy use (per unit of product). Fig. 4.5 shows such a diagram.
The CAREC diagram gives a clear illustration of the different solutions that are possible, with their consequences. In fig. 4.5, point 3 indicates the normal economic optimum; it is evident that the relevant conservation measure can only yield positive financial results if the point representing the present situation is to the right of point 3. The curve between point 3 and point 1 indicates the conservation path: energy conservation starting from the present optimum (point 3) will always result in a point on curve 1–3.

Point 2 is such a point; it represents a solution that is based on certain expectations concerning non-measurable factors (e.g. scarcity), or speculations concerning energy price rises. (The absolute value of the derivative of the curve at point 2 indicates the corresponding energy price rise in comparison with point 3).

If, for a certain conservation measure, the CAREC diagram is available and the present situation is indicated by a point on that curve, the derivative of the curve at that point is equal to the financial benefit per kJ of energy conserved. When this derivative is negative (between points 2 and 3), it indicates the extra cost per kJ of energy conserved. So the value of the derivative can be used for choosing different alternative measures, this means that it can be used for allocating investments in energy conservation.

![CAREC Diagram](image)

**Fig. 4.5** CAREC diagram with different minimum points.
4.3.3 Ranking conservation measures for optimum sequence.

The methods treated in the preceding sub-sections indicate ways in which an arbitrary amount of capital must be invested in the alternative measures under consideration. So, those methods could be considered as tools for ranking different measures too, in order to find the optimum sequence of implementation. However, none of them takes into account the fact that, in general, the savings that can be achieved by a certain conservation measure will diminish as other measures become effective in the same system.

In literature, two approaches have been found that take this effect into account. One of them is the method of conservation-investments curves, which was mentioned in section 4.2. However, as was noticed then, the assumptions of the interactive effects of conservation measures were based on statistical data. It is not possible to adapt or translate these assumptions to the physical behaviour of individual processes or systems; this means that the resulting criterion for ranking conservation measures cannot be considered as being generally applicable for decision-making at the company level.

Meier [4.16, 4.17] also studied the interactive effects of different energy conservation measures and their effects on the sequence in which they should be implemented. His analysis started from the level of individual processes, however, it was limited to conservation measures in the residential sector, especially, for space heating and hot water supplies in dwellings. Meier proposed to rank conservation measures from lowest to highest cost of conserved energy. This implied that, for each measure, the related costs had to be divided by the amount of energy conserved; this ratio he called the "cost of conserved energy" [$/kJ]. The procedure suggested for ranking different measures is as follows:

- the cost of conserved energy is determined for each measure,
- the measure with the lowest cost of conserved energy is ranked as first,
- the energy conserved by the remaining measures is recalculated assuming that each of them would come into effect after the first measure. In general, this amount of energy conserved will be smaller than in the original estimation,
- again, the measure with the lowest cost of conserved energy is chosen (ranked as second)
- these steps are repeated until the list of measures is exhausted.

So the criterion proposed by Meier is in fact the same as that suggested by Valero. An example of the results of the above procedure is the supply curve of conserved energy given in fig. 4.6. Such a supply curve shows the sequence of measures, the cumulative amount of conserved energy and, moreover, the measures which can be realised (and the amount of energy saved) are shown as a function of the energy price.
This criterion for ranking energy conservation measures has been mentioned and applied by several other authors [4.18, 4.19, 4.20]. Independently of the authors mentioned above, the author of this thesis suggested the same criterion [4.21, 4.22] on the grounds of similar qualitative considerations. However, a detailed analysis of divergent combinations of measures made clear that, in certain situations, this criterion does not result in the optimum sequence of measures. This will be discussed in the next section.

4.4 SUITABILITY OF THE AVAILABLE METHODS IN THE PRESENT RESEARCH.

At the beginning of this chapter, the problem dealt with in this part of the research was formulated as follows:

"In a certain industrial production system, if a number of alternative energy conservation measures are possible, which measures have to be implemented and in what sequence in order to obtain maximum financial benefits for the total conservation project?". Each of the recently developed methods that were described in the preceding sections provides a solution; however, each method considers the problem from the viewpoint of a specific area. The application to the present field of interest, which concerns decisions for individual energy conservation measures at company level, will be discussed now.

- The methods of cost-energy dynamics, engineering production functions, and the CAREC diagram (Le Caff) provide tools for investment allocations and, thus, for choosing from various possible measures but, in fact, they are merely based on pure economic considerations adapted to changes of the system that affect energy use. Possible interactions that occur when different measures are combined (integration effects) are left out of consideration,
The method of conservation-investments curves and the supply curve concept are aimed at ranking alternative measures; therefore, they pay special attention to the interactive effects. Both methods achieve the same criterion; since the backgrounds have been explained most explicitly for the supply curve concept [4.16], this method is examined in more detail. It was mentioned earlier that, in [4.16], the supply curve concept was developed from examples of the residential sector. This implies that conservation measures were considered as standardised solutions or standard equipment. The interdependence of conservation measures is then limited to the fact that they affect each other's savings. The technical solution remains unchanged, as do the investments and the cost of the measure.

From a fundamental analysis of several industrial projects it was evident that this assumption did not hold for most industrial energy conservation projects, especially, when production processes were concerned. Then, the equipment and the solutions for reducing energy use were designed especially for that particular situation or it was chosen from a large range of standardised equipment. In such cases, it was evident that the optimum design would change when the energy savings diminished due to other measures that had been implemented earlier. This meant that not only the amount of energy conserved, but also the related investments and cost depended on implementing other measures. So this will provide a set of assumptions more general than those used in the supply curve concept and in the other methods treated earlier.

This generalisation may be unnecessary for residential conservation measures and for all the other measures that are implemented by means of fixed standard solutions, but it is essential for measures that relate to the situation for which the designs are optimized.

4.5 CONCLUSIONS.

From the discussion in the preceding section it is evident that the methods, found in literature, are not suitable for choosing from various possible energy conservation measures in industrial projects, because they do not take full account of the physical interactive effects. It must be concluded that no method was found in literature that takes into account the generalisation, mentioned at the end of section 4.4: consideration of the fact that not only the savings of measures are affected by implementing other measures, but also the design (and, consequently, the cost). Therefore, this problem will be investigated in detail in the next chapter, which is aimed at developing a very general method for decision-making and ranking (at least industrial) energy conservation measures. The method should provide information with respect to the priorities for different measures and about the optimum sequence of implementation.
CHAPTER 5

INTERACTIVE EFFECTS OF ENERGY CONSERVATION MEASURES - IMPACT ON ECONOMIC RESULTS AND DECISION MAKING

5.1 INTRODUCTION

In general, for reducing the energy use in a certain process or a certain production system, a number of possible alternatives are available, see Chapter 3. Each of these can be realised individually; moreover, arbitrary combinations of conservation measures can be made. If different energy conservation measures in one process or system are combined, they will mutually influence each other's effect, viz. the achieved savings. In fact this means that the potential energy savings of a certain measure will decrease if other measures are implemented earlier. This can be illustrated by the very simple example of heating a house: the savings achieved by installing a high-efficiency central heating boiler are smaller if the house was already insulated than in an uninsulated house. On the other hand, the amount of energy saved by insulating a house is smaller if the house has a high-efficiency boiler than in the case of a conventional one.

In case studies of existing industrial installations, it was found that due to the interactive effects of conservation measures, the ultimate project results of energy conservation projects depended on the sequence in which the different measures were implemented, in case they were not implemented all at once. In fact, this means that there is a sequence-dependent relationship between the decisions to implement different measures. Such sequence-dependent relationships between decisions are a very common phenomenon. In general, in such cases, decisions cannot be made until a systematic analysis of all possible sequences and all decision-steps has been made. Especially when there is no systematic underlying connection between the decisions, this is the only way to gain an insight into their ultimate effects, and into the question what to decide in a certain situation. However, where energy conservation measures are concerned, the interactive effects are determined by physical phenomena (the laws of thermodynamics) and thus, they are of a systematic nature. The expectation that the results of decisions in energy conservation projects are determined by both physical and economic aspects was based upon this. Studying these aspects in general, one might be able to derive general criteria for the determination of the priorities for different alternatives in arbitrary situations. Such criteria could serve as a practical tool for decision-making with respect to energy conservation measures, so that extensive calculations for simulating all possible combinations and sequences of the different alternatives can be avoided.

The interactive effects of different energy conservation measures in one
The considerations in this chapter are generally applicable to all kinds of energy conservation projects. However, we focus on situations in industrial production systems because the interactive effects of conservation measures are most noticeable there. Moreover, decision processes and decision criteria are clearest and best defined in this sector.

**Company's general aim**

In literature, many different opinions can be found concerning the general aims of companies. For instance, Ackoff [5.10] states: "Corporations are organizations whose primary functions in society are the production and distribution of wealth". Irrespective of how their functions are defined, we state - as the starting point for the considerations in this thesis - that, in very general terms, the ultimate aim of an industrial enterprise is to continue to exist. In order to realise this, all activities are aimed at maximizing the discounted cash flow into the company. Therefore, this maximization is the aim of the considerations in this chapter too and of the strategy to be derived. Talking about criteria for maximizing the discounted cash flow into a company, the first point to be defined is the point where this cash flow is measured and the units in which it is defined.

**Basis for comparison: Net present value**

The strategy to be derived here is meant for energy saving projects in existing installations in the first place. Therefore, a "Net Benefits Analysis" [5.4] is used, which means that only the changes with respect to the original situation are taken into account (section 5.4). So this defines the point where the cash flow into the company is measured; taxes etc. are left out of consideration here.
With respect to the units, we use monetary units (e.g. Dollars) on a present value basis.

The method applied in the financial calculations is the "capital value method", as described in [5.5]. This method gives a complete insight into the net project results at any moment in the project's lifetime, so that the maximum risk, the economic payback period, etc. can easily be derived. However, for reasons of simplicity and clearness, different possibilities will be compared here on the basis of a single number: the net present value, which is the capital value at the end of the time limit (e.g. the life time) of the particular conservation measure. So the general aim of maximizing the cash flow into the company is translated as maximizing the net present value of the energy saving project. The fact that this net present value is used as the basis for comparison means that, implicitly, equal periods of time are assumed for the different measures. This implies that the lifecycles of the different measures must be (assumed to be) equal, or, in case of great differences, for those with shorter lifetimes re-investments have to be incorporated until the considered time horizons are equal.

So, factors as risk, payback period etc. are left out of consideration in studying the interactive effects of different measures; this means that the decision criterion to be derived in this chapter cannot be used as the only tool for decision making, but it has to be used in addition to the economic criteria that are usual in the particular company.

**Energy conservation: applied definition**

In the investigations in this chapter, the term "energy conservation" is used for changes causing a reduction of the direct energy use (see Chapter 2) of a production system, under the condition that production speed and product quality remains unchanged.

**Conservation measure characteristics**

With respect to the general characteristics of energy conservation measures, we start from the supposition that each conservation measure can be described as a function of one specific variable, with respect to both the achieved energy savings and the expenses (section 5.3). For instance, in thermal insulation projects the thickness of the insulating layer is such a variable. In this context, conservation measures that can only be realized in one specific way, or which have only one fixed amount of expenses, are considered as special cases (section 5.8).

**Step-by-step implementaion of conservation measures**

An important starting point for the considerations in this chapter is the assumption that conservation measures will be realised one by one. In most existing production situations, such a step-by-step procedure is realistic for several reasons, like: limited capital budgets, limited man-power etc., but also, because of a certain "resistance to change" in companies, due to the fact that energy conservation measures often change the process conditions which may affect product quality etc. When performing such a "step" in practice, there is mostly no evidence on what and when the next step will be, or even, if there will be a next step. Therefore, in each step the measure in concern is optimised individually, irrespective of possible subsequent measures. In fact, this implies sub-optimization. The consequences of this will be discussed in sub-section 5.6.1 and investigated in sub-section 5.7.4.
In energy conservation projects with a number of measures that are implemented one by one, the ultimate project benefits over the whole lifetime depend on:
- the results of the individual measures
- the moment of implementation for each of the measures
- the interactive effects of conservation measures, with respect to their energy savings and financial results.

This last point (together with the first one) means that the ultimate project benefits depend on the sequence for implementing the measures. The investigations in this chapter are aimed at these aspects. However, the effects of the time schedule (the second point mentioned above) have nothing to do with the physical characteristics or the interactive effects. That is why, in the considerations here, the effect of the time spans between different steps is eliminated in order to get a clear view of the consequences of the interactive effects of measures. So, in fact, the considerations here are based upon a step-by-step procedure, however, with the time span between the steps approaching zero.

Although the strategy to be derived is based upon an assumed stepwise implementation, it is also useful in other situations, for instance, in designing complete new systems. Such applications for the results of this chapter will be discussed in sections 5.8 and 5.9.

5.3 GENERAL EQUATIONS FOR THE PHYSICAL AND FINANCIAL EFFECTS OF ENERGY CONSERVATION MEASURES

In order to study the way in which different energy conservation measures affect one another's results, a general representation of such measures is needed. By means of general equations representing the characteristics of these measures, this phenomenon can be analysed.

In fact, each conservation measure can be characterised by one specific variable. For instance, in the case of heat recovery, this variable is the heat transfer surface area of the heat exchanger; in the case of insulation, it is the thickness of the layer of insulating material. For the general case, this variable will be called "u". In a certain situation, the energy savings, as well as the expenses of the conservation measure, are functions of this variable "u". However, for reasons of uniformity this variable "u" is replaced by a dimensionless variable "v", with \( v = u/u_\text{ref} \); \( u_\text{ref} \) being a reference or unit value of "u". The optimal value of \( v \) is determined from these two functions. Variable "v" can be defined so that \( 0 < v < \infty \).

Energy savings

With respect to the energy savings, the following general starting points are stated for the considerations in this chapter:
- the function of the energy savings \( E_S(v) \) is a continuous function of \( 0 < v < \infty \)
- \( E_S(v) = 0 \) for \( v = 0 \)
- \( E_S(v) > 0 \) for \( v > 0 \)
- \( E_S(v) \) has a maximum which is reached asymptotically for \( v \to \infty \)

Possible exceptions with respect to these starting points will be discussed in section 5.8.
The simplest general form that satisfies the above points reads:

\[
ES(v) = \frac{d}{v^{-\gamma} + e} \quad (5.1)
\]

in which:

- \( ES(v) \) = energy saved over the whole lifecycle of the conservation measure \([kJ]\)
- \( d \) = characteristic parameters for the conservation measure under consideration: \( d: [kJ] \)
- \( e \) = characteristic exponent, characteristic for this conservation measure, \( e: [-] \)
- \( \gamma \) = exponent, characteristic for this conservation measure, \( \gamma > 0 \)
- \( v \) = dimensionless technical variable, \( v = u/u_{\text{ref}} \) (\( u \) may have any dimension)

From eq. 5.1 it follows that the maximum value of \( ES(v) \) equals \( d/e \).

Fig. 5.1 gives an example of \( ES \)-curves based upon equation 5.1.

As an illustration, in appendix VII expressions of the form of eq. 5.1 are derived analytically for two general cases: insulation and heat recovery.
For instance, the resulting equation for heat recovery (by means of a heat exchanger) with equal primary and secondary mass flows reads as follows (eq. A.41 with numerator and denominator made dimensionless by means of the unit value of \( \Delta h_e \): \( \Delta h_{e-ref} \)):

\[
E3(\Delta h_e) = \frac{C_u \Delta h_e \cdot (T_{2in} - T_{2in}) \cdot \Delta h_{e-ref}}{\Delta h_{e-ref} + \frac{C_u \Delta h_e \cdot \Delta h_{e-ref}}{m \cdot \alpha_p}}
\] (5.2)

in which:

- \( \Delta h_e \) = heat transfer surface area of the heat exchanger \([m^2]\)
- \( \Delta h_{e-ref} \) = reference value of \( \Delta h_e \) \([m^2]\)
- \( C_u \) = constant, determined by the process for which heat is recovered \([-]\)
- \( T_{2in} \) = temperature of the hot primary fluid flowing into the heat exchanger \([K]\)
- \( T_{2in} \) = temperature of the cold secondary medium flowing into the heat exchanger \([K]\)
- \( m \) = mass flowrate (primary and secondary medium) \([kg.s^{-1}]\)
- \( \alpha_p \) = specific heat (primary and secondary medium) \([kJ.kg^{-1}.K^{-1}]\)

In addition, appendix VII compares the conservation measures derived in the case study of Chapter 3 with the general equation 5.1. The results of appendix VII show that eq. 5.1 can very well be used as a generally applicable representation of the energy savings achieved by conservation measures.

**Expenses**

The total expenses of an energy conservation measure consist of investments, expenses for maintenance, operation, etc. In general, they depend on the variable \( "v" \) (at least, partly). However, in most cases, there will be certain expenses that are independent of \( "v" \), in principle. With respect to investments, it is assumed that the \( v \)-dependent part can be described by the exponential cost estimating method, well-known in cost engineering [e.g. 5.6], which reads:

\[
I(u) = I(u_{ref}) \cdot \left| \frac{Y(u)}{Y(u_{ref})} \right|^{\beta}
\] (5.3)

in which:

- \( I \) = investments \([\$]\)
- \( u, u_{ref} \) = different values of the variable which determines the dimensions or the capacity of the installation \([\ldots]\)
- \( Y \) = function indicating the capacity (often proportional to geometrical dimensions) \([\ldots]\)
- \( \beta \) = exponent, depending on the kind of installation; \( 0 < \beta < 1 \) is assumed, which implies that the specific investments are a degressive function of the capacity \([-]\)

In [5.8], values of \( \beta \) are given for a number of different parts of equipment, total units, etc. Most of them are in the range 0.6 - 0.7; the whole range is in fact between 0.5 and 1.0.
In general, for a certain kind of equipment with a fixed technology, expenses for maintenance, operation etc. can be expressed as percentages of investments; additionally, certain fixed amounts are possible. Therefore it is assumed that the total expenses (on a lifecycle basis), including investments, of an energy conservation measure can be expressed as follows:

\[ \text{EXP}(v) = f + g \cdot v^b \]  \hspace{1cm} (5.4)

in which:

- \( \text{EXP} \) = total expenses (over the whole lifecycle) of the conservation measure (present value basis) \([\$]\)
- \( f \) = characteristic parameter of the measure, representing the total amount of "v-independent" expenses (present value basis) \([\$]\)
- \( g \) = characteristic parameter for the "v-dependent" expenses (present value basis) \([\$]\)

Eq. 5.4, which is used here for the total life-cycle expenses, is, in fact, the usual way of expressing the investments of projects or measures, see (e.g.) [5.6], [5.7], [5.8].

So we have now the general equations 5.1 and 5.4 for describing the energy savings and expenses as a function of the characteristic physical variable "v". Exceptions to these equations will be treated in section 5.8.

### 5.4 FINANCIAL RESULTS AND OPTIMAL DESIGN OF INDIVIDUAL CONSERVATION MEASURES

As explained in section 5.2, the basis for comparing the financial benefits of energy conservation measures is the life-cycle net present value. Considering measures to be introduced in existing situations, this means that only the incomes and expenditures from these changes are taken into account. The life-cycle net present value of a conservation measure is given by:

\[ \text{NPV}(v) = p_e \cdot \text{ES}(v) - \text{EXP}(v) \]  \hspace{1cm} (5.5)

in which:

- \( \text{NPV} \) = life-cycle net present value \([\$]\)
- \( p_e \) = weighted average present value of the energy price \([\$\cdot \text{kJ}^{-1}]\)
- \( \text{ES} \) = total life-cycle energy savings \([\text{kJ}]\)
- \( \text{EXP} \) = present value of total life-cycle expenses, including maintenance, operation and investment expenses \([\$]\)

In section 5.3, it was shown that both the savings (ES) and the expenses (EXP) present in eq. 5.5 can be expressed as functions of a dimensionless technical variable "v": eqs. 5.1 and 5.4. So it is evident that the net present value of a conservation measure is also a function of this variable "v". Substituting eqs. 5.1 and 5.4 in eq. 5.5 yields:

\[ \text{NPV}(v) = \frac{p_e \cdot d}{v^{-Y} + e} - f - g \cdot v^b \]  \hspace{1cm} (5.6)
The optimal design of the conservation measure can be determined from the optimal value of "v" which leads to the maximum net present value:

$$\max \{ \text{NPV}(v) \} = \text{NPV}(v_{\text{opt}}) \quad (5.7)$$

Fig. 5.2 illustrates this by means of an arbitrary example. Note that eq. 5.7 can also be written as:

$$\left| \frac{\partial \text{ES}(v)}{\partial v} \right|_{v = v_{\text{opt}}} = \left| \frac{\partial \text{EXP}(v)}{\partial v} \right|_{v = v_{\text{opt}}} \quad (5.8)$$

An implicit equation for $v_{\text{opt}}$ can be derived analytically from eqs. 5.6 and 5.7. However, this implicit equation cannot be solved analytically; $v_{\text{opt}}$ can only be determined numerically, by means of an iterative procedure.

---

**Fig 5.2**

Optimum design of an energy conservation measure.

- Left: present value of $p_e \cdot \text{ES}(v)$, $\text{EXP}(v)$ and $\text{NPV}(v)$.
- Right: derivatives of $p_e \cdot \text{ES}(v)$ and $\text{EXP}(v)$.

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5.5 INTERACTIVE EFFECTS OF ENERGY CONSERVATION MEASURES: PHYSICAL ASPECTS.

5.5.1 Possible relationships among conservation measures in one system

Each energy conservation measure is aimed at:
- introducing or improving one or more of the profitable energy flows in the considered system
or:
- deleting or reducing one or more useless energy flows (e.g. energy losses).

In a real system, the energy flows can be recognized as physical transport phenomena: heat transfer, mass transfer, or mass transport. So, in fact, an energy conservation measure can be considered as a measure that affects a certain physical transport phenomenon. Now, in order to study the interactive effects of different conservation measures in one system, a representation of this system has to be used in which each of these phenomena can be distinguished.

A certain production system can be represented by a process flow diagram, with the process parts as blocks. In order to analyse the effect of one conservation measure upon the energy savings that can be achieved by another measure in the same system, the process diagram has to be detailed to such an extent that each conservation measure under consideration has to relate to a separate block in the process flow diagram.

As an illustration, fig. 5.3 shows a flow diagram for a drying box of the paper dryer described in Chapter 3 (compare fig. 3.6). Such a flow diagram is in fact a network in which energy (or mass) flows from one point to another; the connections between these points are the blocks which represent physical transport phenomena.

From the example given in fig. 5.3 it is clear that, in general, two groups of transfer phenomena can be distinguished: transfer of useful energy (e.g. heat transfer to the paper) and transfer of energy that is lost (e.g. heat conduction through the walls).

Each of these flows is determined by a driving force between the two points and a certain "resistance", which depends on the process block itself. Examples of such driving forces and resistances are given in table 5.1.

Now, it is clear that energy conservation measures are measures that reduce the resistance to profitable flows or increase the resistance to useless flows. The behaviour of the whole system (all flows) can be expressed as a function of these resistances. The effects of a certain conservation measure can be analysed by changing the corresponding resistance. The results combining measures can be determined in the same way.

From the representation of a system by means of a process flow diagram with different resistances, an insight can be gained into the question of relationships between different energy conservation measures. The phenomena that are affected by these measures, represented in the flow diagram as resistances, can be interrelated by the basic forms of connections which are in series or parallel, and all combinations of them. For cases in which all driving forces are of the same kind (e.g. temperatures), the process flow diagram can be replaced by an electric analogy: an electric circuit in which the driving forces are voltages and the resistances are electric resistances. Such cases can be analysed relatively simply; however, in practical cases (e.g. fig. 5.3), there can be different kinds of driving force which have a certain interdependence (e.g. T and T'). In such cases, the interrelationships between conservation measures are much more complicated.
Fig. 5.3 Energy flow diagram of a drying box of the paper dryer (chapter 3)
Table 5.1: Examples of physical transfer or conversion phenomena, with their corresponding driving forces and resistances.

<table>
<thead>
<tr>
<th>phenomenon</th>
<th>mathematical formulation</th>
<th>driving force</th>
<th>resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal conduction</td>
<td>( Q = \frac{\Delta T}{I} )</td>
<td>( \Delta T )</td>
<td>( \frac{1}{\lambda A} )</td>
</tr>
<tr>
<td>convective heat transfer</td>
<td>( Q = \alpha A \Delta T )</td>
<td>( \Delta T )</td>
<td>( \frac{1}{\alpha A} )</td>
</tr>
<tr>
<td>radiative heat transfer</td>
<td>( Q = \frac{\alpha A}{\varepsilon_1 \varepsilon_2} (T^4_2 - T^4_1) )</td>
<td>( \frac{T^4_2 - T^4_1}{\varepsilon_1 \varepsilon_2} )</td>
<td>( \frac{\varepsilon_1 \varepsilon_2}{\sigma A} )</td>
</tr>
<tr>
<td>electric conduction</td>
<td>( I = \frac{V}{\varepsilon r} )</td>
<td>( V )</td>
<td>( \varepsilon r )</td>
</tr>
<tr>
<td>fluid transport through a pipe (laminar)</td>
<td>( V_F = \frac{\pi \text{ diam}^4}{128 \eta L} \Delta P )</td>
<td>( \Delta P )</td>
<td>( \frac{128 \eta L}{\pi \text{ diam}} )</td>
</tr>
<tr>
<td>conversion of mech. energy into heat by friction</td>
<td>( Q = A \cdot W \cdot C_{\text{friction}} )</td>
<td>( W )</td>
<td>( \frac{1}{\alpha C_{\text{friction}}} )</td>
</tr>
<tr>
<td>conversion of electric energy into heat</td>
<td>( Q = \frac{V^2}{\varepsilon r} )</td>
<td>( V^2 )</td>
<td>( \varepsilon r )</td>
</tr>
</tbody>
</table>

**Explanation**

- \( A \) : (surface) area
- \( C \) : friction factor
- \( \text{diam} \) : diameter
- \( \varepsilon_1 \), \( \varepsilon_2 \) : function of \( \varepsilon_1 \) and \( \varepsilon_2 \)
- \( \Delta T \) : temperature difference
- \( \text{er} \) : electric resistance
- \( W \) : velocity
- \( \varepsilon \) : emission coefficient
- \( \eta \) : dynamic viscosity
- \( \lambda \) : thermal conductivity
- \( \Delta P \) : pressure difference
- \( \alpha \) : heat transfer coeff.
- \( \sigma \) : Stephan-Boltzmann constant
- \( \text{er} \) : electric resistance

**5.5.2 In search of possible ways of interaction among Conservation Measures**

From the foregoing subsection, it is evident that the interactions among conservation measures are, in principle, caused by the structure of the process diagram of the complete system. Three different approaches are used to analyse possible combinations of measures and their effects. The three different approaches, together, will yield a reliable insight into the ways in which different energy conservation measures for a system may affect one another's savings. The three approaches are:

- An analysis of the two basic forms of connection between different parts of a process flow diagram: in series and parallel connections. This analysis is performed in subsection 5.5.3.
A theoretical consideration of the general equations for conservation measures, as presented in section 5.3. The results of this consideration are illustrated by an analysis of examples of energy conservation measures represented by equations in a general form. This approach is explained in subsection 5.5.4.

- An empirical approach that uses the case study for the paper dryer as described in Chapter 3. By means of the simulation model of this dryer, the interactive effects of several combinations of measures are calculated, in order to study the general trends and to compare them with the results of the other approaches. Subsection 5.5.5 presents this empirical approach.

Based upon the results of these three different approaches, conclusions will be drawn with respect to the nature of the interactive effects of energy conservation measures in general (subsection 5.5.6).

5.5.3 Approach 1: Analysis of serial and parallel connections

In subsection 5.5.1, it was mentioned that the two basic forms of relationships among the process parts of different energy conservation measures are series and parallel connections. That is why, in this section, some examples of the interactive effects of conservation measures in such connections are analysed. The results for these simplified cases are derived analytically in Appendix VIII. These derivations give an insight into the way in which energy savings of a certain conservation measure, as a function of its related variable, change due to another conservation measure implemented in the same system. Because relevant relationships for series and parallel connections, are the basic forms of all possible relationships, these cases are not just some examples, but they represent the interactive effects of energy conservation measures in general. The considerations are limited to two conservation measures; in section 5.8, their applications in cases with more measures will be discussed. The assumptions made in the derivations are:

- only the energy flows are considered
- all physical phenomena have the same kind of "driving force"

Further, in order to provide a reference base for the considerations, the resulting "product flow" ($\text{E}_{\text{out}}$) is kept constant.

In subsection 5.5.1, two kinds of energy conservation measures were distinguished:

- reducing the resistance to profitable energy flows (improving a "U-transfer phenomenon": $U$ for useful energy)
- increasing the resistance to useless energy flows (reducing an "L-transfer phenomenon": $L$ for energy lost)

Appendix VIII analyses all possible combinations of series and parallel connections of $U$- and $L$-transfer phenomena in their simplest forms. The results of that analysis can be summarized as follows:

For both, series and parallel connections of phenomena affected by energy conservation measures, three different kinds of interactive effects were found:

- Combinations of measures for which the interactive effects cause a proportional decrease of the energy savings functions. This proportionality can be illustrated as follows (measures $A$ and $B$):

$$\frac{\text{ES}_A(v_A) \text{after } B}{\text{ES}_A(v_A)} = 100$$


- Combinations of measures that have interchangeable effects. This means that:
  - the savings potentials (= the maximum savings that can be achieved) of both measures are equal, and, moreover, the savings potential of the combination of both measures is equal to that of each individual measure:

\[
\left[ ES_A(v_A) \right]_{\text{max}} - \left[ ES_B(v_B) \right]_{\text{max}} = \left[ ES_{A,B}(v_A,v_B) \right]_{\text{max}}
\]

- consequently, if one measure is implemented, the resulting decrease of the savings potential of the other one is equal to the savings achieved by the first one:

\[
\left[ ES_A(v_A) \right]_{\text{max}} = \left[ ES_A(v_A) \right]_{\text{max}} - ES_B(v_B)
\]

and:

\[
\left[ ES_B(v_B) \right]_{\text{max}} = \left[ ES_B(v_B) \right]_{\text{max}} - ES_A(v_A)
\]

Such combinations of measures will be called "interchangeable measures".

- Combinations of measures that have no interactive effects. In fact, such combinations can be considered as boundary cases of the group mentioned first.

5.5.4 Approach 2: Consideration on the basis of general equations

In section 5.3, an equation was presented (eq. 5.1) that applies generally to describe the energy savings of a conservation measure as a function of the characteristic variable. The approach discussed here derives the possible interactive effects from the terms that appear in that equation. Therefore, equation (5.1) is repeated here:

\[
ES(v) = \frac{d}{v^{-\gamma} + e}
\]

where: "v" is the dimensionless variable concerned and "d", "e" and "\gamma" are parameters. The values of these parameters describe the characteristics of the conservation measure as such. If one conservation measure is affected by another, this implies that the measure itself (the technical intervention) does not change in principle; only the effects change (the amount of energy conserved diminishes). This means that, in terms of the general equation (5.9), the influence of any measure implemented previously implies a change in one or more of the parameters "d", "e" and "\gamma". Parameter "\gamma" will not change, because it is an exponent of variable "v" and it is fully dependent upon the nature of the conservation measure. So, the only possibilities that remain are changes in the parameters "d" and/or "e".

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Because the changes in the energy savings of a certain measure due to other measures imply a decrease of the energy savings function of the variable "v", this can be represented in three ways:
- a decrease in parameter "d"
- an increase in parameter "e"
- a combination in changes of "d" and "e", so that the ratio of d/e reduces

In appendix VII, equations of the general form of eq. 5.1 have been derived for two examples: eqs. A.36 and A.41. These examples will be treated now in order to illustrate and check the above-mentioned possibilities. The first example concerns the case of thermal insulation, under the conditions mentioned in appendix VII:

\[
ES(\text{Ins}) = \frac{C_{\text{Ins}} * A_w * \omega_w^2 * (T_1 - T_s)}{\lambda_{\text{Ins}} * \omega_w + \omega_w} \tag{5.10}
\]

(The meaning of the symbols is given in appendix VII).

From eq. (5.10), it can be seen that the effect of this conservation measure can be changed by another measure, if that other measure causes a change in one of the following factors: \(C_{\text{Ins}}, A_w, \omega_w\) or \((\omega_w - T_s)\).

A change of \(C_{\text{Ins}}, A_w\) or \((\omega_w - T_s)\) is recognized as a change in the parameter "d" in eq. 5.9, as mentioned above. A change in \(\omega_w\) will cause a change in both the parameters "d" and "e", which was mentioned above as the third possibility.

The second example of a conservation measure, represented in a general form, is heat recovery, for which the assumptions and the resulting equation were given in appendix VII:

\[
ES(\text{Re}) = \frac{C_{\text{Re}} * (T_{\text{Lin}} - T_{2\text{in}})}{1/(\alpha * \text{he}) + 1/(m \cdot c_p)} \tag{5.11}
\]

It is evident that the effect of heat recovery will change if another measure causes a change in \(C_{\text{Re}}, (T_{\text{Lin}} - T_{2\text{in}}), m\) or \(c_p\). Translating these changes into terms of the general equation 5.9, we see that changes in \(C_{\text{Re}}\) and \((T_{\text{Lin}} - T_{2\text{in}})\) affect the numerator "d", and changes in \(m\) and \(c_p\) cause changes in the parameter "e" of the denominator.

These two examples show that each of the three possible effects of interaction can be found in practice.

Analysis:

Analysing these effects, it became evident that:
- A change of parameter "d" can be recognized as a proportional reduction of the energy savings function.
- There is one example of the possibility that only parameter "e" changes: factor \(m \cdot c_p\) in eq. 5.11. Further elaboration of this factor \(m \cdot c_p\) makes clear that, if a reduction in "m \cdot c_p" is also considered as a conservation measure, this measure is interchangeable with heat recovery. This can be seen if the
equation for the energy savings as a function of \( m \cdot c_p \) (\( m_o \cdot c_{po} \) \( \rightarrow \) \( m \cdot c_p \)) and \( a_{he}^* A_{he}^{*}, a_{he}^{*} A_{he}^{*} \) (\( A_{he}^{*} \rightarrow A_{he}^{*} \)) is derived:

\[
ES(a_{he}^* A_{he}^{*}, m^* c_p) = \frac{C_{he}^{*} (T_{lin} - T_{in})^2 m^2 c_p}{a_{he}^{*} A_{he}^{*} + m^* c_p}
\]

\[
* \left[ 1 + \frac{m^2 c_p \cdot (a_{he}^* A_{he}^{*}, m^* c_p) / (m^2 c_p \cdot (a_{he}^{*} A_{he}^{*} + m^* c_p)) - 1 \right]
\]

(5.12)

It is easy to see that the factor between brackets in this equation takes on the following values, depending on \( a_{he}^{*} A_{he}^{*} \) and \( m \cdot c_p \):

\[
\begin{align*}
&0 \quad \text{if} \quad a_{he}^{*} A_{he}^{*} = a_{he}^{*} A_{he}^{*} \\
&\text{and} \quad m \cdot c_p = m_0 \cdot c_{po} \\
&1 \quad \text{if} \quad a_{he}^{*} A_{he}^{*} = a_{he}^{*} A_{he}^{*} + m \cdot c_p = 0
\end{align*}
\]

The interchangeability of heat recovery and air use reduction (reduction of \( m \cdot c_p \)) can easily be understood from the fact that both measures have the same effect in principle: a reduction of the energy losses of the blue gases.

There is also one example of a change of both parameters "\( a_w \)" and "\( m \)" : factor \( a_{wo} \) in eq. 5.10. In order to gain an insight into this possibility, the consequences of changing \( a_{wo} \) (\( a_{wo} + a_{wo} \)) together with implementing thermal insulation will be studied now. Let us start with a heat transfer coefficient \( a_{wo} \) and an insulating layer of thickness \( l_{ins} \) in order to consider the effect of combining two conservation measures: \( a_{wo} \rightarrow a_{wo} + l_{ins} \) and \( l_{ins} \rightarrow 1_{ins} \). The energy savings achieved with this combination can be expressed as follows:

\[
ES(a_{wo}, l_{ins}) = \frac{C_{ins} A_w \cdot (T_{wo} - T_{b})}{(1/a_{wo} + 1/l_{ins})^2}
\]

\[
* \left[ 1 + \frac{1}{1/(1/a_{wo} + 1/l_{ins})} \frac{(1/l_{ins} - 1)}{1/(1/a_{wo} + 1/l_{ins})} \right]
\]

(5.13)

For common situations, with \( l_{ins} \rightarrow 0 \) this reduces to:

\[
ES(a_{wo}, l_{ins}) = \frac{C_{ins} A_w \cdot (T_{wo} - T_{b}) a_{wo}^2}{1/(1/a_{wo} + 1/l_{ins})} + a_{wo}
\]

(5.14)

From these equations it is evident that improving thermal

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insulation and reducing convection from the outer wall are two interchangeable measures; both measures have the same savings potential and if one of them is implemented, the resulting decrease of the savings potential of the other one is equal to the savings achieved by the first one. In fact, this is a practical example of fig. 4.5.c in Appendix VIII.

So we see that the approach of this sub-section shows two ways of interaction of conservation measures:
- proportional reduction of the energy savings function (change in parameter "d")
- interaction of interchangeable measures (change in "e" or in both "e" and "d"). In the examples treated here, these interactions appeared to concern interchangeable measures only.

5.5.5 Approach 3: Analysis of examples from the paper dryer case study

By means of the simulation model for the paper dryer described in Chapter 3, the interactive effects of conservation measures in that dryer can be calculated. This can be done by comparing the energy savings of individual conservation measures (figs. 3.27 to 3.32) with the savings calculated for combinations of measures.

With six conservation measures the number of possible combinations is very large of course, that is why only a few examples will be given here.

Results will be shown for the following combinations:
- reducing the air flow in the drying boxes after increasing the rotational speed of the air fans
- increasing the rotational speed of the fans after reducing the air flow
- increasing the rotational speed of the fans after insulating the boxes
- insulating the boxes after increasing the rotational speed of the fans
- recovering flue gas heat after increasing the number of drying boxes
- increasing the number of boxes after implementing heat recovery
- recovering flue gas heat after reducing the air flow through the drying boxes
- reducing the air flow after implementing heat recovery

For each of these cases, the results are presented in a figure as follows:
- a curve for the energy savings of the particular conservation measure in the original situation as a function of the related variable
- a curve for the savings of this measure implemented after the other measure, as a function of the same variable
- a curve indicating the ratio of these two curves of energy savings as a function of the same variable

The results for the above-mentioned eight cases are given in figures 5.4 to 5.11.
Fig. 5.4 Comparison of the energy savings of air use reduction before and after increasing the air fan rotation speed

Fig. 5.5 Comparison of the energy savings of air fan rotation speed increase before and after reducing the air use

Fig. 5.6 Comparison of the energy savings of air fan rotation speed increase before and after drying box insulation

Fig. 5.7 Comparison of the energy savings of thermal insulation before and after increasing the air fan rotation speed
Comparison of the energy savings of heat recovery before and after adding four drying boxes.

Fig. 5.8

Comparison of the energy savings of an increase of the number of drying boxes before and after introducing heat recovery.

Fig. 5.9

Comparison of the energy savings of heat recovery before and after air use reduction.

Fig. 5.10

Comparison of the energy savings of air use reduction before and after heat recovery.

Fig. 5.11
In these examples, the first six cases (figs. 5.4 to 5.9) show combinations in which the energy savings-curve for one measure implemented after another one is approximately proportional to the curve of the same measure when implemented first (deviations of 5 to 20%). However, the combination of heat recovery and air use reduction (figs. 5.10 and 5.11) is a quite different example. For this combination, no such regular behaviour is found. It appears to be even so that if a very small heat exchanger would be applied (which is not realistic however), the energy savings due to air use reduction after that heat recovery was implemented are bigger than in the case of air use reduction without heat recovery*).

It was found by simulation that the maximum energy savings for heat recovery (with a very large heat transfer surface area) are equal to the maximum energy savings that can be achieved by combining heat recovery and air use reduction (about 50% of the original specific energy use). This means that these measures are interchangeable; this conclusion is the same as the one derived analytically for these two measures in the preceding sub-section. Heat recovery and air use reduction are interchangeable although the savings potential of air use reduction is smaller than that of heat recovery. This is caused by the fact that the air use has a lower limit determined by the combustion process and the evaporation rate of water in the dryer.

The conclusion of the consideration of the examples from the case-study agrees with that of the other approaches: two ways of interaction are found, viz.:
- interactions causing a proportional decrease of the energy savings function.
- interactions of interchangeable conservation measures.

### 5.5.6 Evaluation

The results of the three approaches appear to be the same in principle: Two fundamentally different ways of interaction were found by each of the approaches, viz.:

* Interactions of which the effect on the current measure can be described as a proportional relationship between the function that represents the original energy savings of the measure and the function for the savings after that the other measure has been implemented. In terms of the general equation 5.9, this means that only parameter "d" in the numerator changes by implementing another measure first. Cases in which there are no interactive effects can be considered as boundary cases for this relationship. The proportional relationship is the form of interaction that

*)This phenomenon can be illustrated for the general case by means of eq. 5.9: Assume:
- original savings: \( ES_o(v) \), characterized by parameters \( d_o \) and \( e_o \)
- savings after another measure: \( ES(v) \) with parameters \( d \) and \( e \)

The phenomenon of fig. 5.10 implies that

\[
\lim_{v \to 0} \frac{d}{v} > \lim_{v \to 0} \frac{d}{v}
\]

It can be shown that this occurs if

\[
\frac{d}{e^2} > \frac{d}{e^2},
\]

which is not impossible in principle.
Interactions for which this proportional relationship does not hold; these combinations appear to consist of interchangeable measures. In terms of the general equation 5.9, this form of interaction means a change of parameter "a" (eq. 5.13) or both parameters "d" and "e" (eq. 5.10). The characteristics of these so-called interchangeable conservation measures are:

- The savings potential is equal for each individual measure; the savings potential of the two measures combined is equal to that of each individual measure.
- If one measure is implemented, the resulting decrease of the savings potential of the other one is equal to the savings achieved by the first one.

Now, it is evident that different forms of interactions among energy conservation measures must be distinguished, but the question arises whether these different forms of interaction occur arbitrarily or they are reversible. In Appendix XX this point was investigated; it was found that:

- if measure A, implemented before measure B, causes a proportional reduction of the energy savings function of measure B, then, in the reverse sequence, measure B causes a proportional reduction of the savings function of measure A.
- two interchangeable measures affect each others savings in the same way.

5.5.7 Conclusions

From the foregoing discussions of the interactive physical effects for energy saving, the following conclusions can be drawn:

- The energy flow in a production system can be studied by means of a network of physical phenomena that transfer either favourable or unfavourable energy flows. An energy conservation measure is aimed at affecting such a phenomenon (a network element): a favourable phenomenon is improved or an unfavourable phenomenon is reduced. The relationship between the different elements in such a network can be quite complicated, but it can be reduced always to two basic forms: series and parallel connections.
- The interactive effects of conservation measures were studied by considering two measures that are implemented into a system in different sequences.
- The possible forms of interaction between conservation measures can be divided into two groups in principle:

* Interactions between conservation measures with a proportional reduction in the energy savings over the whole range of possible values for the characteristic variable:

\[
\frac{ES_A(v_A)}{ES_A(v_A) \text{ after } B} \quad \text{is independent of } v_A \quad (5.15)
\]

Such a kind of interaction is always reversible which means that the following expression is a consequence of the preceding one:

\[
\frac{ES_B(v_B)}{ES_B(v_B) \text{ after } A} \quad \text{is independent of } v_B \quad (5.16)
\]
Combinations of interchangeable measures. Such combinations can be characterised as follows (e.g. measures A and B):

\[
\begin{align*}
\{&ES_A(v_A)\}_{\text{max}} = \{ES_B(v_B)\}_{\text{max}} - \{ES_{A,B}(v_A,v_B)\}_{\text{max}} \\
\{&ES_A(v_A)\}_{\text{after } B} = \{ES_A(v_A)\}_{\text{max}} - ES_B(v_B) \\
\{&ES_B(v_B)\}_{\text{after } A} = \{ES_B(v_B)\}_{\text{max}} - ES_A(v_A)
\end{align*}
\]

(5.17)  
(5.18)  
(5.19)

The energy savings for the combination of measures A and B can be expressed as follows:

\[
ES(v_A,v_B) = \frac{1}{fn(v_A,v_B) + e}
\]

(5.20)

with:

\[
fn(v_A,v_B) = \begin{cases} 
0 & \text{if } v_A = 0 \text{ and } v_B = 0 \\
\infty & \text{if } v_A = \pm \infty \text{ or } v_B = \pm \infty
\end{cases}
\]

5.6 FINANCIAL CONSEQUENCES OF THE INTERACTIVE EFFECTS OF ENERGY CONSERVATION MEASURES

In the preceding section, the interactive effects of different measures in one system were described with respect to their physical aspects, i.e. the effects on energy savings. As a result of a change of the energy savings, the economic aspects are affected too. These financial consequences will be discussed in this section.

5.6.1 Effects of a preceding conservation measure on the financial Results And Optimum Design

The energy savings from a conservation measure \(ES(v)\), as discussed in the preceding sections, represent the amount of energy that can be saved if the measure is installed in the existing installation. However, if another conservation measure is implemented first, a new situation occurs, with changed equipment, or at least changed process conditions. Due to this, if the measure under consideration is installed after the first measure, the savings will be smaller in comparison with the original savings \(ES(v)\). This was discussed in section 5.5.

It is evident that, due to the reduced energy savings, the optimum design (viz. the value of \(v_{\text{opt}}\), eq. 5.8) will change. This can be seen from fig. 5.12: The curve for the savings \(P_{E,ES(v)}\) in the left hand part of the figure will be lower and consequently the derivative of that curve in the right part will be lower. The curve for the expenses \(EXP(v)\) remains unchanged and so does the derivative of \(EXP(v)\) in fig. 5.12.*

Consequently, the point of intersection on this right side of the figure,

*) see footnote on next page
which determines the value of \( v_{opt} \), will move to the left. This means that the value of \( v_{opt} \) will diminish due to the conservation measure implemented previously: \( v_{opt} < v_{opt} \) (the equals sign applies to the boundary case in which the measures do not affect each other at all).

Fig. 5.13 indicates the differences between the results in the original situation and those in the case of implementation after another measure. From this figure, it is clear that when comparing the original and the new optimum, not only the energy (cost) savings \( p_e \cdot ES(v) \), but also the expenses \( EXP(v) \) reduce, yielding together a reduction in the net present value \( NPV(v) \). Further, it will become evident that this reduction in the net present value depends not only on the reduction of the energy savings due to the interactive effect of measures, but also, on the characteristics of the curve of the expenses related to the characteristics of the energy savings-curve.

\[
\text{Result of a conservation measure implemented in the original situation (full lines) and those of the same measure implemented after an other one (dotted lines)}
\]

*) In practice, there may be cases in which the expenses-function of conservation measures is lower if they are combined with certain other measures. Such measures will often be implemented together (e.g. "recycling of flue-gases" and "re-use of flue-gases from certain boxes" in Chapter 3); that is why such combinations are considered as one measure in the analysis of the interactive effects.
So, if two conservation measures A and B affect one another's savings, the reduction of NPV, caused by implementing measure B first can only be equal to the reduction of NPV caused by implementing measure A first, if the characteristics (i.e., the savings- and the expenses curves) are the same for both measures or in other exceptional cases. In general, the ultimate results of the combined measures A and B will depend on the sequence in which they are implemented.

This also means that when conservation measures are implemented one at a time (or at least, not all at once), there will be one sequence of measures that will lead to the best project results. This optimum sequence will be investigated in general terms in section 5.7.

In fig. 5.13, which is basically the same as the left part of fig. 5.12, the terms from which the reduction (\(\Delta\text{NPV}\)) of the net present value is built up are indicated:

\[
\Delta\text{NPV} = DS + p_e \cdot AES' - \Delta\text{EXP} \tag{5.21}
\]

in which:

- \(\Delta\text{NPV}\) = reduction of the net present value due to previously introducing another conservation measure

- \(DS\) = decrease in the energy cost savings \(p_e \cdot ES(v)\) at point \(v_{\text{opt}}\)

- \(p_e \cdot AES'\) = additional decrease of the energy cost savings due to the fact that the optimum point moves from \(v_{\text{opt}}\) to \(v'\)

- \(\Delta\text{EXP}\) = decrease in the (dependent) expenses

When a combination of two measures is considered, it can be understood easily that the decrease in savings \(DS\) will be equal for both measures (in both possible sequences): if the second measure should be realised with the same value of \(v\) as the case when it is implemented first \((v_{\text{opt}})\), both sequences A-B and B-A result in exactly the same ultimate situation, and the same energy use. This means that:

\[
p_e \cdot ES_A + (p_e \cdot ES_B - DS_B) = p_e \cdot ES_B + (p_e \cdot ES_A - DS_A) \tag{5.22}
\]

In this equation we see left from the equals sign the total savings of sequence A-B and right from if those of sequence B-A.

From eq. (5.22) it follows that:

\[
DS_A = DS_B = DS \quad \tag{5.23}
\]

This equation, combined with eq. 5.21, shows that the difference between \(\Delta\text{NPV}_A\) and \(\Delta\text{NPV}_B\) is entirely due to the difference between \((\Delta\text{EXP} - p_e \cdot AES')_A\) and \((\Delta\text{EXP} - p_e \cdot AES')_B\). This means that the optimum sequence for introducing two conservation measures can be found by comparing the values of their term \(\text{EXP} - p_e \cdot ES'\) : The measure with the lowest value for this expression has

\[\]
Fig 5.13 Graphic illustration of the terms that determine the reduction $\Delta NPV$ of the net present value.
to be introduced first in order to obtain the highest ultimate net present value for the combination of measures.

It must be realised, however, that the maximum net present value mentioned here is limited by the fact that we started from the assumption that conservation measures will be implemented one at a time, and optimization will take place under the conditions that are present at the moment of implementation. In general, this means that the best result that can be obtained from this step-by-step procedure, is no more than an approximation of the theoretical maximum of the net present value. This fact is illustrated in fig. 5.14 for the simple case of two measures A and B, characterised by the variables $v_A$ and $v_B$.

From this figure it is evident that the ultimate results of conservation measures, if implemented one at a time are inferior in general, to those of simultaneously implemented (and optimised) measures. Still, the consequences of stepwise implementation are analysed here, for the following reasons:

- that analysis gives a clear insight into the way in which conservation measures affect each other and each others results.

- in practice, determining the theoretical optimum requires a lot of knowledge and information (condensed in a model) of the system. Very often such a model is not available and for many systems developing it is not feasible. Step-by-step optimization and implementation is the only possibility then. In fact, this is a question of optimizing the amount of "information" of the system to be acquired.

- the results of this analysis can be made useful for cases in which no stepwise procedure is used (see section 5.8)
5.6.2 Consequences for the priorities for measures

5.6.2.1 Combinations causing a proportional decrease -

The Energy Savings

In section 5.3, general equations were given for the energy savings and for the expenses of conservation measures: eqs. 5.1 and 5.4. Based upon these equations, in this subsection, expressions will be derived for the term \( \Delta \text{EXP} - p_e \Delta ES' \), for the case where the energy savings-function, after being affected by another measure, is proportional to the original one. This term was mentioned in the preceding sub-section as the term that determines the priorities for the conservation measures in one system: the measure with the lowest value of \( \Delta \text{EXP} - p_e \Delta ES' \) has the highest priority. From the preceding sub-section (e.g. fig. 5.13), it is evident that the term: independent expenses "f" in eq. 5.4, has no effect on the differences that result from different conservation measure sequences. That is why the independent expenses are left out of consideration here; only the \( v \)-dependent expenses will be considered:

\[
\text{EXP}_d \text{ep}(v) = \text{EXP}(v) - f - g \cdot v^3
\]  

(5.24)

Now, by combining eqs. 5.1 and 5.24, the dependent expenses \( \text{EXP}_d \text{ep} \) can be expressed as a function of the energy savings \( ES \); or, what will prove to be more useful, as a function of the energy cost savings \( p_e \cdot ES \):

\[
\text{EXP}_d \text{ep}(p_e \cdot ES) = g \cdot \left[ \frac{p_e \cdot \Delta ES'}{p_e \cdot \Delta ES} \right]^{9/4} \left[ 1 - \frac{p_e \cdot \Delta ES'}{p_e \cdot \Delta ES} \right]^{-3/4}
\]  

(5.25)

An example of this function is presented in fig. 5.15, (the full line); this figure also shows the same curve for the case when another measure is introduced previously: the \( \text{EXP}'_d \text{ep} \)-curve (the dotted line). Further, the dimensions \( DS, p_e \cdot \Delta ES' \) and \( \Delta \text{EXP} \) are indicated. With respect to the curves presented in fig. 5.15, the following general remarks can be made:

- The optimum point in the original situation, (viz. before the other measures have been implemented), is point \( P \) on the \( \text{EXP}_d \text{ep} \)-curve. This optimum (maximum NPV) is defined by eqs. 5.7 and 5.8 and they can be transformed into:

\[
\left. \frac{\partial \text{EXP}_d \text{ep}}{\partial (p_e \cdot ES)} \right|_P = 1
\]  

(5.26)

The same thing applies to the optimum point \( R \) on the \( \text{EXP}_d \text{ep}' \)-curve:

\[
\left. \frac{\partial \text{EXP}_d \text{ep}'}{\partial (p_e \cdot ES)} \right|_R = 1
\]  

(5.27)
The \( \text{EXP}_{\text{dep}} \) curve is derived from the \( \text{EXP}_{\text{dep}} \) curve on the basis of the proportional relationship between the energy savings of a certain measure before and after another measure is implemented. Because, in Fig. 5.15, the horizontal distance between the two curves at point P (distance \( Q-P \)) has been denoted as DS (see Fig. 5.13), the relativity factor is:

\[
\frac{p_e \cdot \text{ES}_Q}{p_e \cdot \text{ES}_P} = \frac{p_e \cdot \text{ES}_Q - \text{DS}}{p_e \cdot \text{ES}_P} = 1 - \frac{\text{DS}}{p_e \cdot \text{ES}_P} \tag{5.28}
\]

This factor is constant over the whole \( p_e \cdot \text{ES} \)-range for that measure. So, for instance, this means that:

\[
p_e \cdot \text{ES}_R = (1 - \frac{\text{DS}}{p_e \cdot \text{ES}_P}) \times p_e \cdot \text{ES}_S \tag{5.29}
\]

The distance \( p_e \cdot \Delta \text{ES} \) which was indicated in Fig. 5.13 can be found back here as:

\[
p_e \cdot \text{ES}_Q - p_e \cdot \text{ES}_R = p_e \cdot \Delta \text{ES}' \tag{5.30}
\]

It can easily be seen that due to the above-mentioned proportional relationship between the curves of \( \text{EXP}_{\text{dep}} \) and \( \text{EXP}_{\text{dep}}' \), the same ratio applies to the first derivatives of these curves.
This implies that:

$$\frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES_p)} = \frac{p_e \cdot ES_p}{p_e \cdot ES_p - DS} \frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)}$$

(5.31)

and

$$\frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)} = \frac{p_e \cdot ES_p}{p_e \cdot ES_p - DS} \frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)}$$

(5.32)

Combining eq. 5.31 with eq. 5.26 and eq. 5.32 with eq. 5.27 leads to:

$$\frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)} = \frac{p_e \cdot ES_p}{p_e \cdot ES_p - DS}$$

(5.33)

and:

$$\frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)} = 1 - \frac{DS}{p_e \cdot ES_p}$$

(5.34)

Based upon eqs. 5.25 to 5.34 an expression has to be derived for $(\Delta \text{EXP}_e - \Delta \text{ES}_p)$. From fig. 5.15 it is evident that

$$\Delta \text{EXP}_{\text{dep}} = |\text{EXP}_{\text{dep}}|_p - |\text{EXP}_{\text{dep}}|_S$$

(5.35)

In order to work out this equation with help of eqs. 5.25, 5.26 and 5.34, we first form the general expression for the derivative of the $\text{EXP}_{\text{dep}}$-curve, on the basis of eq. 5.25:

$$\frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)} = \frac{p_e \cdot ES_p}{(p_e \cdot ES_p - DS)} \frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)}$$

(5.36)

By combining eqs. 5.25 and 5.36, $\text{EXP}_{\text{dep}}(p_e \cdot ES)$ can be written as a function of its derivative:

$$\Delta \text{EXP}_{\text{dep}}(p_e \cdot ES) = \frac{\gamma}{\beta} \cdot p_e \cdot ES \cdot (1 - \frac{e}{p_e \cdot ES_p}) \cdot \frac{\Delta \text{EXP}_{\text{dep}}}{\Delta (p_e \cdot ES)}$$

(5.37)

Substituting eq. 5.26 in eq. 5.37 yields:

$$|\text{EXP}_{\text{dep}}|_p = \frac{\gamma}{\beta} \cdot p_e \cdot ES_p \cdot (1 - \frac{e}{p_e \cdot ES_p})$$

(5.38)

For point $S$, the following expression results from substituting eq. 5.34 in eq. 5.37:

$$|\text{EXP}_{\text{dep}}|_S = \frac{\gamma}{\beta} \cdot p_e \cdot ES_s \cdot (1 - \frac{e}{p_e \cdot ES_p}) \cdot (1 - \frac{DS}{p_e \cdot ES_p})$$

(5.39)

In this equation the factor $p_e \cdot ES$ has to be expressed in terms of $p_e \cdot ES_p$, $DS$ en $p_e \cdot \Delta \text{ES}$. From the ratio expressed by the factor (5.28) it follows that:

$$p_e \cdot ES = (1 - \frac{DS}{p_e \cdot ES_p}) \cdot p_e \cdot ES_p$$

(5.40)
which can be transformed into:

\[ p_e \cdot ES_p - DS - p_e \cdot \Delta ES' = (1 - \frac{DS}{p_e \cdot ES_p}) \ast p_e \cdot ES_S \]  (5.41)

Now, eq. 5.41 can be substituted in eq. 5.39; next eqs. 5.38 and 5.39 can be substituted in eq. 5.35. After some rearranging etc., this leads to:

\[ \Delta EXP_{dep} = \frac{\gamma}{\beta} \ast DS \ast (1 - \frac{\Delta EXP\cdot dep \cdot p_e \cdot ES_p}{p_e \cdot ES_p} + \frac{\Delta EXP\cdot dep \cdot p_e \cdot ES_p}{p_e \cdot ES_p} - DS) \]  (5.42)

In fact, this equation expresses \( \Delta EXP \) as a function of \( p_e \cdot \Delta ES' \). Another relationship between these two factors is required too. That relationship can be obtained from the available information on the value of the derivative of the \( EXP_{dep} \)-curve at points Q and R; eqs. 5.27 and 5.33. If we assume the derivative of the \( EXP_{dep} \)-curve to be linear between points Q and R (which is only an approximation), then it is evident that the approximate average value of the derivative at this section is:

\[ \Delta EXP_{dep} \bigg|_{Q-R, app} = 0.5 \ast \left( \frac{\Delta EXP_{dep} \bigg|_{Q} + \Delta EXP_{dep} \bigg|_{R}}{\Delta EXP_{dep} \bigg|_{P_e \cdot \Delta ES'}} \right) \]  (5.43)

On the other hand, it is evident from fig. 5.15 that this average value can also be written as:

\[ \frac{\Delta EXP_{dep} \bigg|_{Q-R}}{\Delta EXP_{dep} \bigg|_{P_e \cdot \Delta ES'}} = \frac{\Delta EXP_{dep}}{p_e \cdot \Delta ES'} \]  (5.44)

Substituting eqs. 5.27 and 5.33 in eq. 5.43, and combining this equation with eq. 5.44 gives:

\[ p_e \cdot \Delta ES_{app} = 2 \ast \left( \frac{p_e \cdot ES_p - DS}{2 \ast p_e \cdot ES_p - DS} \right) \ast \Delta EXP_{dep} \]  (5.45)

Eq. 5.45 combined with eq. 5.42 can be converted into the following expression:

\[ \{ \Delta EXP - p_e \cdot \Delta ES' \}_\text{app} = \left( \frac{\gamma}{\beta} \ast DS \ast (1 - \frac{\Delta EXP_{dep} \cdot p_e \cdot ES_p}{p_e \cdot ES_p}) \ast (1 - \frac{\Delta EXP_{dep} \cdot p_e \cdot ES_p}{p_e \cdot ES_p}) \right) \]  (5.46)

With this equation, we have an expression for approximating the term \( (\Delta EXP \cdot p_e \cdot \Delta ES') \) (with which the priorities of energy conservation measures are determined) as a function of only the data related to the measure itself, except for the decrease of savings DS. Although eq. 5.46 is an implicit function, it will prove to be useful in section 5.7. Recall that one approximation was made: eq. 5.43. The consequences of this approximation will be analysed numerically in subsection 5.7.4.
5.6.2.2 *Combinations of interchangeable measures*

From sub-section 5.6.1 it is evident that the term \( \Delta_{\text{exp}} - p_A \Delta_{\text{ES}} \) determines the priority for the measures: the measure with the lowest value for this term has the highest priority.

In the preceding sub-section, an expression for this term as a function of DS (eq. 5.46) was derived analytically, for combinations of measures for which the interactive effects cause a proportional decrease of the energy savings. The analytical derivation was feasible due to the fact that the basic equations (eqs. 5.29, 5.32 and 5.34) were very simple.

For combinations of interchangeable measures, the relationships are much more complicated. The basic equations for analyzing the above term are the expressions for describing the energy savings of a conservation measure implemented after another one, as a function of the decrease in savings DS. These expressions are derived as follows:

Two arbitrary measures A and B, with the only restriction that their effects are interchangeable, are considered now by means of their equations for the energy savings, according to the general equation 5.1:

\[
\begin{align*}
\text{ES}_A &= \frac{d_A}{-\gamma_A + \epsilon_A} \\
\text{ES}_B &= \frac{d_B}{-\gamma_B + \epsilon_B}
\end{align*}
\]

The fact that \( \text{ES}_{A,\text{max}} = \text{ES}_{B,\text{max}} \) implies that \( \frac{d_A}{\epsilon_A} = \frac{d_B}{\epsilon_B} \).

With respect to the effects of interactions between measures it was previously seen that the exponents \( \gamma_A \) and \( \gamma_B \) remain unchanged because they depend only on the nature of the conservation measure.

**Measure A implemented after B**

For the original conditions of measure A (measure A implemented first), the savings are given by:

\[
\text{ES}_A(v_{A0}) = \frac{d_{A0}}{-\gamma_A + \epsilon_{A0}}
\]

Assume a decrease of the energy savings of measure A — due to measure B — by DS (see fig. 5.13). Parameters \( d_{A0} \) and \( \epsilon_{A0} \) change to \( d_A \) and \( \epsilon_A \). So:

\[
\text{ES}_A(v_{A0}) \text{ after } B = \text{ES}_A(v_{A0}) - \text{DS}
\]

or:

\[
\frac{d_A}{-\gamma_A + \epsilon_A} = \frac{d_{A0}}{-\gamma_A + \epsilon_{A0}} - \text{DS}
\]

By implementing measure B before A, the savings potential of measure A is reduced by an amount equal to \( \text{ES}_B(v_{B0}) \):

\[
\{\text{ES}_A(v_A) \text{ after } B\}_{\text{max}} = \{\text{ES}_A(v_A)\}_{\text{max}} - \text{ES}_B(v_{B0})
\]

or:

\[
\frac{d_A}{\epsilon_A} = \frac{d_{A0}}{\epsilon_{A0}} - \text{ES}_B(v_{B0}) - 118
\]
From eqs. 5.51 and 5.53 the following expressions can be derived for determining parameters \( d \) and \( e \):

\[
e_A = \frac{(e_A - d_A/ES_A(v_A)) \times (ES_A(v_A) - DS)}{ES_A(v_A) + ES_B(v_{A0}) - DS - d_A/e_A} \tag{5.54}
\]

\[
d_A = \frac{d_A}{e_A} \times (ES_A(v_{A0}) - DS) \tag{5.54}
\]

By means of these equations, the energy savings function of \( ES_A(v_A) \) can be written as a function of the original conditions - \( d_{A0}, e_{A0}, ES_A(v_{A0}), ES_B(v_{B0}) \) - and DS.

**Measure B implemented after A:**

For the case that measure B is implemented first, a similar derivation can be given, which leads to the following expressions:

\[
e_B = \frac{(e_B - d_B/ES_B(v_{B0})) \times (ES_B(v_{B0}) - DS)}{ES_B(v_{B0}) + ES_A(v_{A0}) - DS - d_A/e_A} \tag{5.56}
\]

\[
d_B = \frac{d_A}{e_A} \times (ES_A(v_{A0}) - DS) \tag{5.57}
\]

With expressions 5.56 and 5.57, \( ES_B(v_v) \) after A can be written as a function of the original conditions - \( d_{B0}, e_{B0}, ES_A(v_{A0}) \) and \( ES_B(v_{B0}) \) - and DS.

Based upon eqs. 5.54 to 5.57, the differences between the ultimate results of sequences A-B and B-A (given by the terms \( \Delta EXP - p_A, \Delta ES^v \) and \( \Delta EXP - p_B, \Delta ES^v \) ) can be determined as a function of DS. However, due to the complexity of the above expressions, a useful analytical expression for these terms cannot be derived. That is why the analysis of the differences between different sequences will be performed numerically (sub-sections 5.7.2 and 5.7.4).

### 5.7 PRIORITY CRITERION FOR ENERGY CONSERVATION MEASURES

#### 5.7.1 Aim of a priority criterion

In energy conservation projects in which conservation measures are realised one at a time, decisions have to be made with respect to the priority of each of the available measures. In principle, simulation of each of the possible combinations and sequences is the only "precise" basis for decision-making. However, there are some very big obstacles to applying this in practice:

- Firstly, there is no simulation model available for most production systems in industry and developing such a model (however desirable, see Chapters 2 and 3) requires so much time, money and knowledge that many companies will not even consider this possibility.

- Secondly, in the case that a simulation model is available (or will be developed), considering all possible combinations and sequences is hardly possible, except for simple systems with limited numbers of measures.
In the light of these points, it is evident that a criterion for decision-making is needed that is easier to apply. In order to make it useful in practice, the following conditions should be satisfied by such a criterion:

- The information required for using it in a practical case should be limited to the data (savings, expenses, etc.) of the individual conservation measures. In fact, this is the information that is required for any decision.
- In general, when decisions are made on the basis of limited information, the resulting solutions will be no more than approximations of the intended optimum solution. With respect to this, the second condition can be formulated: the solutions resulting from this criterion should be a "close" approximation of the (theoretical) optimum.

So the aim of the intended decision criterion is to determine the optimal sequence of conservation measures on the basis of only the information of the individual measures, so that computing or simulating the effects of combined measures will not be necessary. Such a criterion is derived and checked in the next subsections. General remarks and discussions on the application of this criterion will be given in section 5.8.

5.7.2 Difference between the results of different sequences of measures

As A Function Of The Intensity Of The Interaction

In sub-section 5.6.2, equations were derived for calculating the difference between the (financial) results of different sequences of two measures. These expressions are all functions of the decrease of energy savings (DS) which indicates, in fact, the intensity of the interaction.

Because, for the general case, no indications with respect to the value of DS can be obtained from the data of the individual measures, the intended priority criterion cannot be based on the value of DS. Therefore, the limitations to possible (or relevant) values of DS and their effects on the results of different sequences of measures will be investigated in this sub-section. These investigations will be performed numerically, on the basis of the equations derived in sub-section 5.6.2. When applying these equations, an important point is the fact that the value of DS is the same for both measures (see sub-section 5.6.1).

Combinations of measures with proportional interactive effects

Firstly, an insight into the range of possible DS-values for a certain situation has to be obtained. The lower boundary of this DS-range is evident: \( DS=0 \). This lower boundary represents the case that the two measures have no effect upon each other savings. The upper boundary of the range for relevant DS-values can be found on the basis of eq. 5.34: DS has its maximum when \( S \) (fig. 5.15) is the point where

\[
\frac{d\text{EXP}}{d(p_{e}\cdot\text{ES})}\]

has its minimum. This way, a maximum value of DS can be found with respect to each of the two measures:

\[
DS_{A,\text{max \, pr}} = \left[ p_{e}\cdot\text{ES}_A \cdot \{(1 - \frac{d\text{EXP}}{d(p_{e}\cdot\text{ES}_A)})_{\text{min}}\} \right]
\]

\[
DS_{B,\text{max \, pr}} = \left[ p_{e}\cdot\text{ES}_B \cdot \{(1 - \frac{d\text{EXP}}{d(p_{e}\cdot\text{ES}_B)})_{\text{min}}\} \right]
\]
Now, it will be evident that the maximum value of DS for the combination of these two measures is:

\[ DS_{\text{max}} \text{pr} = \min \left( DS_{A, \text{max}}, DS_{B, \text{max}} \right) \]  

(5.60)

For combinations of measures for which the interactive effects cause a proportional decrease of the energy savings, eq. 5.46 gives an approximating expression for the term \((\Delta X - p_e \cdot \Delta E)\) which determines the difference between the results of different sequences of measures. So, this difference can be found by comparing the values of this term for the two measures. This comparison can be made by determining the difference between the two terms, but another possibility, which will prove to be more attractive here, is comparing them by determining their ratio. It has been illustrated before that the term \((\Delta X - p_e \cdot \Delta E)\) is always positive (fig. 5.12) and it is evident that the break-even point for the comparison will be where the above-mentioned ratio equals unity. Considering the ratio of eq. 5.46 for two conservation measures, the factor DS can be eliminated from the numerator, because it is the same for both measures. So the ratio becomes:

\[
\left( \frac{\Delta X - p_e \cdot \Delta E'}{\Delta X - p_e \cdot \Delta E} \right)_{A} \frac{(Y/B)^*(1-(\sigma/(p_e d)) \cdot p_e \cdot ES_p)}{(2p_e \cdot ES_p / DS - 1)^* \left[ 1 - \frac{Y}{B} \left( 1 - \frac{DS}{2p_e \cdot ES_p - DS} \right) \left( 1 - 2 \cdot e \cdot p_e d \cdot p_e \cdot ES_p \cdot \left( 1 - \frac{\Delta X - p_e \cdot \Delta E'}{\Delta X - p_e \cdot \Delta E} \right) \right) \right]} A
\]

\[
\left( \frac{\Delta X - p_e \cdot \Delta E'}{\Delta X - p_e \cdot \Delta E} \right)_{B} \frac{(Y/B)^*(1-(\sigma/(p_e d)) \cdot p_e \cdot ES_p)}{(2p_e \cdot ES_p / DS - 1)^* \left[ 1 - \frac{Y}{B} \left( 1 - \frac{DS}{2p_e \cdot ES_p - DS} \right) \left( 1 - 2 \cdot e \cdot p_e d \cdot p_e \cdot ES_p \cdot \left( 1 - \frac{\Delta X - p_e \cdot \Delta E'}{\Delta X - p_e \cdot \Delta E} \right) \right) \right]} B
\]

(5.61)

The value of this ratio (5.61) is less sensitive to changes in DS than the individual expressions for the term \((\Delta X - p_e \cdot \Delta E')\). It can be derived that this ratio is determined from DS and only five complex parameters:

\[ \frac{Y_A}{\beta_A}, \frac{Y_B}{\beta_B}, \frac{e_A}{d_A} \cdot ES_{P,A}, \frac{e_B}{d_B} \cdot ES_{P,B}, \frac{ES_{P,A}}{ES_{P,B}} \]

In principle, the following ranges are possible for these parameters:

- For \( \frac{Y_A}{\beta_A} \) and \( \frac{Y_B}{\beta_B} \): 0 < \( \frac{Y}{B} \) < \( \infty \)
- For \( \frac{e_A}{d_A} \cdot ES_{P,A} \) and \( \frac{e_B}{d_B} \cdot ES_{P,B} \): 0 < \( \frac{e}{d} \cdot ES_p < 1 \)
- For \( ES_{P,A}/ES_{P,B} \): 0 < \( ES_{P,A}/ES_{P,B} < 1 \)
- For DS: 0 < DS < DS_{\text{max}}

The parameters \( \beta \) and \( \gamma \) are both positive and, further, \( \beta < 1 \) (see eqs. 5.1 and 5.4).

The complex parameter \( e/d \cdot ES_p \) can be written as \( ES_p/ES_{\text{max}} \), too, from which it is evident that 0 < \( ES_p/ES_{\text{max}} < 1 \).
Curves 1-5 represent the following combinations of parameters:

<table>
<thead>
<tr>
<th>Curve</th>
<th>$\text{ESP}_{\text{A}}$</th>
<th>$\frac{\gamma_A}{\beta_A}$</th>
<th>$\frac{\gamma_B}{\beta_B}$</th>
<th>$\frac{e_A}{d_A}$</th>
<th>$\frac{e_B}{d_B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
<td>1.1</td>
<td>1.1</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
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<td>1.1</td>
<td>2.0</td>
<td>0.4</td>
<td>0.8</td>
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<td>1.4</td>
<td>1.1</td>
<td>2.0</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>1.1</td>
<td>2.0</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Some examples of the curve of the ratio (5.62) as a function of $DS$ for measures with proportional interactive effects.
From the above ranges of parameter values, some examples were taken for which the ratio:

$$\frac{\left[ \Delta \text{EXP} - P_e \cdot \Delta \text{ES}' \right]_A}{\left[ \Delta \text{EXP} - P_e \cdot \Delta \text{ES}' \right]_B}$$

was calculated as a function of DS. The results are presented in fig. 5.16. There is a small difference between the ratios 5.61 and 5.62: the last one represents the exact value while the first one is an approximation (based upon eq. 5.43). The results presented in fig. 5.16 were determined numerically from eqs. 5.25 to 5.39. Because the only thing needed for the question of giving the priorities to the conservation measures is whether the ratio (5.66) is smaller or greater than unity, it is evident from fig. 5.16 that the answer to this question is almost independent of the value of DS.

**Combinations of interchangeable measures**

For interchangeable measures, the range of possible DS-values is not limited to the value of DS$_{\text{max}}$ pr in eq. 5.64, in principle. The only explicit limitation is:

$$\text{DS}_{\text{max}} \text{ic} = \min \left[ \text{ES}_A(v_{A0}), \text{ES}_B(v_{B0}) \right]$$

(5.63)

However, there may be other, implicit limitations to DS, due to certain combinations of parameter values.

The interactive effects of interchangeable measures are described by equations that are quite different from those for measures with proportional effects (sub-section 5.6.2.2 vs. 5.6.2.1). However, there is a link between these two groups, which can be found as follows:

Consider conservation measures A and B. Measure B, if implemented first, will cause a reduction DS of the energy savings of A. For the case that measures A and B have proportional interactive effects, the value of DS determines the savings function of measure A implemented after measure B (see fig. 5.17):

$$\text{ES}_A(v)_{A \text{ after } B} = \frac{\text{ES}_A(v_{A0}) - \text{DS}}{\text{ES}_A(v_{A0})} \cdot \text{ES}_A(v)$$

(5.64)

This implies that the energy savings potential of measure A has reduced from

$$\text{ES}_A(v)_{A \text{ max}} \text{ to } \frac{\text{ES}_A(v_{A0}) - \text{DS}}{\text{ES}_A(v_{A0})} \cdot \text{ES}_A(v)_{A \text{ max}}$$

So, the reduction of the savings potential of measure A is:

$$\text{DS} = \frac{\text{ES}_A(v_{A0}) \cdot \text{ES}_A(v_{A0})}{\text{ES}_A(v_{A0}) \cdot \text{ES}_A(v_{A0})} \cdot \text{ES}_A(v_{A0}) = \text{ES}_B(v_{B0})$$

(5.65)

If, in another case, measures A and B would be interchangeable, this would imply that the reduction of the savings potential of measure A equals ES$_B(v_{B0})$, sec eq. 5.18; this is indicated in fig. 5.17. It means that if we take into account expression (5.65), we see that there is a value of DS for which two interchangeable measures have proportional interactive effects, to wit, if:

$$\text{DS} = \frac{\text{ES}_A(v_{A0}) \cdot \text{ES}_B(v_{B0})}{\text{ES}_A(v_{A0}) \cdot \text{ES}_A(v_{A0})} \cdot \text{ES}_A(v_{A0}) = \text{ES}_B(v_{B0})$$

or:

$$\text{DS} = \frac{\text{ES}_A(v_{A0}) \cdot \text{ES}_B(v_{B0})}{\text{ES}_A(v_{A0}) \cdot \text{ES}_A(v_{A0})} = \frac{\text{ES}_A(v_{A0}) \cdot \text{ES}_B(v_{B0})}{\text{ES}_A(v_{A0}) \cdot \text{ES}_A(v_{A0})}$$

(5.66)
Changed energy savings curves for different values of DS for:

- proportional interactive effects (upper figure)
- interchangeable measures (lower figure)
So, for that value of DS, the characteristics of measures with proportional interactive effects apply to the case of interchangeable measures too. Now, it is interesting to study the behaviour of interchangeable measures with different values of DS. Therefore, the value of the ratio (5.62) is calculated for some examples of interchangeable measures, over the range 0 < DS < \( \text{DS}_{\text{max}} \). These results are presented in fig. 5.18. The parameter-values used here are different from those in fig. 5.16, because most combinations of fig. 5.16 are irrelevant in the case of interchangeable measures. This figure also shows the curves for the case that the same measures would have proportional interactive effects (dashed lines). The point of intersection of these curves with the related curves for interchangeable measures are found at the value of DS given by eq. 5.66. It can be seen from this figure that, for parameter combinations for which the ratio for proportional interaction is greater than unity, it is also greater than unity in the main part of the DS-range for interchangeable measures. On the other hand, if the ratio is smaller than unity for proportional interaction, it is smaller than unity for interchangeable measures too, in the main part of the DS-range. At a small value of DS this no longer holds. With respect to that area, it is noticed that there, with small values of DS, we deal with a ratio of two small numbers; this implies that the difference between these two terms (which is, in fact, the difference between the results of different sequences) is relatively small.

Conclusion

It is evident (from e.g. eq. 5.46) that the absolute value of the difference between the results of different sequences for implementing two conservation measures is sensitive to changes in DS. However, from this sub-section it can be concluded that the problem of the unknown value of DS can pretty well be eliminated by taking the ratio of the terms that determine the priorities for measures (ratio 5.62). It was found that the answer to the question whether this ratio is smaller or greater than unity is hardly sensitive to DS, for both forms of interaction.

5.7.3 Derivation of a criterion for decisions on the priorities for Measures

It is evident from the conclusion of the preceding sub-section that a priority criterion can be based upon the ratio (5.62), determined for a relevant value of DS. An approximating expression for this ratio was given by (5.61). The value of the ratio (5.61) at the lower boundary of the DS-range can be found by determining the limit for DS \( \rightarrow 0 \):
Curves 6-10 represent the following combinations of parameters:

<table>
<thead>
<tr>
<th>curve</th>
<th>$\frac{ES_{PA}}{ES_{PB}}$</th>
<th>$\frac{\gamma_A}{\beta_A}$</th>
<th>$\frac{\gamma_B}{\beta_B}$</th>
<th>$\frac{e_A}{d_A}$</th>
<th>$e_B$</th>
<th>$ES_{PA}$</th>
<th>$ES_{PB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.15</td>
<td>0.5</td>
<td>1.0</td>
<td>0.05</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
<td>0.7</td>
<td>1.0</td>
<td>0.31</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
<td>0.44</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.19</td>
<td>0.7</td>
<td>0.7</td>
<td>0.56</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6.7</td>
<td>1.3</td>
<td>0.7</td>
<td>0.82</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Some examples of the curve for the ratio $(5.62)$ as a function of $DS$ for interchangeable measures (full lines) and measures with proportional effects (dashed lines).
Because eq. 5.43, which is the underlying approximation that was used in eq. 5.61, is exact for the point DS=0, the value of the limit of eq. 5.67 is exact too. From eq. 5.67, it can be seen that only data for the individual measures is required for determining this ratio: in fact it is a ratio of two expressions, each of which is characteristic of one conservation measure.

The only thing needed for giving the priorities to the conservation measures is whether this ratio is smaller or greater than unity; consequently, the limiting value of the ratio - eq. 5.67 - offers a pretty good indication of the real priorities for the main part of the DS-range (see figures 5.16 and 5.18). It is evident from these figures that there will be a certain "transition zone"; an area in which the value of the ratio moves from smaller to greater than unity, or conversely, depending on the value of DS. However, this happens only in a very limited number of cases; moreover, in such cases, the deviations from the results for the optimum sequence will be relatively small, because the ratio is very close to unity then. So, these effects can be considered as a certain "inaccuracy" when using the ratio (5.67) as a decision criterion with respect to the priorities for energy conservation measures. Its accuracy will be treated numerically in the next subsection.

The ratio (5.67) is easily applied as a decision criterion because it requires only the data of the individual measures, as was mentioned before.

For each of the two measures, the value of the following expression has to be determined:

\[
\frac{\frac{\gamma}{\delta}(1 - \frac{\alpha}{d} \times ES_p)}{1 - \frac{\gamma}{\delta} \times (1 - 2 \times \frac{\alpha}{d} \times ES_p) \times ES_p}
\]

(5.68)

Using eq. 5.38 this can be written as:

\[
\frac{\exp_{dep,P}}{p_e \times ES_p \times \left[1 - 2 \times \frac{\exp_{dep,P}}{p_e \times ES_p} + \frac{\exp_{dep,P}}{p_e \times ES_p \times (1 - (e/d) \times ES_p)}\right] \times ES_p}
\]

(5.69)

Considering the fact that the energy price \( p_e \) is the same for both measures, and further that \( d/e = ES_{\text{max}} \) (the maximum value of ES, which is reached if \( v = o \)), this expression can be replaced by:

\[
\frac{\exp_{dep,P}}{(p_e \times ES_p)^2 \times \left[1 - 2 \times \frac{\exp_{dep,P}}{p_e \times ES_p} + \frac{\exp_{dep,P}}{p_e \times ES_p \times (1 - ES_p / ES_{\text{max}})}\right]}
\]

(5.70)

So, the priority criterion requires the value of expression (5.70) for both measures; the priorities are determined by comparing these two values. The measure for which this expression has the lowest value, will have the highest priority (see eq. 5.21); that measure has to be implemented first in order to obtain the sequence of conservation measures that will ultimately yield the highest financial results.
Because the inverse of expression (5.70) has a form that is somewhat more simple, this inverse is used in the definite formulation of the above-mentioned priority criterion:

"In conservation projects in which two different measures can be implemented, the measure for which the following priority decision number (PDN):

\[ PDN = P_e^*E_{Sp} - \left\{ \frac{P_e^*E_{Sp} - \text{EXP}_{dep,P}}{\text{EXP}_{dep,P}} \right\} \cdot \frac{E_{Sp}}{E_{Sp}^{\text{max}} - E_{Sp}} \]  \hspace{1cm} (5.71) \]

has the highest value should be implemented first in order to obtain the best ultimate financial results."

From this expression for PDN, it can be seen that three factors determine the priorities for measures:

1. the energy cost savings \( P_e^*E_{Sp} \)
2. the ratio of the energy cost savings over the (dependent) expenses: \( \frac{P_e^*E_{Sp}}{\text{EXP}_{dep,P}} \)
3. the degree to which the potential energy savings are realised: \( \frac{E_{Sp}}{E_{Sp}^{\text{max}}} \)

The influence of these factors on the priorities for measures can be explained as follows:

- Firstly, recall that the difference between the NPV's of different sequences of measures is caused by the fact that the optimum point for measures changes if another measure is implemented previously in the system. The first measure causes a decrease of the energy cost savings (DS) of the second one and, due to that, the original optimum point is no longer an optimum. As the optimum changes, both the (cost) savings and the expenses change. The difference between these two changes is positive; it will be called here the "effect of delay".

It is evident now that the measure for which the "effect of delay" is largest, has to be implemented after the other one. So, the measure with the smallest "effect of delay" has the highest priority.

- Eq. (5.71) shows that the priority is higher with:
  1. higher values for \( P_e^*E_{Sp} \)
  2. higher ratios of \( \frac{P_e^*E_{Sp}}{\text{EXP}_{dep,P}} \)
  3. higher values for \( \frac{E_{Sp}}{E_{Sp}^{\text{max}}} \)

(It must be remembered that the PDN is only for comparing different measures. That is why the term "higher" is used)

- As the "effect of delay" is caused by a certain decrease of energy cost savings (DS), the change in the optimum is smaller when this decrease applies to a larger \( P_e^*E_{Sp} \) and it is larger when DS applies to a smaller \( P_e^*E_{Sp} \). So, the "effect of delay" is smaller with higher \( P_e^*E_{Sp} \) values.

- A higher \( \frac{E_{Sp}}{E_{Sp}^{\text{max}}/\text{EXP}_{dep,P} \) ratio means that a certain decrease of the energy cost savings has a smaller effect on the (dependent) expenses. Consequently, the change in the optimum - and, thus, the "effect of delay" - is smaller.

- A higher \( \frac{E_{Sp}}{E_{Sp}^{\text{max}} \) ratio implies that the original optimum point was closer to the asymptotical maximum energy (cost) savings, so, at a relatively "flat" part of the energy savings curve. Consequently, the expenses-curve is relatively flat too. Then, a certain decrease of the energy (cost) savings will cause a relatively small "effect of delay".

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- In conclusion, the above points make it evident once more that, as the origins of the interactions is of a physical nature and the aim of determining priorities is a financial one, both the physical and the economic characteristics play a part in the priority criterion (PDN).

The application of the priority criterion in cases with more than two alternatives will be discussed in section 5.8.

From expressions 5.74 and 5.75, it can be seen that \( \text{EXP}_{\text{dep},P}, \text{ESP}_p, \text{ES}_{\max} \) (for each measure) and \( p \) are the only data required to apply the criterion. \( \text{ES}_p \) and \( p \) are known, of course; \( \text{EXP}_{\text{dep},P} \) can be derived from the total expenses of the measure and \( \text{ES}_{\max} \) can be determined from a simple physical analysis, or by estimation. In appendix X, a numerical example is given for applying the priority criterion.

### 5.7.4 Accuracy of the priority criterion

From the discussions in the preceding subsection and from fig. 5.16 for example, it is evident that the decision criterion that was derived will be based upon a rather close approximation of the exact description of the proportional interactive effects of the energy conservation measures.

However, as the criterion is meant for decisions of the "yes/no" kind, the consequences of the approximation cannot be analysed simply as inaccuracies in the results. Considering the simple case of two conservation measures, the criterion indicates the optimum sequence of implementation, in general, but due to the approximation mentioned above, there will be a limited number of cases in which the sequence indicated by the criterion may not be the optimal one. Now, in order to get an indication of the application, two aspects are analysed numerically:

- the possibility that applying the criterion in an arbitrary case leads to the "wrong" sequence. An indication of where or when this possibility occurs is obtained by considering a large number of cases representing the whole range of possible combinations of measures. For this whole range, the proportion of cases in which the criterion leads to the "wrong" sequence is determined.

- for these "wrong" cases: the difference between the ultimate project results for the "wrong" sequence and those for the optimal sequence. In fact, this difference can be seen as the inaccuracy of the priority criterion.

For these analyses, it is necessary to consider the whole range of possible combinations of two conservation measures in order to draw conclusions for the general suitability of the criterion. In principle, this would mean that all possible combinations of the parameter-values in eqs. 5.1 and 5.4 for both measures, covering the whole range of each parameter, would have to be investigated. This would require calculations for the whole range of the ten parameters. However, it will be evident that, with respect to the applicability of the criterion, we are not interested in every detail of every combination, but only in whether the criterion indicates the optimum sequence and, if not, whether there are relevant deviations between the ultimate results from different sequences of measures or not. These deviations etc. are indicated by the ratio (5.62). It was mentioned in sub-section 5.7.2 that this ratio is determined by DS and five complex parameters:
Expression (5.68) shows that the priority criterion is determined by only these five parameters. So, for investigating the applicability of the criterion, it is sufficient to consider all the realistic combinations of these five complex parameters and DS.

Numerical analysis of this complete range of combinations starts by determining the range of possible values for each of the parameters; these ranges were given in sub-section 5.7.2.

Now, this numerical analysis and its results will be described separately for the two possible forms of interaction.

Combinations of measures with proportional interactive effects

For combinations with proportional interactive effects, it is clear (e.g. from Fig. 5.16) that, with respect to DS, the difference between the ratio (5.62) - which represents the real phenomena - and the ratio of two expressions of the kind of (5.70) - which represents the priority criterion - is largest when DS = DS\text{max}_{pr}. Therefore, in the first place, the value DS = DS\text{max}_{pr} must be considered in the numerical analysis. In fact, this is the worst case, which means that, for each combination of the remaining parameters, the calculated deviation is the maximum deviation that is possible theoretically.

To give an insight into the way that the ratio (5.62) behaves when compared with the results of the criterion, Figures 5.19 to 5.23 show the results of the ratio (5.62) for \(\lim DS \to 0\) and for DS = DS\text{max}_{pr} as a function of each of the above-mentioned complex parameters, for an arbitrary case.

\[\frac{\Delta \text{EXP}_D - \Delta \text{ESP}_A}{\Delta \text{EXP}_D + \Delta \text{ESP}_B} \approx 1\]

\[\lim DS \to 0\]

\[DS = DS\text{max}_{pr}\]

\[\text{Fig. 5.19} \quad \text{Range of possible values of ratio (5.62) as a function of} \quad \frac{\text{ESP}_A}{\text{ESP}_B}\]

\[\gamma_A/\beta_A = 1.1 \quad \gamma_B/\beta_B = 2.0 \quad \frac{\gamma_A}{\beta_A}\text{ESP}_A = 0.4 \quad \frac{\gamma_B}{\beta_B}\text{ESP}_B = 0.8\]
A large number of cases, covering the whole range of possible combinations, was analysed numerically. For each of the five relevant parameters, values were taken from the range shown in sub-section 5.7.2. Six series of calculations were performed; four of them for proportional interaction and two for interchangeable measures. They were based upon two different sets of parameter values, see Table 5.2. Each set contained eight values for each parameter, resulting in $8^5 = 32768$ combinations. However, not all of these combinations were relevant: combinations of measures for which one (or both) resulted in a negative net present value were excluded. From eqs. 5.5 and 5.30 it can be seen that such cases could be identified easily: if $\gamma/\beta_0 = (1\pm e^{d_i})^{\delta_{S_0,0}} > 1$, then NPV < 0.

Series I, III and V (Table 5.2) start from a set of parameter values which covers the complete range of theoretical values (the maximum values considered for $\gamma/\beta$ and $E_{S_A}/E_{S_B}$ resp. 7.0 and 12.5 - are both very extreme). Series II, IV and VI are based upon values from a limited range, representing most common situations and combinations.

For proportional interaction, two series (I and II) were made for a theoretical check on the accuracy of the priority criterion: $DS$ was taken equal to $DS_{\max pr} = 0.95 \times DS_{\max pr}^*$. These calculations were of a more

*)The value $DS_{\max pr} = 0.95 \times DS_{\max pr}$ was used as an approach to $DS_{\max pr}$, because $DS = DS_{\max pr}$ is a boundary case which would cause additional computational problems.
Ron 50% of possible values of ratio (5.62) as a function of $\frac{E_{PA}}{d_A}$ $E_{PA}/E_{PB}=1$, $\gamma_A/\beta_A=11$
$\gamma_B/\beta_B=2.0$; $\frac{E_{PB}}{d_B} E_{PB}=0.6$

Fig. 5.22

$\frac{E_{PA}}{d_A}$ $E_{PA}$

Range of possible values of ratio (5.62) as a function of $\frac{E_{PB}}{d_B}$ $E_{PB}$

$E_{PA}/E_{PB}=1$, $\gamma_A/\beta_A=11$
$\gamma_B/\beta_B=2.0$; $\frac{E_{PA}}{d_A} E_{PA}=0.4$

Fig. 5.23

theoretical nature, because the value of DS$_{max pr}$ (or DS$_{max pr}$) was based only on theoretical considerations. In some cases, this value of DS caused negative NPV's of the measure to be implemented secondly. Nevertheless, these series of calculations were important, because they represented the whole range of theoretically possible situations, the "worst cases". In addition to these more theoretical calculations, calculations were made for series III and IV, starting from a value of DS that led to positive NPV's for both the measures in both sequences. That value of DS was determined by iteration for every single case.

Series V and VI are for combinations of interchangeable measures.
Table 5.2 Survey of parameter values used in the numerical analysis.

<table>
<thead>
<tr>
<th>Series of calculations</th>
<th>Proportional interaction</th>
<th>Interchangeable values for</th>
<th>Values for</th>
<th>Values for</th>
<th>Values for</th>
<th>Values for</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DS = DS_{max} pr</td>
<td>Y_A/\alpha_A</td>
<td>e_A/\alpha_A</td>
<td>e_B/\beta_B</td>
<td>\epsilon_A</td>
<td>\epsilon_B</td>
</tr>
<tr>
<td>I</td>
<td>X</td>
<td>0.5; 0.7; 1.0;</td>
<td>0.03; 0.18; 0.31;</td>
<td>0.44; 0.56; 0.69;</td>
<td>0.15; 0.3; 0.5; 1.0;</td>
<td>1.9; 3.5; 6.7; 12.5</td>
</tr>
<tr>
<td>III</td>
<td>X</td>
<td>1.3; 1.8; 2.6;</td>
<td>0.82; 0.95;</td>
<td>0.5; 1.0; 3.5; 12.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>X</td>
<td>3.6; 5.0;</td>
<td>6.7; 12.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>X</td>
<td>1.0; 1.06; 1.12;</td>
<td>0.4; 0.47; 0.54;</td>
<td>0.3; 0.42; 0.58; 0.80;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>X</td>
<td>1.19; 1.26; 1.34;</td>
<td>0.61; 0.69; 0.76;</td>
<td>1.1; 1.5; 2.2; 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>X</td>
<td>1.42; 1.5;</td>
<td>0.83; 0.90;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results of the calculations for series I and II are summarized in Table 5.3 and those for series III and IV in Table 5.4. For each of these series, the following results are given:
- number of relevant parameter combinations which implies, in fact, the total number of relevant cases under consideration;
- number of "transition"-cases. A "transition" case is a combination of parameter values for which the ratio (5.62) is smaller than unity for lim DS + 0 and greater than unity for the considered "maximum" value for DS (e.g. DS_{max}), or conversely. So a "transition"-case is a case for which the priority criterion may indicate a sequence of measures that is not the optimum sequence.
- number of transition cases (in %) of the total number of relevant cases;
- average difference between NPV_{AB} and NPV_{BA} (ultimate project NPV of resp. sequences A-B and B-A) as % of the max \{NPV_{AB}, NPV_{BA}\}, for all relevant cases;
- average difference between NPV_{AB} and NPV_{BA} as % of max \{NPV_{AB}, NPV_{BA}\}, for the "transition" cases;
- average difference between NPV_{max} (the result of simultaneous optimization) and the ultimate NPV of the most favourable sequence in stepwise implementation of measures (in % of NPV_{max}), for all relevant cases;
- for the transition cases: the average difference between NPV_{max} and the ultimate NPV of the ("wrong") sequence indicated by the priority criterion in those cases.
Table 5.3 Results of numerical calculations for the accuracy of the priority criterion: theoretical boundary cases with $DS = DS_{max}$

<table>
<thead>
<tr>
<th>series of calculations</th>
<th>number of relevant combinations</th>
<th>number of &quot;transition cases&quot;</th>
<th>percentage of &quot;transition cases&quot;</th>
<th>average absolute value of the difference (%) between $NPV_{AB}$ and $NPV_{BA}$ (for all relevant combinations)</th>
<th>$NPV_{AB}$ and $NPV_{BA}$ (for all relevant combinations)</th>
<th>$NPV_{max}$ and $NPV_{min}$ (for all relevant combinations)</th>
<th>$NPV_{max}$ and $NPV_{min}$ (for all relevant combinations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>9140</td>
<td>768</td>
<td>8.4</td>
<td>6.4</td>
<td>1.4</td>
<td>1.4</td>
<td>3.1</td>
</tr>
<tr>
<td>II</td>
<td>32768</td>
<td>2817</td>
<td>8.0</td>
<td>7.3</td>
<td>2.3</td>
<td>1.1</td>
<td>5.1</td>
</tr>
</tbody>
</table>

No conclusions can be drawn from the results in these tables without indications concerning the parameter values of the (or; most) transition cases. Detailed results (not given in the tables) showed that the number of "transition cases" in % of the number of relevant cases is approximately constant for almost all parameter values. Three areas were found where scarcely any "transition cases" appeared:

- if $ES_A - ES_B$ ($ES_A/ES_B < 1$)
- if $ES_A^*_A < 0.3$ ($\frac{\epsilon_A}{c_A} < 0.3$)
- if $ES_B^*_B < 0.3$ ($\frac{\epsilon_B}{c_B} < 0.3$)

No parameter values were found where the percentage of "transition cases" was substantially higher than average. Nor were there indications of systematic differences between "transition cases" and other relevant cases with respect to other characteristics, except for the difference between $NPV_{AB}$ and $NPV_{BA}$: the fact that, for "transition cases", this difference was only about 1/3 of that for an arbitrary relevant case (fifth and sixth columns) applied to all parameter values. These results indicate that the
figures in tables 5.3 and 5.4 are representative of all possible cases, except for the areas mentioned above. From tables 5.3 and 5.4 the following can be deduced:

- The percentage of "transition" cases is small. Moreover, because generally in practice, DS will be smaller than the considered "maximum" value for DS, the real percentage of "transition" cases will be even smaller than the percentages (7.2 - 8.6) that were found for these DS-values.

- Comparing the fifth and sixth columns of each table proves what was expected from figs. 5.19 to 5.23: the differences between the ultimate NPV's of the two possible sequences were smaller for the "transition" cases than for the rest of the cases. Similar ratios were found for the maximum values of these differences and for the variation coefficient. The result is that when a "transition" case occurs - which means that the "wrong" sequence is indicated by the priority criterion - the effect of this "wrong" sequence is less serious than the mean effect of choosing the "wrong" sequence in an arbitrary case.

- The results for the most common cases (series II and IV) agreed fairly well with those for the wide range of parameter values (series I and III).

- It can be concluded from the seventh column (compared with the fifth) that, in general, the NPV of the most favourable sequence is very close to the theoretical maximum NPV.

- If we compare the sixth and the eighth columns, it becomes clear that "transition cases" appear especially in cases where the difference between the results of stepwise and simultaneous optimization (the theoretical maximum NPV) is relatively large (and the difference between the results of different sequences is relatively small).

Summarizing these conclusions, it must be stated that, when the priority criterion is applied for arbitrary combinations of measures with proportional interactive effects, the resulting sequence of measures is almost always the most favourable one. Only in cases in which the differences between the ultimate financial results of different sequences are relatively small, it is possible that the resulting sequence is not the most favourable one.

The conclusions that can be drawn from these tables with respect to the relevance of the priority criterion and the step-by-step implementation of measures will be discussed in subsection 5.7.6 and section 5.8.

**Combinations of Interchangeable measures**

For combinations of interchangeable measures, the priority criterion was checked and its accuracy was determined on the basis of eqs. 5.54 to 5.57. The parameter values of Table 5.2 were used in principle, however without those for \((e_B/d_B)\*ES_B\). This is because of the restriction of eq. 5.17, which means that the number of degrees of freedom is reduced by one for interchangeable measures. This implies that the value of \((e_B/d_B)\*ES_B\) is determined by the values of the other parameters.

For these interchangeable measures, cases are considered over the whole range \(0 < DS < DS_{max ic}\), where \(DS_{max ic}\) is determined by eq. 5.67. For each relevant parameter combination of Table 5.2, ten cases were considered with \(DS = 0.1*DS_{max ic}; 0.2*DS_{max ic}; \ldots \ldots ; 1.0*DS_{max ic}\).

The results of this numerical analysis are summarised in table 5.5.
Table 5.5 Results of numerical calculations on the accuracy of the priority criterion: combinations of interchangeable measures

<table>
<thead>
<tr>
<th>Series of calculations</th>
<th>Number of relevant combinations</th>
<th>Number of &quot;transition cases&quot;</th>
<th>Percentage of transition cases</th>
<th>Average absolute value of the difference (%) between NPV_{AB} and NPV_{BA} (for all relevant combinations)</th>
<th>Average absolute value of the difference (%) between NPV_{AB} and NPV_{BA} (for transition cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>984</td>
<td>160</td>
<td>16.3</td>
<td>5.5</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>2003</td>
<td>160</td>
<td>8.0</td>
<td>5.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

From this table 5.5, the following conclusions can be drawn:
- The numbers of relevant parameter combinations (second column) were small compared with those in tables 5.3 and 5.4. This was due to the fact that, for combinations of interchangeable measures, the parameter combinations are restricted by the fact that $\text{ES}_{A,\text{max}} \leq b_{SR,\text{max}}$.
- The percentage of transition cases was relatively small. In comparison with the results for combinations with proportional interaction (tables 5.3 and 5.4), it was somewhat higher, as could be expected.
- For the transition cases, the difference between the results of different sequences of measures was smaller than for other cases (compare the last two columns in table 5.5).
- Taking the preceding two points together, the priority criterion is considered to be suitable for this group of combinations of measures too: it proved to be satisfactorily accurate.

Evaluation

The results of the numerical analysis described in this subsection, in which the accuracy of the priority criterion for stepwise introduction of energy conservation measures was investigated, can be summarized as follows:
- The priority criterion was tested by analyzing a large number (about 80,000) of theoretical combinations of measures; these cases covered the whole range of possible combinations.
- In about 90% of the cases, the priority criterion indicated the most favourable sequence for implementing the measures.
- The remaining 10% of the cases, in which the criterion indicated the less favourable sequence, were relatively close to the break-even point, where the results of both possible sequences are equivalent. Consequently, for those cases, the effect of not choosing the most favourable sequence was limited.
5.7.5 Examples of applications for the paper dryer case study

In this subsection, three simple examples are presented for applying the criterion that was developed for determining the most favourable sequence of implementing energy conservation measures in one system. The examples are taken from the paper dryer case study presented in Chapter 3. Each example deals with the combination of two conservation measures in this dryer. The two possible sequences of implementation are simulated and the ultimate financial results are compared with the outcome of the priority criterion applied to the measures in question.

The three examples concern the following combinations of conservation measures in the paper dryer:

- air use reduction and heat recovery
- air fan rotational speed increase and thermal insulation
- re-use of flue gases (from four boxes) and thermal insulation

These examples will be treated now one by one.

* Combination of air use reduction and heat recovery

For reducing the air use, the simulated energy cost savings $p_{e}\cdot ES$ as a function of the degree of reduction are shown by the upper full line in fig. 5.24 (which corresponds to fig. 3.27). The expenses are independent of the degree of reduction:

\[ \text{EXP} = \$ 2000. \]

These expenses are shown by the dashed line in fig. 5.24. The net present value, which is the difference between these two curves, is given by the lower full line. The maximum NPV is found at an air use reduction of 80%.

The figures for this point are:

\[ p_{e}\cdot ES = \$ 22,600 \]
\[ \text{EXP} = \$ 2,000 \]
\[ \text{NPV} = \$ 20,600 \]

The priority decision number (PDN) is $\text{eq. 5.75} - \text{eq. for this conservation measure: PDN} = \infty$, because $\text{EXP}_{\text{dep}} = 0$.

The simulated energy savings from heat recovery (fig. 3.28) are given in fig. 5.25 by the upper full line. The expenses of heat recovery are:

\[ \text{EXP}(A_{\text{he}}) = 7000 + 336\left(\frac{A_{\text{he}}}{A_{\text{he-ref}}}ight)^{0.65} [\$] \]

in which:

\[ A_{\text{he}} = \text{heat transfer surface area of the heat exchanger} \quad [\text{m}^2] \]
\[ A_{\text{he-ref}} = 1 \quad [\text{m}^2] \]

These expenses are indicated by the dashed line in fig. 5.25. The net present value is again given by the lower full line; its maximum is at point $A_{\text{he}} = 209$ [m$^2$]. This point shows the following values:

\[ p_{e}\cdot ES = \$ 40,250 \]
\[ \text{EXP} = \$ 17,025 \]
\[ \text{NPV} = \$ 22,425 \]
Results of air use reduction in the paper drier before (full lines) and after (dotted lines) heat recovery.

Fig. 524

Results of heat recovery in the paper drier before (full lines) and after (dotted lines) air use reduction.

Fig. 525

The maximum energy savings \( P_{1} B_{\text{max}} \) (for \( A_{\text{he}} = \infty \)) amount to $50,000. Now the priority decision number for heat recovery can be determined:

\[
P_{\text{DN}} = 40,250 \times \left( \frac{40,250 - 10,825}{10,825} \right) + \frac{40,250}{50,000 - 40,250^2} = 275,570
\]

It is evident that the P\(\text{DN} \) for air use reduction is highest, which indicates that this measure should be implemented first, according to the priority criterion and heat recovery afterwards in order to obtain the highest ultimate financial results. This will be checked now by determining the ultimate results for both possible sequences.

Sequence: air use reduction – heat recovery

If the air use of the dryer is reduced first, the results of this measure agree with those mentioned above: \( \text{NEV} = $20,600 \). Implementing heat recovery after that gives the energy savings indicated by the upper dotted line in Fig. 5.25 that was found by simulation. The net present value of heat recovery in that situation is shown by the lower dotted line in that figure.
Then the maximum NPV appears at $A_{\text{he}} = 34 \text{ \text{m}^2}$; the figures at this point are:

\[
\begin{align*}
\text{p}_{\text{ES}} &= $22,125 \\
\text{EXP} &= $10,325 \\
\text{NPV} &= $11,800
\end{align*}
\]

So the ultimate net present value for this sequence is:

\[
\text{NPV}_{\text{tot}} = $20,600 + $11,800 = $32,400
\]

Sequence: heat recovery - air use reduction

The results of heat recovery if implemented first have been given already: NPV = $22,425. In fig. 5.24 the upper dotted line shows the simulated energy savings for air use reduction if implemented after that heat recovery had been realised. The lower dotted line in that figure, representing the NPV, has its maximum at 80% air use reduction again:

\[
\begin{align*}
\text{p}_{\text{ES}} &= $7,125 \\
\text{EXP} &= $2,000 \\
\text{NPV} &= $5,125
\end{align*}
\]

Thus the ultimate net present value for the sequence: heat recovery - air use reduction becomes:

\[
\text{NPV}_{\text{tot}} = $22,425 + $5,125 = $27,550
\]

* Combination of air fan rotational speed increase and thermal insulation

As for the former combination, the energy savings from increasing the fan rotational speed and from thermal insulation were determined by simulation, both for implementation as the first measure as well as for the reverse sequence. The results are presented graphically in figs. 5.26 and 5.27. The curves for the expenses of the measures are also given in these figures; they were determined by the following expressions:

Fan rotational speed increase:

\[
\text{EXP}(\omega) = 4,185 \times \left(\frac{\omega}{\omega_{\text{ref}}}\right)^{0.9} \quad [\$]
\]

in which:

\[
\begin{align*}
\omega &= \text{fan rotational speed increase} \quad [\text{s}^{-1}] \\
\omega_{\text{ref}} &= \text{present rotational speed} \quad [\text{s}^{-1}]
\end{align*}
\]

Thermal insulation:

\[
\text{EXP}(l_{\text{ins}}) = 700 + 800 \times \left(\frac{l_{\text{ins}}}{l_{\text{ins-ref}}}\right)^{0.9} \quad [\$]
\]

in which:

\[
\begin{align*}
l_{\text{ins}} &= \text{thickness of insulating material} \quad [\text{m}] \\
l_{\text{ins-ref}} &= 0.01 \quad [\text{m}]
\end{align*}
\]

The numerical results for this combination of measures in two possible sequences for implementation are summarized in table 5.6.
Result of air fan rotational speed increase before (full lines) and after (dotted lines) thermal insulation.

Result of thermal insulation of the drying boxes before (full lines) and after (dotted lines) increase of the air fan rotational speed.

Table 5.b: Results for the combination of air fan rotational speed increase and thermal insulation in the paper dryer.

<table>
<thead>
<tr>
<th>Sequence of Implementation</th>
<th>results of first measure</th>
<th>PDN of first measure</th>
<th>results of second measure</th>
<th>ultimate net present value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;o&lt;/sup&gt; air fans</td>
<td>$\omega_{\text{opt}} = \lambda_{1,14} \omega_{\text{ref}}$</td>
<td>$p_{\text{ES}} = $24,585</td>
<td>$p_{\text{ES}} = $2,690</td>
<td>$NPV_{\text{tot}} = $10,055</td>
</tr>
<tr>
<td>2&lt;sup&gt;o&lt;/sup&gt; insulation</td>
<td>$\omega_{\text{opt}} = \lambda_{1,14} \omega_{\text{ref}}$</td>
<td>$\lambda_{1,14}$</td>
<td>$p_{\text{ES}} = $2,690</td>
<td>$NPV_{\text{tot}} = $9,815</td>
</tr>
<tr>
<td>1&lt;sup&gt;o&lt;/sup&gt; insulation</td>
<td>$\omega_{\text{opt}} = \lambda_{1,14} \omega_{\text{ref}}$</td>
<td>$\lambda_{1,14}$</td>
<td>$p_{\text{ES}} = $2,690</td>
<td>$NPV_{\text{tot}} = $9,815</td>
</tr>
<tr>
<td>2&lt;sup&gt;o&lt;/sup&gt; air fans</td>
<td>$\omega_{\text{opt}} = \lambda_{1,14} \omega_{\text{ref}}$</td>
<td>$\lambda_{1,14}$</td>
<td>$p_{\text{ES}} = $2,690</td>
<td>$NPV_{\text{tot}} = $9,815</td>
</tr>
<tr>
<td>2&lt;sup&gt;o&lt;/sup&gt; insulation</td>
<td>$\omega_{\text{opt}} = \lambda_{1,14} \omega_{\text{ref}}$</td>
<td>$\lambda_{1,14}$</td>
<td>$p_{\text{ES}} = $2,690</td>
<td>$NPV_{\text{tot}} = $9,815</td>
</tr>
</tbody>
</table>

*) $P_{e, ES_{\text{max}}} (\text{air fans}) = $35,120

**) $P_{e, ES_{\text{max}}} (\text{insulation}) = $14,330

From this table, according to the priority criterion, it can be seen that
the fan speed has to be increased before the drying boxes are insulated. The difference between the ultimate results of both sequences confirms this.

* Combination of re-using the flue gases and thermal insulation

For these two measures, figs. 5.28 and 5.29 present the results graphically. Energy savings (before and after the other measure) were determined by simulation. The expenses for re-using the flue gases are independent of the percentage of flue gases that is re-used: \( \text{EXP} = \$ 3,500 \).

The expression for the expenses of thermal insulation was given above.

Table 5.7 summarizes the numerical results for this combination of measures.
Table 5.7 Results for the combination of re-using the flue gases and thermal insulation in the paper dryer.

<table>
<thead>
<tr>
<th>sequence of implementation</th>
<th>results of first measure</th>
<th>PDN of first measure</th>
<th>results of second measure</th>
<th>ultimate net present value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1° re-use flue gas</td>
<td>opt: 100% re-use (from 4 boxes)</td>
<td>pₐ.ES = $24,500</td>
<td>EXP = $3,500</td>
<td>NPV = $21,000</td>
</tr>
<tr>
<td>2° insulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 1° insulation              | opt: 100% re-use (from 4 boxes) | pₐ.ES = $11,750 | EXP = $4,105 | NPV = $7,645 |
| 2° re-use flue gas         |                          |                      |                           |                           |

*Evaluation*

In subsection 5.7.4, a numerical analysis was made for testing the priority criterion on the basis of numerous cases. These cases were described with the general equations for the energy savings and the expenses of measures (eqs. 5.1 and 5.4) and by an exactly constant ratio between the savings of a measure before and after one another (eq. 5.9a) or exact interchangeability of the measures.

From appendix VIII (figs. A.2 to A.5) and figs. 5.4 to 5.11, it is evident that, in practice, these conditions are not satisfied completely.

The examples treated in this subsection show how the priority criterion appears for such cases in practice. It is seen that, in each of these cases, the sequence of measures indicated by the priority criterion (which means comparison of the PDN's (priority decision number) is indeed the sequence that yields the highest ultimate financial result. In two cases, the difference between different measures is rather small; the other case shows a substantial difference. However, they are just examples. More important than the numerical results from these cases is the fact that they illustrate the principal difference between different sequences of measures, and the fact that the priority criterion proves to be useful for finding the most favourable sequence.

Another important point was shown by the first example: it was found that the most favourable sequence starts with the measure that has the lowest Net Present Value. So, if the Net Present Value of the individual measures would have been used as the criterion—which is often done in practice—this would have resulted in inferior project results.

5.7.6 Relevance of the priority criterion

With respect to the relevance of using the priority criterion in practice, the following remarks are made:

- From the figures presented in the numerical analysis (Tables 5.3, 5.4 and 5.5) one could get the impression that the question of the priority of conservation measures is irrelevant in practice, because the average difference between the results of different
sequences of measures is quite small. However, because those numerical calculations leave the "independent expenses" out of consideration (sub-section 5.6.1.2), the differences in percents of the ultimate results will be larger in practice, when "independent expenses" are involved.

- The average differences are small, so it is true that for a lot of situations the sequence in which measures are implemented has hardly any consequences. On the other hand there is an important number of cases in which the difference between the results of different sequences is significant. The differences can be as large as several tens of percents. Fig. 5.30 illustrates this for the combinations of which the results were presented in table 5.4. This figure shows the number of cases (in % of the total number of relevant cases) in which a certain difference between NPV and NPV is exceeded as a function of that difference.

- The difference between different sequences of measures is a fundamental difference. This means that it cannot simply be compared with the inaccuracy of project calculations (that applies to all the measures in the project). Irrespective of the inaccuracy of those calculation results, it is relevant to take into account the priorities for measures.

- The first example in the preceding subsection shows what effect can be obtained by determining the optimum sequence. Also, this example shows that common ways of decision-making can result in "wrong" decisions.

![Fig. 5.30 Difference between the net present values of different sequences of two conservation measures](image)
5.6 DISCUSSION

An evaluation of the theory and the results described in this chapter gives rise to a number of remarks:

General equations for conservation measures

The considerations were based upon the assumption that each energy conservation measure can be characterised by one specific variable "\( v \)" with \( 0 < v < \infty \), so that energy savings as well as expenses are described as continuously rising functions of \( v \) (section 5.3). If, in practice, these functions have relatively small discrete steps, they can be approximated easily by such a continuously rising function.

However, there are some exceptions that do not satisfy the above assumptions. For instance, there is a group of measures for which the expenses are independent of variable "\( v \)". Examples of this group are: air flow reduction in the paper dryer (Chapter 3); installation of control units (e.g. thermostatic controls) in processes; etc. The expenses for such measures are independent of the set-points that are chosen. In such cases, the energy savings are not described by a continuously rising function of "\( v \)" but they will show a certain maximum at a finite value of "\( v \)" (e.g. figs. 3.27 and 3.29). It is evident that implementation of such a measure must be done at that point of maximum energy savings. The question of priorities for measures can be answered easily for this kind of measure: since there are no "dependent" expenses, their priority is the highest possible (see section 5.6).

Different measures of this same group of exceptions can be implemented in an arbitrary sequence, because the ultimate project outcome is independent of the sequence of them.

Another group of exceptions comprises measures that show similar functions as those given in section 5.3, but for which the variable "\( v \)" is restricted to a certain range. If the optimum value of "\( v \)" (see section 5.4) is within this range, the measure can be treated just like those that satisfy the general equations. If the optimum value of "\( v \)" is determined by the boundary condition, the measure can be treated as if it were fixed at that point, i.e. just like those of the group of exceptions mentioned above.

It can be concluded from this discussion that the priority criterion applies to these exceptional cases as well.

Aspects not taken into account by the priority criterion

It was mentioned earlier that the sequence of conservation measures that results from applying the priority criterion is a sequence that takes into account the physical interactions among conservation measures and their financial implications. Aspects, such as: the range of investments, moment of investment, maximum financial risk, and even the net present value itself, are not taken into account. This implies that the priority criterion can only be applied together with the economic criteria that are relevant and/or usual in the circumstances.

Of course, this applies to all the other (non-economic) criteria and aspects that may affect decisions about the implementation of energy conservation measures too.

It has been explained that the difference between the ultimate results of different sequences of measures is independent of the "independent expenses" for that measure. Consequently, the priority criterion does not take into account these "independent expenses" either. This means that a measure with a high priority may yield a negative net present value, thus, it should not be implemented. The implications of this for the decision procedure in energy conservation projects will be discussed in the next section. Considering this point, the effect of the priority criterion can be...
formulated as follows:

"For a given combination of energy conservation measures, the priority criterion indicates the implementation sequence that yields the most favourable financial results for the complete set of measures, irrespective of the question whether certain measures make a negative contribution to these results or not."

**Exceptional cases**

From the formulation of the priority criterion at the end of section 5.7 it follows that the fact that in this project measure A has a higher PON than measure B means no more than that $NPV_{AB} > NPV_{BA}$. If in the sequence B-A, $NPV_A$ is negative, then $NPV_B > NPV_{BA}$. This means that it is possible that $NPV_B > NPV_{AB}$.

Evaluating this example, it becomes evident that this problem may occur only if each of the following conditions is satisfied:

- the $NPV$ of the measure with the highest priority is smaller than that of at least one other measure (e.g. $NPV_A < NPV_B$).
- The $NPV$ of the measure with the highest priority would become negative if it would be implemented after one of the measures that have a higher $NPV$ (e.g. $NPV_A$ after $B < 0$).
- for one of the measures with a higher $NPV$, the difference between that $NPV$ and the $NPV$ that is achieved if that measure would be implemented after the one with the highest priority is larger than the $NPV$ of the measure with the highest priority itself (e.g. $\Delta NPV_B > NPV_A$, with $\Delta NPV_B = NPV_B - NPV_B$ after $A$).

Considering these conditions, it is clear that only in exceptional cases there is a possibility that this problem occurs. If one of the conditions is not satisfied, there is no problem at all.

When applying the procedure in practice, one should be aware of the possible occurrence of this problem. The condition mentioned first is easy to check; however, the last two are not. They depend on the effect of the interaction of the two measures in concern. An estimation has to be made of $\Delta NPV$. In general, the following rough indications will be satisfactory in most practical cases:

- there is no problem as long as the $NPV$'s remain positive if the measures are implemented after each other.
- it can be "dangerous" to implement a measure for which $NPV < 0$, because in such cases, there is a big chance that the $NPV$ becomes negative due to the interaction with an other measure. It will be evident that, also from a purely economic viewpoint, such cases are considered to be risky.

**More than two conservation measures**

Up to now, all the considerations and derivations concerned sets of only two conservation measures that can be implemented in two possible sequences. The priority criterion that resulted from these considerations was based on a "priority decision number" (PON) that can be determined for each individual conservation measure in a project. The PON of a certain measure is determined from data concerning that measure itself and it is independent of the other measures and of the way and the degree to which they interact with that measure. This implies that in a project with more than two measures, the one with the highest priority is found by simply choosing the one with the highest PON. This measure should be implemented first. The priority of the remaining measures cannot be derived simply from their PON's, because implementing the first measure may have different effects on different measures. Therefore, after implementing the first measure, the remaining measures should be evaluated in the new situation. Based upon these results, a new PON is determined for each of the remaining measures.
Then, the one with the highest value has the highest priority and, thus, it should be chosen as the second measure to be implemented. For the measures that remain, again, new values for PMU have to be determined for the new situation (after implementing the second measure) etc. This procedure can be repeated until all the measures have been implemented.

So, it will be evident that the derivations in this chapter, that were based on a combination of only two conservation measures, are relevant to cases with an arbitrary number of measures.

**Step-by-step implementation of measures**

The priority criterion that was derived, was based upon the assumption that energy conservation measures in a project are implemented one at a time. This criterion appeared to be a powerful tool because it enables the decision-maker to take into account the effect of the interactions between different conservation measures without simulating (or calculating) those effects.

In general, stepwise optimization and implementation of conservation measures can only result in an approximation of the theoretically optimum design. However, the numerical analysis showed that, on average, this approximation will be fair if the priority criterion is applied. The difference between the results of the most favourable and the unfavourable sequence in stepwise implementation is twice to four times as large as the difference between the results of the most favourable sequence and those, obtained from simultaneous optimization and implementation. This implies that – although the simultaneous option is always preferable – in case it is not applicable, stepwise implementation by applying the priority criterion gives a rather good approximation of the optimum result.

**Simultaneous optimization**

In cases where conservation measures can be optimized and/or implemented altogether (e.g. when completely new installations are built and a simulation model of the process is available), the derived criterion can be useful for accelerating the optimization procedure. This optimization can be performed by e.g. the method of steepest ascent \(5.9\): an iterative procedure in which step size and direction in each iteration step are determined on the basis of the partial derivatives for the variables in question. So, this method requires a description of all the partial derivatives, which will give problems in practice, even if a complete simulation model is available. Because of that, in practice, it is more likely that simple iterative procedures will be applied, in which just a few variables (or only one) have to be changed at a time. In such procedures, the priority criterion can be used for choosing the variable(s) to be changed in a certain situation (at a certain step in the procedure). Application of the priority criterion may speed up the convergence greatly.

**5.9 General decision procedure for energy conservation projects.**

In the preceding section, it was mentioned that, in energy conservation projects when different measures are implemented at different times, decisions on the choice of measures to be implemented have to be made on the basis of both the priority criterion and one (or more) economic criteria. The priority criterion indicates the sequence of measures and the economic criteria are for selecting: whether or not a measure must be implemented. For instance, such an economic criterion can be: "If the net present value of a measure is positive, it has to be implemented; if negative, it has to
be rejected". Because stepwise implementation of conservation measures is considered, the decision procedure is also a stepwise procedure; in each step, one measure is chosen. Due to the interaction between different conservation measures in one project, the financial results (e.g. the net present value) of a certain measure will be lower (or at best remain the same) in later steps. This means that, if, in a certain step, a measure does not satisfy the economic criteria, it will not satisfy them at all in later steps. So, if in a certain step a measure is rejected, it can be rejected definitely: it need not to be considered anymore in later steps.

On the basis of these considerations, we come to the following decision procedure for energy conservation projects with stepwise implementation of measures:

In each step the following points have to be performed:

1. Start from the condition of the project (the installation) before this present step.

2. Determine the optimum point (section 5.4) for each of the measures available in this step; further, determine the energy cost savings ($p_e$,$E_S$) and the total expenses (EXP) of the measure at that point. The net present value will be the difference between these two (eq. 5.10).

3. Check the economic criteria for each of the measures. Those that do not satisfy the criteria must be rejected and not considered further in the project.

4. Determine the dependent expenses ($EXP_{dep}$) for each of the remaining measures by subdividing the total expenses into an independent and a dependent part: $EXP = EXP_{dep} + EXP_{indep}$. Further, for each measure, the maximum energy savings ($p_e$,$E_S_{max}$) are determined on the basis of considerations of limit values (the case that the extent to which the measure is performed becomes infinitely large).

5. Calculate the priority decision number (PDN) for each measure:

$$PDN = p_e,E_S \times \left\{ \frac{p_e,E_S - EXP_{dep}}{EXP_{dep}} + \frac{E_S}{E_S_{max} - E_S} \right\}$$

6. Choose (and implement) the measure with the highest PDN value.

Then, the next step is performed by starting again at point "1" of the procedure, for the remaining conservation measures. This is repeated until all measures have been implemented or rejected.

So, it will be seen that by performing this procedure, the conservation measures are selected and the attractive ones are implemented in the most favourable sequence.

In this procedure, point "4" may cause some trouble in practice, because the determination of $EXP_{dep}$ and $E_S_{max}$ is "unconventional". With respect to this, some recommendations will be given:

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- In many cases, the maximum energy savings ($ES_{max}$) can be found from rather simple process calculations. For instance, for insulation: calculate the energy savings for zero heat losses; for heat recovery: consider the case in which the temperature of the primary outgoing medium is equal to that of the incoming secondary medium; for improvement of process control: consider the situation that the process operates continuously under optimal conditions.

- The dependent expenses ($EXP_{dep}$) can be estimated by analysing the sensitivity of the total expenses for changes of the characteristic variable of the measure. For instance, this can be done by comparing the expenses for various values of that variable: insulation with various thicknesses of the insulating layer, heat recovery with various dimensions of the heat exchanger, etc.

Modified procedure for simultaneous optimization

In section 5.8, some attention was paid to simultaneous optimization of different conservation measures as opposed to step-by-step optimization and implementation (for instance, when constructing completely new installations). It was mentioned that, in general, the priority criterion could be useful then for accelerating convergence in the optimization procedure.

Considering the procedure given above for stepwise implementation, it can be concluded that that procedure is also a suitable basis for simultaneous optimization. In that case, after choosing a certain measure, changes of this measure have to be considered in future steps, with the possibility of negative changes to the characteristic variable. So, all measures must remain under consideration in each step of the procedure. This means that we are dealing with an iterative procedure and the steps must be repeated until a satisfactory accuracy for the convergence is obtained.

However, apart from the points of special attention and the remarks that have been made in this section, there is one fundamental point that must be considered when the procedure is used for simultaneous optimization: The fact that in a certain step of the procedure a measure does not satisfy the economic criteria, does not imply that this measure will not appear in the (simultaneous) optimum solution. It is possible that a measure is rejected in a certain stage of the iteration, but in a later stage it is re-introduced as a result of changed conditions in the other measures.

This means that, if the procedure is applied for simultaneous optimization as proposed above, it is possible that certain measures will be rejected although they are a necessary as part of the optimum solution. The "optimum" point that would be found then is below the results of the real optimum. This problem can be overcome by a check afterwards: After performing the procedure given above, the measures that have been rejected must be checked one by one in order to see whether they can improve the results if added to the "optimum" point that was found. If one or more of them can, the iteration has to be repeated, including these measures, until the real optimum is found.

In this chapter, the considerations and the derivations of the priorities for energy conservation measures led to a relatively simple and straightforward procedure for decision-making in energy conservation projects. This procedure, in two different forms, applies to the step-by-step approach as well as to simultaneous optimization of different measures.

The procedure has a general application, especially because of the fact that step a) in the procedure (the check on economic criteria) can be interpreted in its widest sense.
The main conclusions from the investigations described in this thesis can be summarized as follows:

- For industrial companies, the best way of finding and evaluating energy conservation opportunities is by means of process analysis. In such analyses, simulation models for the static behaviour of the processes play a key role. For decision-making at company level, it is sufficient to consider only the direct energy use, on an enthalpy basis. More sophisticated methods of analysis are required only for special purposes:
  - inclusion of the indirect energy use in the analyses is necessary for strategic considerations of companies, and for studies at a macro economic level.
  - analysis on an energy basis (second law analysis) is useful in theoretical considerations, in fundamental research and in education. For decisions in practical energy conservation projects it has little advantage.

- An elaborate case study was performed in which an industrial paper drying process was analysed in order to find all the relevant methods for reducing its energy usage. A simulation model describing the stationary behaviour of the process was developed on a partly analytical, partly empirical basis. Test results showed that the accuracy of the model was in the range of 10%, which was considered to be satisfactory for evaluating energy conservation measures and combinations of them.
  The most important conservation methods and possible related savings are:
  - reducing specific air use : up to 30% saving
  - recovering flue-gas heat : up to 50% saving
  - re-using flue-gases : up to 35% saving
  - increasing air fan rotational speed : up to 20% saving
  - increasing the number of drying boxes : up to 15% saving
  - insulating the drying boxes : up to 10% saving
  The real savings depend on the extent to which the measures are implemented.

- A practical procedure was proposed for developing simulation models for existing industrial processes. Such models provide the possibility of deriving energy conservation methods systematically and give quantitative information about energy savings. Moreover, they contribute to a better understanding of the behaviour of the processes.
- With respect to the interactive effects of energy conservation measures in one system, a theoretical - and partly empirical - analysis showed that energy conservation measures can be divided into three groups:
  - combinations of measures that are independent
  - combinations of measures that are interchangeable
  - combinations of measures that cause a proportional reduction in one another's energy savings function.

- A decision procedure for industrial energy conservation projects was developed on the basis of the analysis of the interactive effects of conservation measures. This procedure aims at maximizing the ultimate financial results of the complete project. The key point of this procedure is to determine the priorities of the available measures for the project.

- The priorities are found by comparing the "Priority Decision Numbers" (PDN's) for all measures. The PDN of a measure is calculated as follows:

$$PDN = p_e \cdot ES \cdot \left[ \frac{p_e \cdot ES - EXP_{dep}}{EXP_{dep}} + \frac{ES}{ES_{max} - ES} \right]$$

where:
- $ES$ = energy savings [kJ]
- $p_e \cdot ES$ = energy cost savings (present value) [$\$]
- $ES_{max}$ = energy savings that would be obtained if the measure would be performed to maximum extent [kJ]
- $EXP_{dep}$ = "dependent" expenses of the measure: that part of the expenses that is dependent of the extent to which the measure is performed (present value) [$\$]

Each of these quantities is calculated on a life-cycle basis. $ES$ and $EXP_{dep}$ are values that apply to the optimum of each individual measure.

The expression for PDN shows that the priorities of measures can be determined from the data for the individual measures only, without analyzing the effects of combining measures. This means that the procedure can be applied on the basis of a limited amount of information. Actually, the information required is no more than what is available in common practice.

- The priority criterion is applicable in two different versions of decision procedures:
  - For projects in which the different measures are implemented one at a time (or at least, not all at once) the criterion provides, ultimately, a near-optimum solution for the complete project.
  - For projects in which the measures are considered simultaneously, the priority criterion accelerates the convergence that will lead to the optimum combination of measures.
A check of the developed procedure by numerical calculations showed that for a large number (about 85,000) of combinations of measures, covering all possible alternatives, the priority criterion gave a correct indication of the priorities in about 90% of the cases. It was found that the remaining 10% of the cases concerned combinations of measures for which the priority was less important: the difference between the ultimate results of different sequences of measures appeared to be small compared with the deviations from the theoretical optimum.

The first version of the decision procedure mentioned above starts from the supposition that conservation measures are implemented one at a time. This can give only a near-optimum solution. However, the improvement obtained by this solution appeared to be about 80% of the improvement that could be achieved by the true (theoretical) optimum.

Differences between the ultimate project results of different sequences for measures can be even more than 30%. In the numerical analysis, a difference of more than 10% was found in about 15% of the cases. This illustrates the relevance of the priority criterion.

Applied to the practical case of the paper dryer, the procedure proved to be a useful tool in determining the most favourable sequence for conservation measures.
APPENDIX I.

HEAT AND MASS TRANSFER COEFFICIENTS IN SITUATIONS WITH FORCED CONVECTION

Heat transfer by forced convection takes place at the paper sheet and at the inner side of the drying box walls. Moreover, the mass transfer from the paper sheet is by forced convection. The transfer coefficients for forced convection are determined by means of the correlations given by Kast et al. [3.12].

These correlations use the well-known dimensionless numbers of Reynolds (Re), Prandtl (Pr), Nusselt (Nu), Sherwood (Sh) and Schmidt (Sc) in which all relevant material properties and flow conditions are expressed. These dimensionless numbers are explained in the list of symbols.

Since air is the fluid here, considerations are limited to correlations for \( \text{Pr} = 0.72 \). For this case, according to [3.12], correlations for the heat transfer coefficient \( \alpha \) are as follows, where different correlations for different values of the Reynolds number are distinguished:

- for \( 10 < \text{Re} < 2 \times 10^3 \):
  \[
  Nu = 0.66 \times \text{Re}^{0.5} \times \text{Pr}^{0.33}
  \]  
  \( (A.1) \)

- for \( 2 \times 10^5 < \text{Re} < 7.5 \times 10^6 \):
  \[
  Nu = \frac{0.0376 \times \text{Re}^{0.8} \times \text{Pr}}{1 + 1.58 \times (\text{Pr}-1) \times \text{Pr}^{-0.25} \times \text{Re}^{-0.1}}
  \]  
  \( (A.2) \)

- for \( \text{Re} > 7.5 \times 10^6 \):
  \[
  Nu = \frac{0.017 \times \text{Re}^{0.85} \times \text{Pr}}{1 + 1.1 \times (\text{Pr}-1) \times \text{Pr}^{-0.25} \times \text{Re}^{-0.075}}
  \]  
  \( (A.3) \)

- for \( 2 \times 10^3 < \text{Re} < 2 \times 10^5 \):
  \[
  a \text{ linear relationship is assumed between } \ln(\text{Nu(Re)}) \text{ and } \ln(\text{Re}), \text{ with } \ln(\text{Nu(Re=2\times10^3)}) \text{ determined according to eq. (A.1) and } \ln(\text{Nu(Re=2\times10^5)}) \text{ calculated by means of eq. (A.2)}
  \]  
  \( (A.4) \)

Heat transfer coefficient \( \alpha \) can be calculated directly from the Nusselt number resulting from one of the equations (A.1) to (A.4), as follows:

\[
\alpha = \frac{Nu \times \lambda}{L}
\]  
\( (A.5) \)

where:
- \( \alpha \) = heat transfer coefficient \([\text{kJ.s}^{-1}.\text{m}^{-2}.\text{K}^{-1}]\)
- \( \lambda \) = thermal conductivity of the air \([\text{kJ.s}^{-1}.\text{m}^{-1}.\text{K}^{-1}]\)
- \( L \) = characteristic length of the geometry \([\text{m}]\)

According to [3.12] the characteristic length is taken as equal to the drying box length for heat transfer to the paper as well as to the inner box walls. For the open spaces between the boxes, it is equal to the length of this space (the distance between two boxes). All material properties of the gas mixture used for the calculations, like density, viscosity and thermal conductivity, are determined at the average conditions \( \bar{\rho}, \bar{\eta}, \bar{\kappa} \) in the boundary layer, as explained in subsection 3.4.3.1.
The determination of the mass transfer coefficients is analogous to the determination of the coefficients for heat transfer. This analogy is based upon the fact that for equimolar\(^*\) mass transfer the general differential equations describing the heat and mass fluxes have similar forms. However, in drying processes we deal with non-equimolar mass transfer. In such cases, the analogy is only an approximation \([3,12]\). Nevertheless, because deviations are acceptably small due to relatively low mass fluxes, mass transfer coefficients are determined by means of correlations which are analogous to the correlations (A.1) to (A.4). Then, the correlations for mass transfer coefficients are as follows:

- for \(10 < \text{Re} < 2 \times 10^3\):
  \[
  \text{Sh} = 0.66 \times \text{Re}^{0.5} \times \text{Sc}^{0.33}
  \]  
  \[:=(A.6)\]

- for \(2 \times 10^5 < \text{Re} < 7.5 \times 10^6\):
  \[
  \text{Sh} = \frac{0.0376 \times \text{Re}^{0.8} \times \text{Sc}}{1 + 1.58 \times (\text{Sc}-1) \times \text{Sc}^{-0.25} \times \text{Re}^{-0.1}}
  \]  
  \[:=(A.7)\]

- for \(\text{Re} > 7.5 \times 10^6\):
  \[
  \text{Sh} = \frac{0.017 \times \text{Re}^{0.85} \times \text{Sc}}{1 + 1.1 \times (\text{Sc}-1) \times \text{Sc}^{-0.25} \times \text{Re}^{-0.075}}
  \]  
  \[:=(A.8)\]

- for \(2 \times 10^3 < \text{Re} < 2 \times 10^5\):
  a linear relationship is assumed between \(\ln(\text{Sh(Re)})\) and \(\ln(\text{Re})\), with \(\ln(\text{Sh(Re}=2 \times 10^3))\) determined according to eq. (A.6) and \(\ln(\text{Sh(Re}=2 \times 10^5))\) calculated by means of eq. (A.7) \[:=(A.9)\]

From the value of the Sherwood number obtained from any of the equations (A.6) to (A.9), the mass transfer coefficient \(k\) can be determined as follows:

\[
\textit{k} = \frac{\text{Sh} \times \text{D}}{L}
\]  
  \[:=(A.10)\]

where:  
- \(k\) = mass transfer coefficient \([\text{m.s}^{-1}]\)
- \(D\) = mass diffusivity of water in air \([\text{m.s}^{-2}]\)
- \(L\) = characteristic length of the geometry [m]

\(*\)Equimolar mass transfer occurs when mass transport of one component coincides with mass transport of the other component in opposite direction, for instance, in a binary mixture of fluids, so that the total net molar transport equals zero.
APPENDIX II.

COMPUTATION OF MATERIAL PROPERTIES OF HUMID AIR AND WET PAPER

Many material properties of humid air appear in the equations that describe the phenomena involved in the drying process (chapter 3). In this appendix, the equations for computing these properties are summarized:

- for humid air:
  - density
  - specific heat
  - enthalpy
  - kinematic viscosity
  - thermal conductivity
  - Prandtl number
  - diffusion coefficient of water vapour in air
  - partial vapour pressure of water in air
  - saturation vapour pressure of water

- for wet paper:
  - specific heat

These equations have been included in a subroutine library in the computer program of the simulation model, together with correlations for heat and mass transfer coefficients etc.

The applied equations are as follows:

1. density of humid air \([3.20]\):

   \[
   \rho = \frac{x + 1}{x/M_x + 1/M_a} \frac{P}{R \times T} \quad [\text{kg.m}^{-3}] \quad \text{(A.11)}
   \]

   where:
   - \(x\) = moisture content \([\text{kg H}_2\text{O.}(\text{kg dry air})^{-1}]\)
   - \(M_x\) = molar weight of water vapour \((-18)\) \([\text{kg.kmol}^{-1}]\)
   - \(M_a\) = molar weight of air \((-28.96)\) \([\text{kg.kmol}^{-1}]\)
   - \(R\) = gas constant \((=8.3143)\) \([\text{kJ.kmol}^{-1}\cdot\text{K}^{-1}]\)
   - \(P\) = pressure \((=10^5)\) \([\text{Pa}]\)
   - \(T\) = temperature \([\text{K}]\)

2. specific heat of humid air (at constant pressure):

   \[
   c = \frac{c_a + x \times c_x}{x + 1} \quad [\text{kJ.kg}^{-1} \cdot \text{K}^{-1}] \quad \text{(A.12)}
   \]

   where \([3.6]\):
   - \(c_a\) = specific heat of dry air, \([\text{kJ.kg}^{-1} \cdot \text{K}^{-1}]\)
     \(c_a = 1.88 \times (1 + 22\times10^5 \times \theta)\)
   - \(c_x\) = specific heat of water vapour \([\text{kJ.kg}^{-1} \cdot \text{K}^{-1}]\)
     \(c_x = 1.006 \times (1 + 5\times10^{-7} \times \theta^2)\)

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. enthalpy of humid air (reference base 0°C):

\[ h = c_a \cdot \theta + x \cdot \left( r_{x,0} + c_x \cdot g \right) \quad \text{[kJ.kg}^{-1} \] \quad (A.13)

where [3.17]: \( \theta \) = temperature \quad \text{[°C]}

\( r_{x,0} \) = heat of vaporization of water at 0°C

\( = 2500 \quad \text{[kJ.kg}^{-1} \]

. kinematic viscosity of humid air [3.3, 3.6]:

\[ \nu = \frac{P_x \cdot \eta_v + (P_{tot} - P_x) \cdot \eta_a}{P_{tot} \cdot \rho_a} \quad \text{[m}^2\cdot\text{s}^{-1}] \quad (A.14)\]

where: \( P_{tot} \) = total pressure \quad \text{[N.m}^{-2} \]

\( P_x \) = partial water vapour pressure \quad \text{[N.m}^{-2} \]

\( \eta_v \) = dynamic viscosity of vapour \quad \text{[kg.m}^{-1}.\text{s}^{-1} \]

\( \eta_a \) = dynamic viscosity of dry air \quad \text{[kg.m}^{-1}.\text{s}^{-1} \]

\( \rho_a \) = density of the humid air \quad \text{[kg.m}^{-3} \]

. thermal conductivity of humid air [3.6]:

\[ \lambda = \frac{P_{tot}}{P_x/\lambda_x + (P_{tot} - P_x)/\lambda_a} \quad \text{[kJ.m}^{-1}.\text{s}^{-1}.\text{K}^{-1}] \quad (A.15)\]

where: \( \lambda_x \) = thermal conductivity of water vapour

\( = -1.62 \times 10^{-6} \quad \text{[kJ.m}^{-1}.\text{s}^{-1}.\text{K}^{-1}] \]

\( \lambda_a \) = thermal conductivity of dry air

\( = 2.54 \times 10^{-6} \quad \text{[kJ.m}^{-1}.\text{s}^{-1}.\text{K}^{-1}] \]

. Prandtl number for humid air [3.6, 3.17]:

\[ Pr = \frac{x \cdot Pr_x + Pr_a}{x + 1} \quad [-] \quad (A.16)\]

where: \( Pr_x \) and \( Pr_a \) are Prandtl numbers for water vapour and air respectively

. diffusion coefficient of water vapor in air, at atmospheric pressure:

\[ D = 22.63 \times 10^{-6} \times \left( \frac{T}{273.15} \right) \cdot 1.81 \quad \text{[m}^2\cdot\text{s}^{-1}] \quad (A.17)\]

. partial vapour pressure of water in air:

\[ P_x = P_{tot} \cdot \frac{x/M_x}{x/M_x + 1/M_a} \quad \text{[N.m}^{-2}] \quad (A.18)\]
.  saturation vapour pressure of water [3.22]:

\[
P_{x, \text{sat}} = 10^{4.692} \cdot 10^{2} \cdot 0.0101325 \cdot (\tau - 0.422) \cdot (0.577 - \tau) \cdot e^{-12\tau} [N \cdot m^{-2}]
\]

(A.19)

where: \( \tau = \frac{T}{T_{\text{critical}}} = \frac{\theta + 273.16}{647.3} \)

\[
\sigma = \bar{\sigma} + \frac{E}{\theta + 273.16} + \frac{C \cdot X}{\theta + 273.16} \cdot \left(10^{D \cdot X^2} - 1\right) + F \cdot 10^{G \cdot X^5 / 4}
\]

with: \( \bar{\sigma} = 5.426651 \)

\( E = -2005.1 \)

\( C = 1.3869 \cdot 10^{-4} \)

\( \bar{X} = (\theta + 273.16)^2 - 2.937 \cdot 10^5 \)

\( D = 1.1965 \cdot 10^{-11} \)

\( F = -0.0044 \)

\( G = -0.0057148 \)

\( \bar{Y} = 374.11 - \theta \)

.  specific heat of wet paper:

\[
c_p = \frac{1.34 + x_p \cdot 4.19}{1 + x_p} [kJ \cdot kg^{-1} \cdot K^{-1}]
\]

(A.20)

where: \( x_p \) = moisture content of the paper [kg H_2O/(kg dry paper)^{-1}]
APPENDIX III
COMPUTATION METHOD FOR RADIANT HEAT EXCHANGE IN THE DRYING BOXES

In the drying boxes, radiant heat is exchanged among the burners, the paper sheet and the inner box walls. The other contributions, viz., those from the gas mixture and the air fans, are negligible. In fact a drying box is an enclosure with only three different "surfaces": burners, paper sheet and inner walls. In (3.24), this case has been treated extensively with respect to the radiant heat exchange. This appendix is limited to the derivation of the set of equations 3.11 to 3.13 - which describe the relations among surface temperatures and radiant heat fluxes - and the results of the applicability study of this method for the present simulation model.

Relations among surface temperatures and radiant fluxes

The applied computation method starts from a rather simplified consideration of the radiation phenomenon. It is defined by the following postulates:
- the N surfaces involved form an enclosure with an arbitrary geometry
- each of the surfaces is isothermal
- each surface is grey (emissivity \( \varepsilon = \) absorptivity \( \alpha \)) and opaque (absorptivity + reflectivity \( = 1 \))
- the radiation emitted and reflected from any surface is diffusely distributed and is constant along the surface. As the surface is assumed to be isothermal, this means that the incident flux must be uniform as well.

The total radiant flux coming from a surface \( i \) is called the radiosity \( B_i \) (W m\(^{-2}\)); the total incident flux is denoted as \( H_i \) (W m\(^{-2}\)). It is evident that:

radiosity = emitted radiation + reflected radiation

or:

\[
B_i = \varepsilon \cdot \sigma \cdot T_i^4 + (1 - \varepsilon_i) \cdot H_i
\]

(A.21)

where: \( \varepsilon_i \) = emissivity of surface \( i \)

\( \sigma_i = \) Stephan-Boltzmann constant: \( 5.77 \cdot 10^{-8} \) \([\text{W}m^{-2}K^{-4}]\)

The incident flux of surface \( i \) is coming from all surfaces of the enclosure, thus:

\[
H_i = \frac{1}{A_i} \cdot \sum_{j=1}^{N} \nu \cdot \sigma \cdot B_j \cdot s_{ij} \cdot F_{ij}
\]

(A.22)

where: \( A \) = surface area \([\text{m}^2]\)

\( F_{ij} \) = viewfactor (see eq. 3.13) \([-]\)

Applying the rule of reciprocity (eq. 3.14) yields:

\[
H_i = \sum_{j=1}^{N} B_j \cdot s_{ij} \cdot F_{ij}
\]

(A.23)
In fact, what we are looking for is an expression for the net radiant fluxes at the surfaces. For surface $i$ this net flux, denoted as $\Phi_i$ (W.m$^{-2}$) is simply found by:

$$\Phi_i = H_i - B_i$$  \hfill (A.24)

Now we have the basic equations for this problem: A.21, A.23 and A.24. From these equations $B_i$ and $H_i$ are eliminated as follows:

Combining eqs. A.21 and A.23 leads to:

$$B_i = \sigma * T_i^4 + \frac{1 - \varepsilon_i}{\varepsilon_i} * \Phi_i$$  \hfill (A.25)

Substituting eq. A.25 in A.23 gives:

$$H_i = \sum_{j=1}^{N} \left[ \phi_j * T_j^4 + \frac{1 - \varepsilon_j}{\varepsilon_j} * \Phi_j \right] * x_{ij}$$  \hfill (A.26)

Substituting eqs. A.25 and A.26 in eq. A.24 leads to the desired expression for the relationship among net radiant fluxes and surface temperatures:

$$\sum_{j=1}^{N} \Phi_j = \sum_{j=1}^{N} A_{ij} * \Phi_j * T_j^4 \quad i = 1,2,...,N$$  \hfill (A.27a)

in which:

$$x_{ij} \equiv \frac{\delta_{ij} - (1 - \varepsilon_j) * F_{ij}}{\varepsilon_j}$$  \hfill (A.27b)

$$h_{ij} = F_{ij} - \delta_{ij}$$  \hfill (A.27c)

Here, $\delta_{ij}$ is the Kronecker delta:

$$\delta_{ij} = 1 \text{ if } i = j$$

$$\delta_{ij} = 0 \text{ if } i \neq j$$

In subsection 3.4.4.1 this set of equations A.27 is represented as eqs. 3.11, 3.12 and 3.13 for the considered enclosure consisting of three "surfaces": burners, paper sheet and box walls.

**Test results of the computation method**

Before applying the method presented here to the general simulation model of the drying process, it was tested. These tests were performed by comparing the results of radiation computations to the measurement results. Measurements of various of temperatures, air flow conditions, paper moisture contents, paper sheet velocity, fuel supply, etc. were performed in the paper dryer under different operating conditions. For each drying box, the burner temperature and the radiant heat fluxes were calculated by means of...
the presented method, using temperature measurements as prescribed variables (temperatures of paper sheet, inner and outer box walls and gas mixture). On the other hand, from measurements of the fuel supply, the paper sheet temperature and moisture content and the gas temperatures, the overall energy balance, of the whole dryer (six boxes) was determined. From this balance, the total radiative heat transfer to the paper sheet was derived, as well as the net radiant flux from the burners.

The outcomes of the tests are:
- The computed burner temperatures appeared to be within the temperature range that was measured at the burners.
- The results of the comparison for radiant heat fluxes of burners and paper sheet are given in table A.1.

They can be summarised as follows:
- average deviation between measured and calculated radiant fluxes: burners 4 %, paper 6 %
- standard deviation: burners 12 %, paper 18 %
- average absolute value of deviations: burners 9 %, paper 14 %.

Taking into account the accuracy of the measurements (see subsection 3.2.3), these test results are considered to be satisfactory. Based upon these test results it was decided to apply the presented method in the simulation model of the dryer.

Table A.1. Comparison between results of the radiation model and experimental results.

<table>
<thead>
<tr>
<th>situation</th>
<th>net radiant heat flow (kW)</th>
<th>deviation (%)</th>
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<tr>
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APPENDIX IV

CORRELATION FOR THE TOTAL AERATION OF THE BURNERS

In determining the heat transfer from the burners in the drying boxes not only the natural gas supply has to be known, but also the related air consumption by the burners. This air consumption by the burners has in fact no relationship with the (prescribed) total air use in the drying box, because there is a forced flue gas extraction from the drying boxes, causing air inflow through all kinds of openings and holes in the box walls.

For the burners, no information was available on the aeration as a function of burner load. Within the present research it would be excessive to determine these characteristics of the burners with special measurements. Therefore, it was decided to derive a correlation on the basis of the results of the measurements that were performed in the drying section.

For a number of different situations, the net radiation of the burners was calculated from measurement results (appendix III). Now, for each of these cases, the ratio (air use/natural gas supply) was determined, starting from this net radiation, eqs. 3.22 and 3.23, the energy balance of the burners, and of course the natural gas supply, using an iterative procedure.

With respect to the kind of relationship between the burner load (natural gas supply) and the total aeration (which is the sum of primary and secondary aeration) we have the following indications:

- The burners in the drying boxes are of an atmospheric type. In general, the characteristics of this type with respect to the primary aeration are well known [3.25]. The ratio of the natural gas supply and the primary air use appears to be constant for nearly the whole range of the burner.
- However, with respect to the secondary aeration, it is very hard to find any useful information, especially, because this depends very much on the geometry etc. of the burners.
- Moreover, hardly any information is available on the total aeration characteristics of atmospheric burners, especially, because most of the installations equipped with such burners have on/off-controls; therefore, load variations and part loads are not taken into account most of the time. One exception was found in [3.26], where results of measurements on gas-heaters were presented, for burner loads varying from 30 to 100 %. From background information on these measurements, it was derived that the absolute total air use of the burners was almost constant over the range considered. This meant that the ratio of the total air used divided by the natural gas supply was inversely proportional to the burner load. However, this is of course only one example.

Based upon the above indications, the following can be concluded:
- If we would make one extreme assumption, viz. that the behaviour of the total aeration would be the same as that of the primary aeration, we would get:

\[
\text{RAT}_b = \text{BC}
\]

(A.28)

where:

- \( \text{RAT}_b \) = ratio of air volume flow and natural gas volume flow \( [\text{m}^3/\text{m}^3] \)
- BC = constant, depending on the burner properties \([-]\)
The other extreme assumption concerns a situation where the total absolute air flow is constant when the burner load changes. This would give:

\[
\text{RAT}_b = \text{BC} \times \left( \frac{\text{FC}_{\text{ref}}}{\text{FC}} \right)^{\xi}
\]

(A.29)

in which: \( \text{FC} \) = natural gas consumption (per burner) \([\text{m}^3\cdot\text{s}^{-1}]\)
\( \text{FC}_{\text{ref}} \) = natural gas consumption at reference burner load \([\text{m}^3\cdot\text{s}^{-1}]\)

These two extreme relationships A.28 and A.29 can be written consistently as follows:

\[
\text{RAT}_b = \text{BC} \times (\text{RAT}_p)^0 \quad \text{and} \quad \text{RAT}_b = \text{BC} \times (\text{RAT}_p)^{-\xi}
\]

where: \( \text{RAT}_p = \frac{\text{FC}}{\text{FC}_{\text{ref}}} \)

Considering these extreme expressions, we can expect a correlation for the total variation, as follows:

\[
\text{RAT}_b = \text{BC} \times (\text{RAT}_p)^{-\xi} \quad \text{with} \quad 0 < \xi < 1
\]

Now, on the basis of measurement results, the values of BC and \( \xi \) have to be determined, and the deviations of the resulting correlations have to be checked.

From the measurement results mentioned before, which cover diverging situations and burner loads, values for BC and \( \xi \) were derived by means of the method of least squares.

The results are (with \( \text{FC}_{\text{ref}} = 448 \times 10^{-6} \text{ m}^3\cdot\text{s}^{-1} \)): \( \text{BC} = 24.25 \) and \( \xi = 0.4 \).

An indication of the variations around these values is given as follows: when \( \xi = 0.4 \) is chosen, the resulting standard deviation of BC from \( \text{BC} = 24.25 \) was 2.75 (11\%). From this it was concluded that the accuracy is satisfactory.

Thus the following correlation results:

\[
\text{RAT}_b = 24.25 \times \left( \frac{\text{FC}_{\text{ref}}}{\text{FC}} \right)^{0.4}
\]

(A.30)

with: \( \text{FC}_{\text{ref}} = 448 \times 10^{-6} \text{ m}^3\cdot\text{s}^{-1} \) per burner.

In deriving the burner radiant fluxes and the air/fuel-ratios from the measurement results used for this correlation, the emissivity of the burners was taken as \( \varepsilon_b = 0.6 \). Consequently correlation A.30 can be applied to the conditions if \( \varepsilon_b = 0.6 \).

Besides, from additional calculations, it is evident that the air/fuel ratio depends only weakly on the assumed emissivity: Calculations with \( \varepsilon_b = 0.3 \) and \( \varepsilon_b = 0.9 \), which are very extreme values, showed deviations of no more than 10\%.

However, what is more important, is the fact that if another value than 0.6 is assumed for \( \varepsilon_b \), this would indeed give a different correlation for the air/fuel-ratio, but the results of overall simulations would not be different as long as in the simulation model the corresponding value of \( \varepsilon_b \) was used.
APPENDIX V.

HEAT TRANSFER COEFFICIENTS IN SITUATIONS WITH FREE CONVECTION

Heat is lost from the outside of the drying boxes to the surrounding air by free convection. The heat transfer coefficients for this phenomenon are determined by means of correlations given in [3.8] and [3.10]. These correlations use the dimensionless numbers of Nusselt (Nu), Grashof (Gr) and Prandtl (Pr), see the list of symbols.

Different correlations apply to vertical and horizontal surfaces; moreover, for horizontal surfaces, a distinction must be made between the upper and lower side of the boxes. The different correlations can be written in a general form, as follows:

\[ Nu = \tilde{x} \cdot (Gr \cdot Pr)^{\tilde{y}} \]  \hspace{1cm} (A.31)

The values of \( \tilde{x} \) and \( \tilde{y} \) depend on the way in which the surface is sited:

- According to [3.8] the following values apply to the vertical walls of the boxes:
  \[ \tilde{x} = 0.517 \]
  \[ \tilde{y} = 0.25 \]
  The characteristic length in the Nusselt number is equal to the height of the box.

- Assuming the upper and lower side of the box to be square, the values must be taken as follows [3.10]:
  * upper side:
    \[ \text{if } 10^5 < Gr \cdot Pr < 2 \times 10^7: \]
    \[ \tilde{x} = 0.54 \]
    \[ \tilde{y} = 0.25 \]
    \[ \text{if } 2 \times 10^7 < Gr \cdot Pr < 3 \times 10^{10}: \]
    \[ \tilde{x} = 0.14 \]
    \[ \tilde{y} = 0.33 \]
  * lower side, for \( 3 \times 10^5 < Gr \cdot Pr < 3 \times 10^{10}: \)
    \[ \tilde{x} = 0.27 \]
    \[ \tilde{y} = 0.25 \]

For the upper and lower side the characteristic length is taken to be equal to the average of length and width of the box.

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APPENDIX VII:

DETERMINATION OF THE AVERAGE SATURATION WATER VAPOUR PRESSURE IN THE BOUNDARY LAYER ON THE PAPER

In each subsection of the dryer (a drying box or an open space), the paper sheet temperature changes somewhat. In the present situation this change amounts up to about 25°C; however, in most of the subsections it is much smaller. When computing the rate of evaporation (Chapter 3), the partial water vapour pressure has to be determined for the boundary layer on the paper, as well as for the bulk of the gas mixture. As the boundary layer is (assumed to be) saturated, its saturation vapour pressure changes with changing temperature. That is why the total rate of evaporation should be determined by integration along the subsection. However, as the gas mixture in one subsection is assumed to be ideally mixed, this integration can be reduced to one single calculation, based upon the weighted average water vapour pressure in the boundary layer.

In order to determine this weighted average vapour pressure, the temperature difference in the length direction is subdivided into ten steps. This number of steps was chosen more or less arbitrarily. For each of these ten temperatures, the saturation vapour pressure is determined. Then, the weighted average vapour pressure in the boundary layer in the dryer subsection (drying box or open space) under consideration is calculated as the average of these ten saturation vapour pressures. So, implicitly, a linear change in the paper temperature with time, or with the length parameter, is assumed within a dryer subsection.
APPENDIX VII

EXAMPLES OF ENERGY CONSERVATION FUNCTIONS REPRESENTED IN A GENERAL FORM

In this appendix a number of examples are given of the general description of the energy savings (eq. 5.1) applied to a particular conservation measure. Firstly, for two conservation measures, equations are derived analytically. These measures are of a general nature. After that, four examples are given of conservation measures resulting from the case study of Chapter 3 (simulation results).

Analytical derivations

Equations for the energy savings as a function of the characteristic physical variable are derived analytically for a case of thermal insulation and a case of heat recovery. Although these cases are of a general nature, the exact formulations used here are based upon the case study of the paper dryer that was treated in Chapter 3.

**Thermal Insulation**

Assumptions:
- the drying boxes to be insulated are placed in a hall with a constant air temperature \( T_s \)
- the outer wall temperature of the boxes \( T_w \) is constant
- the heat transfer coefficient \( (a_w) \) for the heat transfer to the surrounding air is constant
- the increase of the total outer surface area \( (A_w) \) due to insulation is neglected
- radiative heat losses are neglected

The heat losses of the boxes without insulation are:

\[
Q_{\text{WS}} = A_w \cdot a_w \cdot (T_w - T_s) \quad (A.32)
\]

After insulating, the heat losses will be:

\[
Q'_{\text{WS}} = A_w \cdot a_w \cdot (T_w - T_s) \cdot (1 - \frac{\Delta T_{\text{ins}}}{T_w - T_s}) \quad (A.33)
\]

in which \( \Delta T_{\text{ins}} \) is the temperature difference between the inner and the outer side of the layer of insulating material.

As the heat losses expressed in eq. A.33 are equal to the heat transferred through the insulating material by means of conduction, the heat losses can also be expressed as follows:

\[
Q'_{\text{WS}} = \Delta T_{\text{ins}} \cdot \lambda_{\text{ins}} \cdot A_w / l_{\text{ins}} \quad (A.34)
\]

in which:

\[
\lambda_{\text{ins}} = \text{thermal conductivity of the insulating material} \quad [\text{kJ.m}^{-1}.\text{s}^{-1}.\text{K}^{-1}]
\]

\[
l_{\text{ins}} = \text{thickness of the insulating layer} \quad [\text{m}]
\]

Combining equations (A.33) and (A.34) leads to:

\[
Q'_{\text{WS}} = \frac{A_w \cdot a_w \cdot (T_w - T_s)}{1 + \frac{a_w \cdot l_{\text{ins}}}{\lambda_{\text{ins}}} \lambda_{\text{ins}}} \quad (A.35)
\]

Assuming the energy savings to be proportional to the decrease of the heat
losses (ratio $C_{\text{ins}}$), the energy savings - as a function of the thickness of the insulating layer - can be written as follows:

$$RS(1_{\text{ins}}) = C_{\text{ins}} \frac{(Q_{\text{in}} - Q_{\text{s}})}{\varepsilon} = C_{\text{ins}} \frac{A_{\text{w}} \cdot (T_{\text{w}} - T_{\text{s}}) / \lambda_{\text{ins}}}{A_{\text{w}} / \lambda_{\text{ins}}} \frac{(T_{\text{w}} - T_{\text{s}})}{\lambda_{\text{ins}} + \alpha_{\text{w}} / \lambda_{\text{ins}}}$$  (A.36)

This equation has the same form as the general equation 5.1 in Chapter 5.

*Heat recovery*

Assumptions:
- Consider a countercurrent gas-to-gas heat exchanger with equal primary and secondary mass flows ($m$); temperatures are denoted according to Fig. A.1.
- Temperatures of the incoming gas streams ($T_{\text{in}}$) and ($T_{\text{lin}}$) are constant.
- Specific heat of both gas streams is equal ($c_p$).
- Energy savings are proportional to the amount of heat that is recovered (factor $C_{\text{he}}$).
- The heat losses of the heat exchanger are neglected.
- No condensation takes place in the primary gas stream.

Due to the fact that both mass flows are equal and the specific heat of both streams are equal as well, the temperature difference between them is constant:

$$\Delta T = T_{\text{lin}} - T_{\text{lin}} - T_{\text{lin}} - T_{\text{lin}}$$  (A.37)
The heat transfer to the secondary stream can be expressed as follows:

\[ Q_{he} = K_{he} \times A_{he} \times \Delta T \]  

(A.38)

in which:

- \( K_{he} \) = heat transmission coefficient \([kJ.m^{-2}.s^{-1}.K^{-1}]\)
- \( A_{he} \) = heat transfer surface area of the heat exchanger \([m^2]\)

The energy balance of the heat exchanger yields:

\[ Q_{he} + m \times c_p \times (T_{1in} - T_{1out}) = m \times c_p \times (T_{2out} - T_{2in}) \]  

(A.39)

If we now write \( \Delta T \) in equation (A.38) as \( T_{1in} - T_{2in} - (T_{1in} - T_{1out}) \) and next combine equations (A.38) and (A.39) we find:

\[ Q_{he} = \frac{K_{he} \times A_{he} \times (T_{1in} - T_{2in})}{1 + \frac{K_{he} \times A_{he}}{m \times c_p}} = \frac{K_{he} \times (T_{1in} - T_{2in})}{1/A_{he} + K_{he} / (m \times c_p)} \]  

(A.40)

So the energy savings achieved by heat recovery can be written by the following equation, which agrees with the general equation 5.1:

\[ ES(\Delta T) = \frac{Q_{he} \times K_{he} \times (T_{1in} - T_{2in})}{1/A_{he} + K_{he} / (m \times c_p)} \]  

(A.41)

**Simulation results**

In Chapter 3, section 3.6, six energy conservation measures were derived for the considered paper dryer:

- air use reduction
- heat recovery
- re-use of the gases
- improvement of convection
- increase of the number of drying boxes
- thermal insulation

The energy savings of these measures were given in figs. 3.27 to 3.32. Two of these measures, to wit: "air use reduction" and "re-use of flare gases", belong to a special kind of conservation measures of which the expenses are independent of the degree to which the measure is realised (as discussed in section 5.3). For such measures the general equations treated in this appendix are not applicable but also irrelevant (section 5.8). Each of the remaining four measures has a characterizing physical variable "\( v \)" with \( 0 < v < \infty \). The expenses (EXP) depend on "\( v \)" with \( EXP(v) \rightarrow \infty \) for \( v + \infty \). So these four measures can be used for testing the general equation (5.1).

These tests can be performed by determining the accuracy with which the simulation results of Chapter 3 (figs. 3.28, 3.30, 3.31 and 3.32) can be described by equations of the form of eq. (5.1). For each of these measures the simulation results of a number of points were used for searching suitable values of the parameters of eq. (5.1). The results were that, for each of the considered conservation measures, solutions were found which showed a standard deviation of less than 10 percent.
These solutions are:

**Heat recovery:**

\[
\text{ES}(A_{\text{he}}) = \frac{2.32}{(A_{\text{he-ref}}/A_{\text{he}})^{0.9} + 0.0385} \quad [\text{kJ.s}^{-1}] \tag{A.42}
\]

with \( A_{\text{he-ref}} = 1 \text{ [m}^2\text{]} \)

**Improvement of convection:**

\[
\text{ES}(\omega) = \frac{6.03}{(\omega_{\text{ref}}/\omega)^{1.4} + 0.2} \quad [\text{kJ.s}^{-1}] \tag{A.43}
\]

where \( \omega_{\text{ref}} \) is the presently usual rotational speed of the air fans in the boxes.

---

**Fig. A2** Simulated energy savings of heat recovery and its representation by a general equation

**Fig. A3** Simulated energy savings of better convection and its representation by a general equation
*Increase of the number of drying boxes:

\[
ES(nr) = \frac{5.84}{nr - 1.27 + 0.21} \quad [\text{kJ.s}^{-1}] \quad (A.44)
\]

with \( nr \) = the number of added drying boxes.

*Thermal insulation:

*Thermal insulation:

\[
ES(l_{\text{ins}}) = \frac{11.04}{(l_{\text{ins-ref}}/l_{\text{ins}})^{1.07 + 0.64}} \quad [\text{kJ.s}^{-1}] \quad (A.45)
\]

with \( l_{\text{ins}} \) is the thickness of the insulating layer in [m], and \( l_{\text{ins-ref}} = 0.01 \) [m]

The curves according to eqs. A.42 to A.45 are represented in Figs. A.2 to A.5, together with the corresponding simulation results (of Figs. 3.28, 3.30, 3.31 and 3.32). From these figures it can be seen that these real energy conservation measures can very well be represented by equations of the general form (3.1).

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<table>
<thead>
<tr>
<th>(GJ per year)</th>
<th>(GJ per year)</th>
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<td><strong>Energy savings</strong></td>
<td><strong>Energy savings</strong></td>
</tr>
<tr>
<td><strong>Simulation</strong></td>
<td><strong>Simulation</strong></td>
</tr>
<tr>
<td><strong>General equation</strong></td>
<td><strong>General equation</strong></td>
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Fig. A.4 Simulated energy savings of more boxes and its representation by a general equation.

Fig. A.5 Simulated energy savings of insulation and its representation by a general equation.
EQUATIONS FOR THE INTERACTIVE EFFECTS OF CONSERVATION MEASURES CONCERNING PHENOMENA CONNECTED IN SERIES AND IN PARALLEL

In this appendix, equations are derived to describe the effect of one conservation measure on the savings of another one, for some simplified cases, viz. process parts connected in series and in parallel.

The following assumptions are made:
- only energy flows are considered
- the resulting "product flow" is constant
- all physical phenomena in the system considered have the same kind of "driving force" (e.g. temperature difference).

In subsection 5.4.1 it was argued that for investigating the interactive effects of process parts, they must not have a characteristic efficiency number (e.g. fig. A.6), but they must be further subdivided so that each individual physical phenomenon can be distinguished. Then, each energy transfer phenomenon (including those phenomena that determine the energy losses) is considered separately.

![Diagram of energy flow in a process part](Image)

**Fig. A.6** Usual representation of a process part in a process flow scheme

**Fig. A.7** Representation of a process part with subdivision into a useful energy transfer phenomenon and a transfer phenomenon for the energy losses.

So, the process part of fig. A.6 is represented as a (parallel) combination of a useful energy transfer phenomenon (U-transfer) and a phenomenon that transfers the energy losses (L-transfer), see fig. A.7. Both phenomena are characterized by their resistances: $r_U$ and $r_L$. The energy flow of a transfer phenomenon is proportional to the related driving force and inversely proportional to the resistance to that phenomenon. If we denote the driving force for the U-transfer: $DF_U$ and that for the L-transfer: $DF_L$, the energy flows can be written as:

$$E_{n_{out}} = \frac{DF_U}{r_U}$$  \hspace{1cm} \text{(A.46)}

$$\text{loss} = \frac{DF_L}{r_L}$$  \hspace{1cm} \text{(A.47)}
Then, the efficiency number of fig. A.6 is given by:

\[ \eta = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{DF_U/r_U}{DF_U/r_U + DF_L/r_L} = \frac{1}{1 + DF_U/r_U (DF_U/r_L)} \quad \text{(A.48)} \]

Energy conservation can be realized in this process part by increasing \( r_U \) or reducing \( r_L \). Note that the total resistance of this process part changes and affects the whole energy flow distribution in the system network of which this transfer phenomenon is a part.

Now, the results of the two possible conservation measures will be derived; reduction of \( r_U \) is called measure A and increase of \( r_L \) is called measure B. Resistances in the original situation are denoted by \( r_{U0} \) and \( r_{Lo} \).

**Measure A:** Consider a variable \( V_A \) which determines the resistance \( r_U \) so that \( r_U(V_A) = r_{U0} \) for \( V_A = 0 \) and \( r_U(V_A) = r_{U0} \) for \( V_A \rightarrow \infty \). A general equation that satisfies these boundary conditions is:

\[ r_U(V_A) = r_{U0} \left( 1 + \left( \frac{V_A}{Y_A + 1} \right) \right) \quad \text{with} \quad Y_A > 0 \quad \text{(A.49)} \]

Now, we can find the expression for \( E_{SA}(V_A) \).

If \( r_U \) is reduced by measure A, the driving forces \( DF_U \) (and, consequently, \( DF_L \)) will change. However, the difference between \( DF_U \) and \( DF_L \) remains the same, because it is determined by external conditions. This difference is denoted by:

\[ DF_{\text{indep}} = DF_U - DF_L \quad \text{(A.50)} \]

Then, eq. (A.47) can be written as:

\[ \text{loss} = \frac{DF_U - DF_{\text{indep}}}{r_L} \quad \text{(A.51)} \]

Combining eqs. (A.46) and (A.51) gives:

\[ \text{loss} = \frac{E_{\text{out}} \left( r_U - \frac{DF_{\text{indep}}}{r_L} \right)}{r_L} \quad \text{(A.52)} \]

Now, \( E_{\text{in}} \) can be written as:

\[ E_{\text{in}} = E_{\text{out}} \left( 1 + \left( \frac{r_U}{r_L} \right) \right) = \frac{DF_{\text{indep}}}{r_L} \quad \text{(A.53)} \]

The energy savings of measure A are given by:

\[ ES_A(V_A) = E_{\text{in}}(V_A = 0) - E_{\text{in}}(V_A) \quad \text{(A.54)} \]

Combining eqs. (A.49), (A.53) and (A.54) leads to:

\[ ES_A(V_A) = \frac{r_{U0} \times E_{\text{out}}}{r_{Lo}} \left( \frac{1}{Y_A + 1} \right) \quad \text{(A.55)} \]

**Measure B:** Variable \( v_B \) determines the resistance \( r_L \) with the following boundary conditions: \( r_L(v_B) = r_{Lo} \) for \( v_B = 0 \) and \( r_L(v_B) = \infty \) for \( v_B \rightarrow \infty \). On the basis of these boundary conditions, the following general equation is assumed:

\[ r_L(v_B) = r_{Lo} \left( 1 + \left( \frac{\gamma_B}{Y_B + 1} \right) \right) \quad \text{with} \quad Y_B > 0 \quad \text{(A.56)} \]
Now, \( \text{ES}_B(v_B) \) can be found in the same way as \( \text{ES}_A(v_A) \); this results in:

\[
\text{ES}_B(v_B) = \text{En}_1(v_B = 0) - \text{En}_1(v_B) - \frac{r_{\text{in} \times \text{En}_\text{out}}}{r_L} \frac{\gamma_{B+1}}{v_B} - \text{DF indep}/[v_B]^{\gamma_{B+1}} \quad (A.57)
\]

**Combinations**

From the preceding equations, we can find the savings that are achieved when the two measures are combined. This can be done most simply with a stepwise analysis: consider that the second measure is to be implemented after the first one has been realised. The savings from the first measure are given by eq. A.55 or A.57. The aim now is, to determine the savings achieved by one measure when it is implemented after the other one. Let us firstly consider the sequence: measure A - measure B. The savings from measure A are given by eq. A.55; the value of \( r_{\text{in}}(v_A) \) by eq. A.49.

The savings achieved by measure B can be found by substituting eq. A.49 in eq. A.57:

\[
\text{ES}_B(v_B) \text{ after } A = \frac{r_{\text{in} \times \text{En}_\text{out}}}{r_L} \frac{\gamma_{A+1}}{v_A} - \frac{\gamma_{B+1}}{v_B} \quad (A.58)
\]

If we compare eq. A.57 with eq. A.58 it becomes clear that the ratio

\[
\frac{\text{ES}_B(v_B) \text{ after } A}{\text{ES}_B(v_B)}
\]

is independent of \( v_B \); this means that the functions \( \text{ES}_B(v_B) \text{ after } A \) and \( \text{ES}_B(v_B) \) are proportional.

Now, the sequence: "measure B - measure A" is analyzed in a similar way. The savings of measure B are given by eq. A.57. Substitution of eq. A.56 - which gives the value of \( r_{\text{in}}(v_B) \) after measure B - in eq. A.55 yields:

\[
\text{ES}_A(v_A) \text{ after } B = \frac{r_{\text{in} \times \text{En}_\text{out}}}{r_L} \frac{\gamma_{B+1}}{v_B} \frac{\gamma_{A+1}}{v_A} \quad (A.59)
\]

Now, it can be derived from eqs. A.55 and A.59 that:

\[
\frac{\text{ES}_A(v_A) \text{ after } B}{\text{ES}_A(v_A)} = 1 / (v_B + 1) \quad (A.60)
\]

It is evident that the ratio A.60 is independent of \( v_A \), which means that the functions \( \text{ES}_A(v_A) \text{ after } B \) and \( \text{ES}_A(v_A) \) are proportional.

**Systematic analysis of connections in series and in parallel**

In fact, fig. A.7 is the simplest representation of the energy flows in a process (part). More complicated forms are possible, with different U- and L-transfer phenomena in series or parallel connections. In the following, the simplest forms of series and parallel connections of U- and L-transfer phenomena will be analysed systematically with regard to the interactive effects of the related energy conservation measures. In principle, the basic form of fig. A.7 (a U-transfer branche and an L-transfer branche in parallel) is maintained then, because other forms are futile. Each of these branches can be built up with U- and/or L-transfer phenomena in series or parallel connections.
In order to perform a systematic analysis of all possibilities, the following cases will be analysed subsequently:

- connection in series of:  
  - two U-transfers  
  - a U-transfer and an L-transfer  
  - two L-transfers

- parallel connection of:  
  - two U-transfers  
  - a U-transfer and an L-transfer  
  - two L-transfers

The related flow diagrams are given in figs. A.8 and A.9. The resistances are denoted as $r_{UI}$, $r_{II}$, $r_{III}$ and $r_{L}$; the values for the original situation have an index "0". Four conservation measures are considered:

A: reducing $r_{UI}$; variable $v_A$: $r_{UI}(v_A) = r_{UI0}/(v_A^\gamma + 1)$

B: increasing $r_{II}$; variable $v_B$: $r_{II}(v_B) = r_{II0}(1 + v_B^\gamma)$

C: reducing $r_{III}$; variable $v_C$: $r_{III}(v_C) = r_{III0}/(v_C^\gamma + 1)$

D: increasing $r_{L}$; variable $v_D$: $r_{L}(v_D) = r_{L0}(1 + v_D^\gamma)$

Exponents $\gamma$ are 0.

The resulting energy flow ($E_{out}$) is assumed to be constant.

Connections in series

Two U-transfers in series.

See fig. A.8.a: measures A and C.

Here, we will use the same notations as in the preceding derivations: $DF_U$, $DF_L$, $DF_{indep}$ and $r_U$; $r_U$ is divided into $r_{UI}$ and $r_{III}$. So, the energy flows are written as:

$$E_{out} = \frac{DF_U}{r_{UI} + r_{III}}$$  \hspace{1cm} (A.61)

$$loss = \frac{DF_L}{r_L} = \frac{E_{out}*(r_{UI} + r_{III})}{r_L} - \frac{DF_{indep}}{r_L}$$  \hspace{1cm} (A.62)

In analogy to eq. A.55, the energy savings of these measures can be expressed as follows:

$$ES_A(v_A) = \frac{r_{UI0}*E_{out}}{r_{L0}} (v_A^{-\gamma} + 1)$$  \hspace{1cm} (A.63)

$$ES_C(v_C) = \frac{r_{UI0}*E_{out}}{r_{L0}} (v_C^{-\gamma} + 1)$$  \hspace{1cm} (A.64)

From eq. A.63 it will be evident that $ES_A(v_A)$ is independent of $r_{III}(v_C)$. This means that the savings of measure A are independent of the question whether or not measure C had been implemented previously. Moreover, eq. A.64 shows that the savings of measure C are independent of the implementation of measure A.
Fig. A8a. Two U-transfer phenomena connected in series

Fig. A8b. A U-and on L-transfer phenomenon connected in series

Fig. A8c. Two L-transfer phenomena connected in series
a U- and an L-transfer connected in series. See fig. A.8.b: measures A and D*).

For this situation, we consider three different driving forces:
- \( DF_U \) for \( En_{\text{out}} \) (\( r_{UI} \) and \( r_{UL} \))
- \( DF_{LI} \) for loss \( I \) (\( r_{LI} \))
- \( DF_{LI} \) for loss \( II \) (\( r_{UL} \) and \( r_{LI} \))

Then, there are two independent differences in driving forces:
\[
\begin{align*}
DF_{\text{indepI}} &= DF_U - DF_{LI} \\
DF_{\text{indepII}} &= DF_U - DF_{LI} \\
\end{align*}
\]

(A.65)

(A.66)

It can be derived that:
\[
\begin{align*}
\text{loss}_I &= \frac{En_{\text{out}}^*[r_{UIO}+(r_{UL}^*r_{ULI})/r_{LI}+r_{ULII}]}{r_{LI}} - \frac{(DF_{\text{indepII}}*r_{UL})}{r_{LI}} + \frac{DF_{\text{indepI}}}{r_{LI}} \\
\text{loss}_{II} &= \frac{En_{\text{out}}*r_{ULII}}{r_{LI}} - \frac{DF_{\text{indepII}}}{r_{LI}} \\
\end{align*}
\]

Then, with:
\[
En_{\text{in}} = En_{\text{out}} - \text{loss}_I - \text{loss}_{II}
\]

the following equations can be found:
\[
\begin{align*}
ES_A(v_A) &= En_{\text{out}}^*[1 + \frac{r_{ULII}}{r_{LIO}}*\frac{r_{UIO}}{r_{LIO}}/(v_A + 1)] \\
ES_D(v_D) &= (En_{\text{out}}*r_{ULII} - DF_{\text{indepII}})*[\frac{r_{ULII}}{r_{LIO}}/(v_D + 1)] \\
\end{align*}
\]

(A.67)

(A.68)

Now, let us consider the consequences of combining the measures A and D. From eq. A.69, it can be seen that, if measure D would have been implemented previously, only the factor \((1+r_{ULII}/r_{LIO})\) would have changed into:
\[
1 + \frac{r_{ULII}}{r_{LIO}}/(v_D + 1)
\]

So, this change is independent of \( v_A \), which means that the functions of \( ESA(v_A) \) after D and \( ESA(v_A) \) are proportional.

*) In this case (fig. A.8.b) the \( U_{\text{II}} \)-transfer was added because, otherwise, the process would be futile.
If measure A would be implemented before D, the only change in eq. A.70 is in the factor $\frac{\mu A}{\mu A + 1}$, which changes into:

$$\frac{\mu A}{\mu A + 1} \left( \frac{\mu A}{\mu A + 1} + 1 \right)$$

This makes it clear that the savings functions $ES_A(v_A)$ after A and $ES_D(v_D)$ are proportional, since this change is independent of $v_D$.

two transfers in series.
See fig. A.8.c: measures B and D.

For this case, the energy flows can be expressed as:

$$\text{loss} = (\text{En} - \text{En}_A)/(\mu A)$$  \hspace{1cm} (A.71)

$$\text{En}_m = \text{En}_A + (\text{En} - \text{En}_A)/(\mu A)$$ \hspace{1cm} (A.72)

From this, the following expressions can be derived for the energy savings of the individual measures:

$$ES_B(v_B) = \left[ \frac{(\text{En} - \text{En}_A)/(\mu A)}{\mu A} \right] / \left[ (r_{LI0} + r_{LII0})^2 \right]$$  \hspace{1cm} (A.73)

$$ES_D(v_D) = \left[ \frac{(\text{En} - \text{En}_A)/(\mu A)}{\mu A} \right] / \left[ (r_{LI0} + r_{LII0})^2 \right]$$ \hspace{1cm} (A.74)

The savings of one measure implemented after the other one can be expressed as follows:

$$ES_B(v_B) \text{ after } D = \frac{(\text{En} - \text{En}_A)/(\mu A)}{\mu A} + \frac{r_{LI0}}{r_{LI0} + r_{LII0}(1 + v_D)}$$ \hspace{1cm} (A.75)

$$ES_D(v_D) \text{ after } B = \frac{(\text{En} - \text{En}_A)/(\mu A)}{\mu A} + \frac{r_{LI0}}{r_{LI0} + r_{LII0}(1 + v_D)}$$ \hspace{1cm} (A.76)

From eqs. (A.73) to (A.76) it can be seen that there is no simple relationship between $ES_B(v_B)$ after B $\text{ or } ES_B(v_B)$ or between $ES_D(v_D)$ and $ES_D(v_D)$.

However, this combination of measures B and D appears to have other specific characteristics, which can be seen from the expression for the total savings of measures B and D together:

$$ES_{B,D}(v_B, v_D) = \frac{(\text{En} - \text{En}_A)/(\mu A)}{\mu A} + \frac{1}{r_{LI0} + r_{LII0}(1 + v_D)}$$ \hspace{1cm} (A.77)
This equation shows that:

* the maximum savings that can be achieved by measure $B$ is equal to that of measure $D$ and, moreover, they are equal to the maximum savings that can be achieved by the combination of $B$ and $D$.

* consequently, if one measure is implemented, the resulting decrease of the potential (maximum) savings of the other one is equal to the savings achieved by the first one.

Taking these points together, it can be stated that measures $B$ and $D$ are fully interchangeable with respect to their effects to the rest of the system. Because of that, such combinations will be denoted here as "interchangeable conservation measures".

---

**Parallel connections**

two U-transfers in parallel connection

See fig. A.9.a: measures $A$ and $C$.

The following expressions were derived for the energy savings of the individual measures:

\[
ES_A(v_A)_{\text{out}} = \frac{r_{\text{ULo}} * r_{\text{ULio}}^2}{r_{L} * (r_{\text{ULo}} + r_{\text{ULio}})^2} \frac{1}{v_A} (v_A + r_{\text{ULo}} r_{\text{ULio}}) \tag{A.78}
\]

\[
ES_C(v_C)_{\text{out}} = \frac{r_{\text{ULo}} * r_{\text{ULio}}^2}{r_{L} * (r_{\text{ULo}} + r_{\text{ULio}})^2} \frac{1}{v_C} (v_C + r_{\text{ULo}} r_{\text{ULio}}) \tag{A.79}
\]

The savings of one measure implemented after the other one can be expressed as follows:

\[
ES_A(v_A)_{\text{after C}} = \left\{ \frac{r_{\text{ULo}} * r_{\text{ULio}}^2}{r_{L} * (r_{\text{ULo}} + r_{\text{ULio}}^2)} \right\} \frac{1}{v_A} (v_A + r_{\text{ULo}} (1 + v_C) + r_{\text{ULio}}) \tag{A.80}
\]

\[
ES_C(v_C)_{\text{after A}} = \left\{ \frac{r_{\text{ULo}} * r_{\text{ULio}}^2}{r_{L} * (r_{\text{ULo}} + r_{\text{ULio}}^2)} \right\} \frac{1}{v_C} (v_C + r_{\text{ULo}} (1 + v_A) + r_{\text{ULio}}) \tag{A.81}
\]

From these four equations, it can be seen that there is no simple relationship between $ES_A(v_A)_{\text{after C}}$ and $ES_A(v_A)_{\text{after C}}$ or between $ES_C(v_C)_{\text{after A}}$ and $ES_C(v_C)$. 

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Fig. A.9.a Two U-transfer phenomena in parallel connection

Fig. A.9.b A U-and an L-transfer phenomenon in parallel connection

Fig. A.9.c Two L-transfer phenomena in parallel connection
The energy savings of measures A and C together can be described by:

\[ E_{A,C}(v_A, v_C) = \frac{E_{out} \cdot U_{IO} \cdot r_{ULIO}}{r_{LO} \cdot (r_{ULIO} + r_{ULIO})} \]

with \( r_{ULIO} = \frac{1}{v_C} + \frac{1}{v_A} + \frac{1}{r_{ULIO} + r_{ULIO}} \)

This eq. A.82 shows that these measures A and C form a combination of interchangeable measures, as defined before.

A U-transfer and an L-transfer in parallel connection.
See fig. A.9.b: measures A and B.

This case is the same as the one treated earlier in this appendix: fig. A.7, the general representation of a process part. It was shown (eqs. A.55 to A.59) that there is a relationship between \( E_{A}(v_A) \) after B and \( E_{A}(v_A) \) so that:

\[
\frac{E_{A}(v_A) \text{ after } B}{E_{A}(v_A)} \text{ is independent of } v_A
\]

and a relationship between \( E_{B}(v_B) \) after A and \( E_{B}(v_B) \) so that:

\[
\frac{E_{B}(v_B) \text{ after } A}{E_{B}(v_B)} \text{ is independent of } v_B
\]

This means that the energy savings function of a measure implemented after the other one is proportional to the savings function in the original situation.

Two L-transfers in parallel connection.
See fig. A.9.c: measures B and D.

The driving force for loss I is \( D_{FI} \) and for loss II: \( D_{FII} \). Then, two constant differences in driving forces are defined by:

\[
D_{F indemp} = D_{F} - D_{FI} \quad (A.83)
\]

\[
D_{F indemp II} = D_{F} - D_{FII} \quad (A.84)
\]

This makes it possible to write the energy flows as a function of \( E_{out} \), as follows:

\[
\text{loss I} = \frac{E_{out} \cdot r_{UL}}{r_{LI}} - D_{F indemp} \quad (A.85)
\]

\[
\text{loss II} = \frac{E_{out} \cdot r_{UL}}{r_{LII}} - D_{F indemp II} \quad (A.86)
\]

\[
E_{in} = E_{out} \left[ 1 + r_{UL} \left( \frac{1}{r_{LI}} + \frac{1}{r_{LII}} \right) \right] - \frac{D_{F indemp}}{r_{LI}} - \frac{D_{F indemp II}}{r_{LII}} \quad (A.87)
\]
The savings achieved by the individual measures can be expressed as follows:

\[
\mathcal{E}_B(v_B) = \frac{\text{En}_{\text{out}}(v_B) - D^F_{\text{indep1}}}{r_{LI0}} \left( v_B + 1 \right)^{-\gamma_B} \quad (A.88)
\]

\[
\mathcal{E}_D(v_D) = \frac{\text{En}_{\text{out}}(v_D) - D^F_{\text{indepII}}}{r_{LI0}} \left( v_D + 1 \right)^{-\gamma_D} \quad (A.89)
\]

These equations show that the savings functions are independent of the question whether or not the other measure had been implemented previously.

**Evaluation**

The analysis of the simplest forms of connections in series and in parallel of \( U \)- and \( L \)-transfer phenomena showed three different kinds of effects of the interactions between energy conservation measures:

- Interactions between interchangeable measures: eqs. A.77 and A.82, see figs. A.5.c and A.9.a.
- Combinations of measures for which there is no effect of interaction: eqs. A.63, A.64, A.88 and A.89, see figs. A.8.a and A.9.c.
APPENDIX IX:

THE RECIPROCITY OF DIFFERENT WAYS OF INTERACTION BETWEEN ENERGY CONSERVATION MEASURES.

In section 5.4, it was found that two different ways of interaction between conservation measures have to be distinguished:
- Interactions in which the measure implemented first causes a proportional reduction of the savings of the second measure. In terms of the general equation 5.9:

  \[ \text{ES}(v) = \frac{d}{v - y + e} \]  

  (A.90)

  this means that the value of parameter "d" of the second measure is reduced by implementing the first one.
- Interactions between "interchangeable" measures.

The reciprocity of each of these ways of interaction is treated now.

Interaction with proportional reduction of energy savings

Consider measures A and B. Eq. A.83 applied to measure A gives:

  \[ \text{ES}_A(v_A) = \frac{d_A}{v_A + e_A} \]  

  (A.91)

The ratio \( d_A/e_A \) is the energy savings potential of A (the maximum achievable savings, if \( v_A \to \infty \)).

However, because each energy conservation measure can be considered as a way to reduce an energy loss flow, the ratio \( d_A/e_A \) is also equal to the energy use related to the energy loss flow that is affected by measure A.

If implementation of measure B before measure A causes a decrease of "d" from \( d_{AO} \) to \( d_A \), this implies that the energy loss flow mentioned above reduces from \( d_{AO}/e_{AO} \) to \( d_A/e_A \). This means, that the part of the energy savings of measure B that interacts with measures A can be written as:

  \[ \text{ES}_B(v_B) = \frac{d_{AO}}{e_{AO}} - \frac{d_A}{e_A} - \frac{d_{AO} - d_A}{e_{AO}} \]  

  (A.92)

The total energy savings of B may be larger; that would mean that there is another effect that has no interaction with measure A:

  \[ \text{ES}_B(v_B) = \text{ES}_B(v_B)_{\text{dep}} + \text{ES}_B(v_B)_{\text{indep}} \]  

  (A.93)

This independent part of the savings \( \text{ES}_B(v_B)_{\text{indep}} \) is left out of consideration for a moment.

Eq. A.92 provides an expression for the "dependent" part of the savings of measure B if implemented as the first measure. The savings of B if implemented after A will be derived now.

It was mentioned earlier that, in the original situation the energy use related to the energy loss flow affected by measure A is \( d_{AO}/e_{AO} \).
By implementing measure A with \( v_A \) being the realized value of \( v_A \), this loss-related energy use is reduced to:

\[
\frac{dA}{\varepsilon_A} - \frac{dA}{\varepsilon_A} / (v_A + \varepsilon_A) = \frac{dA}{\varepsilon_A} \cdot \left\{ \frac{-\gamma_A}{v_A + \varepsilon_A} \right\}
\]

If, after that, measure B is implemented, this energy use is reduced further to:

\[
\frac{dA}{\varepsilon_A} \cdot \left\{ \frac{-\gamma_A}{v_A + \varepsilon_A} \right\}
\]

So the "dependent" energy savings of measure B if implemented after A are:

\[
ES_B (v_B) \text{ dep after } A = \frac{dA}{\varepsilon_A} \cdot \left\{ \frac{-\gamma_A}{v_A + \varepsilon_A} \right\}
\]  \hspace{1cm} (A.94)

Comparison of eqs. A.92 with A.94 makes clear that, at least for the "dependent" part of the energy savings, interaction of measures resulting in a change of parameter "d" is reciprocal: measure B causes a change of the savings of A by a ratio \( dA/dA \), and A changes the savings of B by a factor

\[
\left\{ \frac{-\gamma_A}{v_A + \varepsilon_A} \right\}
\]

Now, the "independent" part of the savings has to be included in the consideration. If conservation measure B (a change of variable \( v_B \)) affects different energy loss flows – of which only one has an interaction with measure A –, the different effects will be of the same nature. For instance, think of the combination of boiler improvement and wall insulation as measures to reduce the energy use for heating a dwelling. Wall insulation affects the energy use related to the energy loss flow through the walls only. Boiler improvement affects the energy use related to different energy loss flows: through walls, windows, floor, roof, ventilation. Due to the fact that the effects of boiler improvement on each of these flows are all of the same nature, the ratio of

energy savings of boiler improvement related to wall losses
energy savings of boiler improvement related to other losses

will be independent of the variable that characterises the improvement of the boiler. Expressed in general terms (measures A and B treated above), this means that

\[
\frac{ES_B (v_B) \text{ dep}}{ES_B (v_B) \text{ indep}} \text{ is independent of } v_B
\]  \hspace{1cm} (A.95)
And consequent to that:

\[
\frac{ES_B(v_B)}{ES_B(v_B)_{dep}} \text{ is independent of } v_B
\]  

(A.96)

This independence holds, irrespective of the question whether or not an other measure (e.g., A) was implemented before. Thus, from eqs. A.92, A.94 and A.96 it can be concluded that:

\[
\frac{ES_B(v_B)_{after \ A}}{ES_B(v_B)} \text{ is independent of } v_B
\]  

(A.97)

Obviously, this same derivation can be applied to measure A if only a part of \( ES_A \) interacts with measure B.

In conclusion, the above-given considerations point out the reciprocity of the way of interaction that is characterised by a change of parameter "d" in general equation A.90.

Interaction between interchangeable measures

Only two different ways of interaction are distinguished. Taking into account the previous part of this appendix, it is evident that the second way of interaction between measures is reciprocal too.

The fact that interchangeable measures affect each others savings in the same way can be explained by the fact that their effects are of the same nature: they affect "resistances" that have similar functions in the system. This is illustrated very clearly by eqs. 5.11, 5.14 and 5.20: the characteristic variables of both measures play the same role in the general savings-equation.
NUMERICAL EXAMPLE OF AN APPLICATION OF THE PRIORITY CRITERION

In this appendix, an arbitrary example is given of a combination of two conservation measures, defined according to the general equations 5.1 and 5.4. The consequences of the interaction between these measures are illustrated numerically and graphically and their priorities are determined by means of the priority criterion (the PDN, see eq. 5.75).

For the two measures (A and B), the values of the parameters in concern were chosen arbitrarily as follows:

<table>
<thead>
<tr>
<th></th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>ℓ</th>
<th>γ</th>
<th>p_e</th>
</tr>
</thead>
<tbody>
<tr>
<td>measure A</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>1.79</td>
<td>0.8</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>measure B</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>2.02</td>
<td>0.5</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Measures A and B have proportional interactive effects; the value of DS will be taken equal to 0.8*DS_{maxpr}, where DS_{maxpr} is given by eq. 5.64.

Conservation measure A

- Energy savings as a function of \( v_A \), according to eq. 5.1:
  \[
  ES_A(v_A) = \frac{5}{v_A + 0.8} + 2
  \]  \( (A.98) \)

  The curve of \( p_e \cdot ES_A(v_A) \) is shown in fig. A.10.

- The (dependent) expenses are described according to eq. 5.4:
  \[
  EXP_A(v_A) = 1.79 \cdot v_B^{0.3}
  \]  \( (A.99) \)

  This function is shown in fig. A.10 as well.

- By means of eqs. A.98 and A.99, the expenses can be written as a function of the energy cost savings (\( p_e \cdot ES_A \)), as follows:
  \[
  EXP_A(p_e, ES_A) = 1.79 \cdot \left[ \frac{p_e \cdot ES_A}{5} \right] \cdot \left[ 1 - 0.4 \cdot p_e \cdot ES_A \right] = 0.952
  \]  \( (A.100) \)

  This function is presented in fig. A.11 by the full line. The first derivative of this function can be written as (compare eq. 5.3b):

  \[
  \frac{dEXP_A}{d(p_e, ES_A)} = \frac{1.79}{5(0.87/0.84)} \cdot 0.8 \cdot (p_e \cdot ES_A)^{-0.04/0.84} \cdot (1 - 0.4 \cdot p_e \cdot ES_A)^{-1.64/0.84}
  \]  \( (A.101) \)

  or:

  \[
  \frac{dEXP_A}{d(p_e, ES_A)} = 0.37 \cdot (p_e \cdot ES_A)^{-0.048} \cdot (1 - 0.4 \cdot p_e \cdot ES_A)^{-1.952}
  \]  \( (A.102) \)

  This derivative is given in fig. A.12 by the full line. The optimum for measure A is found where this derivative equals unity.
(eq. 5.26); it can be derived (and seen from fig. A.12) that the optimum (point P in fig. 5.15) is at $p_{e, E_B} = 1$, with expenses: $\text{EXP}_{\text{dep}_{\text{opt}}} = 0.63$; $v_{\text{opt}} = 0.27$). The function (A.102) has its minimum at $p_{e, E_A} = 0.05$:

\[
\frac{\partial \text{EXP}_A}{\partial (p_{e, E_A})}_{\text{min}} = 0.442
\]

With eq. (5.62) it follows that:

\[
D_{S, \text{max}} = 1 \times (1-0.442) = 0.558
\]

**Conservation measure b**

- Energy savings function:

\[
\text{ES}_B(v_B) = \frac{5}{v_B^{0.6} + 1}
\]  

(A.103)

- The (dependent) expenses are described by:

\[
\text{EXP}_B(v_B) = 2.02 \times v_B^{0.5}
\]  

(A.104)

fig. A.13 shows both the curves for $p_{e, E_B}(v_B)$ and for $\text{EXP}_B(v_B)$.

- The expenses can be written as a function of the energy cost savings, as follows:

\[
\text{EXP}_B(p_{e, E_B}) = 2.02 \times \left(\frac{p_{e, E_B}}{5}\right)^{0.167} \times (1-0.2 \times p_{e, E_B})^{-0.533}
\]  

(A.105)

This function is given in fig. A.14 (full line).

The first derivative of eq. A.105 reads:

\[
\frac{\partial \text{EXP}_B}{\partial (p_{e, E_B})} = 0.44 \times (p_{e, E_B})^{0.167} \times (1-0.2 \times p_{e, E_B})^{-1.833}
\]  

(A.106)

The full line in fig. A.15 represents this eq. A.106.

The optimum point for measure B (where eq. A.106 equals unity) is found at $p_{e, E_B} = 2/5$; $v_{\text{opt}} = 0.51$. Then, the expenses are:

\[
\text{EXP}_{\text{dep}_{\text{opt}}} = 1.44
\]

The minimum value for

\[
\frac{\partial \text{EXP}_B}{\partial (p_{e, E_B})}
\]

equals 0.597, for $p_{e, E_B} = 0.42$

So, $D_{S, \text{max}} = 2 \times (1 - 0.597) = 0.806$

- Now, eq. (5.64) gives:

\[
D_{\text{max}} p_r = \min \{0.558 , 0.806\} = 0.558
\]

In this example, we choose $D_S$ as follows:

\[
D_S = 0.8 \times D_{\text{max}} p_r = 0.446
\]
Applying the priority criterion

Based upon the data from the individual measures A and B, their "Priority Decision Number" (eq. 5.75) can be determined:

\[
PDN_A = 1 \times \left[ \frac{1-0.63}{0.63} + \frac{1}{5/2-1} \right] = 1.25 \text{ \$} \\
PDN_B = 2 \times \left[ \frac{2-1.44}{1.44} + \frac{2}{5/1-2} \right] = 2.11 \text{ \$}
\]

This means that the ultimate financial benefits of the sequence B-A will be larger than those of the sequence A-B. This will be checked now by calculating the total results for both sequences.

Sequence A-B

The characteristics and the results of measure A are as described above. This means (compare eq. 5.5):

\[
NPV_{A,\text{max}} = 1 - 0.63 = 0.37 \text{ \$}
\]

The curves for measure B, given by the full lines in figs. A.13, A.14 and A.15 change, except for the expenses-curve in fig. A.13. At the point \( v = 0.51 \), the energy cost savings reduce with \( \text{BS} = 0.446 \) to \( p_e,BS_B (0.51) = 2-0.446 = \$ 1.554 \)

Now, due to the fact that the effect of the interaction between measures A and B cause a proportional reduction of the energy savings, the curve for \( BS_B(v_B) \) after A is determined by this value of \( \text{DS} \); this curve is given in fig. A.13, the dashed line. Also, the changed curves for figures A.14 and A.15 are represented by dashed lines. In fig. A.15, the intersection of this dashed line with the horizontal line "1" shows the point where the new optimum occurs; this relates to the point denoted by "R" in fig. 5.15.

The parameter \( dB \) changes from 5 to \((1.554/2)*5=3.885\).

Eq. (A.105) changes into:

\[
\text{EXP}_B(p_e,BS_B) = 2.02 \times (\frac{p_e,BS_B}{3.885} - 0.833 \times (1 - 0.257*p_e,BS_B)^{-0.833}
\]

Of course, its derivative changes accordingly.

The new optimum appears to be at \( p_e,BS_B = \$ 1.131 \), \( v_{\text{B Opt}} = 0.227 \)

Then:

\[
\text{EXP}_B(v_B=0.227) = \$ 0.962 \\
NPV_B = 1.131 - 0.962 = \$ 0.169
\]

So, the total \( \text{NPV} \) for sequence A-B is:

\[
\text{NPV}_{AB} = 0.370 + 0.169 = \$ 0.539
\]
Sequence B-A

From the data mentioned earlier in this appendix, it can be seen that, if measure B is implemented first:

\[ \text{NPV}_B = 2.1 - 1.44 = \$ 0.56 \]

If measure A is implemented after B, with DS=0.446, the savings functions change to the dashed lines in figures A.10, A.11 and A.12.

The parameter \( d_B \) changes from 5 to \((0.554/1) * 5 = 2.77\)

The equations for \( \text{EXP}_A(p_e \cdot ES_A) \) and \( \frac{\partial \text{EXP}_A}{\partial (p_e \cdot ES_A)} \)

The total NPV for sequence B-A becomes:

\[ \text{NPV}_{BA} = 0.560 + 0.031 = \$ 0.591 \]

Conclusion

According to what was indicated by the priority criterion, the sequence B-A yields the largest financial benefits: \( \text{NPV}_{BA} \) is about 10% larger than \( \text{NPV}_{AB} \).
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A10</td>
<td>Energy cost savings and dependent expenses for measure A as a function of ( v_A ).</td>
</tr>
<tr>
<td>A11</td>
<td>Dependent expenses of measure A as a function of the energy cost savings ( p_e \cdot ES ).</td>
</tr>
<tr>
<td>A12</td>
<td>First derivatives of the functions of figure A.11.</td>
</tr>
</tbody>
</table>
Energy cost savings and dependent expenses for measure B as a function of $v_B$

Dependent expenses of measure B as a function of the energy cost savings $p_{e,ES}$

First derivatives of the functions of figure A.14
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SUMMARY

This thesis describes a study in the field of industrial energy conservation, focussed on two questions:

- How can the opportunities for reducing the energy used in an existing production process be found?
- How must decisions be made with respect to the choice between different opportunities, taking into account the fact that they have mutual effects upon each others results?

The starting point for this study was the fact that the energy crisis is not a temporary phenomenon but it is of a structural nature. For industrial - and other - companies this means that they have to be able to adapt themselves to the present and future changes in the energy situation. In many industries - particularly in those which are based on more or less traditional production processes - the know-how required for that is still missing, especially the know-how about the physical behaviour of the processes. Several energy management handbooks etc. suggest analysis methods that can be applied to gain this insight. However, these methods are presented in very general terms and they hardly pay attention to the practical application.

Beside the insight into the physical behaviour, the insight into the financial consequences of possible energy conservation measures is required. The fact that different energy conservation measures mutually affect each others savings is one of the points relevant to decision-making. However, there are no practical methods available that take into account this aspect; as far as we know, nobody has presented a scientific analysis of the backgrounds and the consequences of the interactions between energy conservation measures.

The research started with a study of the literature of methods for analyzing energy conservation opportunities. With respect to the intended field of applications - to wit: energy conservation projects in existing or new industrial production systems - it was concluded that process analysis with help of simulation models is the best way. In such an analysis, it is sufficient to consider only the direct energy use, on an enthalpy basis. More sophisticated methods of analysis (second-law analysis; inclusion of the indirect energy use) are hardly relevant to decision-making in the field under consideration. The same applies to the dynamic behaviour of many processes. Because, in literature, few practical applications were given for searching and developing energy conservation opportunities, we made a detailed case-study for an existing industrial process; this concerned the drying process in a paper-coating machine. In order to derive systematically the possibilities to reduce the energy used, a simulation model was developed for describing the stationary behaviour of the process. This model was developed on a partly analytical, partly empirical basis. By simulating variations for all process parameters and variables, all energy conservation opportunities were found and quantified. Based upon this case-study, a general and practical procedure was proposed for developing simulation models for existing (industrial) processes. Such models make it possible to determine energy conservation measures systematically and, moreover, they contribute to a better understanding of the behaviour of the processes in general.

An analysis of some concrete cases (a.o.: the paper coating machine mentioned above) made it clear that the right choice between different energy conservation measures (= determining the priorities) cannot be made by simply applying economic criteria to the individual measures, because the
effects of the interactions between the measures are ignored completely
then.

The theoretical solution to this selection problem is to optimize the
process by means of a model (as discussed above) and a mathematical
optimization method. However, this solution requires full "information" of
the system: this information must be compressed in the simulation model. In
practice, such a model is available only in exceptional cases and, moreover,
in many cases it is not feasible (on economic grounds) to develop one. These
considerations were the main reasons to go further into this selection
problem.

In literature, a number of methods are found, aimed at decision-making with
respect to the implementation of energy conservation measures. Some of them
were developed for considerations at the macro-level (e.g. energy politics);
others are aimed specifically at the micro-level (the industrial
enterprise).

However, none of these methods gave a fundamental analysis of the
interactions between different energy conservation measures and the
consequences of these interactions with respect to decision-making. That is
why this subject, which can be translated into a selection problem, was
treated extensively, in the last part of this thesis.

A simplified theoretical approach started from the assumption that every
energy conservation measure can be considered as
- either an increase of the resistance to one or more useless energy flows
  (energy losses)
- or a reduction of the resistance to one or more profitable energy flows.

The fact that, in certain cases, the behaviour of the (integrated) process
can be described by means of an electric analogon, illustrates this
assumption. The results of this approach were compared with those of some
cases that were formulated analytically and with those of the case-study of
the paper dryer. Based upon these considerations, a general theory on the
physical interactions between conservation measures was developed which
defines and orders the possible effects of interaction. Starting point for
the analytical approach was the assumption that each conservation measure
can be related to a change of one characteristic process parameter or
variable and that the energy savings and the expenses of the measure can be
expressed as a function of that same variable, by means of general
equations.

With help of the above-mentioned description of the interactive effects, the
financial results of conservation measures implemented in different
sequences, were analyzed. This analysis showed that the differences between
the results of different sequences of measures are determined by both the
physical and financial characteristics of the individual measures as well as
by the physical relationship between them. This means that the priorities
for measures are determined by these aspects.

For the analysis of the financial consequences of the interaction between
conservation measures, it was assumed that the measures are implemented and
optimized one at a time. The differences between the ultimate project
results of different sequences of measures are caused by the fact that, in
general, the potential energy savings of a measure diminish when it is
combined with another measure in the same system. Due to the realization of
a measure, the optimum points of realization of the other measures change
and therefore both the energy savings and the expenses change; however,
these two changes are not the same.

The analysis of the overall interactive effects pointed out that the
priorities for measures (with respect to each other) can be determined
fairly well on the basis of data from the individual measures. Calculations
for a large number of cases covering the whole range of possible
combinations showed that the indication of the priorities so obtained
resulted in the most favourable sequence of measures in 90 % of the cases.
Most of the resulting 10% of the cases concerned combinations of measures for which the differences between different sequences were relatively small. From these results it was concluded that the priorities can be determined and decisions can be made on the basis of limited information: namely, without making calculations for combinations of measures. This was illustrated with combinations of measures from the case-study mentioned earlier.

For general application in energy conservation projects, a decision procedure was developed on the basis of the above-mentioned results. This procedure aims at the most favourable (with respect to ultimate financial benefits) sequence of implementation of measures.

The procedure is based upon a Priority Decision Number (PDN), which can be calculated for each individual measure. This priority criterion cannot be used in stead of the usual economic criteria, but it provides additional information. That is why both the priority criterion and an economic criterion were applied in the decision procedure.

A modified version of this procedure was presented, which can be used in cases in which all conservation measures are considered and realised simultaneously (e.g. for new installations). In such cases, this modified procedure will accelerate the convergence of the optimization process.
SAMENVATTING

In dit proefschrift wordt een onderzoek op het gebied van industriële energiebesparing beschreven, dat gericht is op twee vragenpunten:
- Hoe kunnen in een gegeven produktieproces de mogelijkheden tot vermindering van het energiegebruik gevonden worden?
- Hoe moeten beslissingen t.a.v. de keuze tussen verschillende besparingsmogelijkheden genomen worden, rekening houdend met het feit dat deze elkaar onderling beïnvloeden?

Het uitgangspunt voor het onderzoek is het feit dat de energiecrisis niet een eenmalig, maar een structureel karakter heeft. Voor industriële bedrijven (evenals voor andere instanties) betekent dit dat zij in staat moeten zijn zich aan te passen aan de - huidige en toekomstige - veranderingen in de energiesituatie. Het inzicht dat daartoe vereist is, in het midden het fysisch gedrag van de productiesystemen, ontbreekt nog bij veel industriërs, vooral bij die welke gebaseerd zijn op min of meer traditionele produktieprocessen. Diverse handboeken e.d. op het gebied van energiebesparing geven aan hoe d.m.v. analyse dit inzicht verkregen kan worden. Deze aanwijzingen zijn echter veelal globaal en gaan nauwelijks in op de praktische uitvoering van dergelijke analyses.

Naast inzicht in het fysisch gedrag is in zin ook inzicht in de financiële consequenties van de mogelijke maatregelen van belang. Het feit dat verschillende energiebesparende maatregelen binnen hetzelfde systeem elkaar beïnvloeden is mede bepalend voor beslissingen t.a.v. te nemen maatregelen. Het ontbreekt echter zowel aan praktische methoden die met dit aspect rekening houden, als aan een wetenschappelijke analyse van de oorzaken en de gevolgen van deze interacties.

Het onderzoek is gestart met een literatuurstudie, gericht op methoden voor het analyseren van energiebesparingsmogelijkheden. Voor wat betreft het beoogde toepassingsgebied, te weten besparingsprojecten in bestaande of nieuw te bouwen industriële productiesystemen, wordt geconcludeerd dat procesanalyse, veelal met behulp van simulatiemodellen, de aangewezen weg is. Daarbij kan volstaan worden met het beschouwen van het directe energiegebruik (de proces-energie) op enthalpiebasis. Het toevangen van analyses op energie-basis en het meebeschouwen van het indirecte energiegebruik is nauwelijks relevant voor de te nemen beslissingen op dit toepassingsgebied. Dit geldt in een deel van de gevallen ook voor het dynamisch gedrag van de processen. Omdat in de literatuur voor het zoeken en bepalen van energiebesparingsmogelijkheden weinig praktische aanwijzingen voor concrete gevallen worden gegeven, is een "case-study" uitgevoerd, en wel voor het droogproces in een papier-coatingmachine. Voor het systematisch bepalen van alle mogelijkheden tot vermindering van het energiegebruik is een - grotendeels analytisch, gedeeltelijk empirisch - simulatiemodel ontwikkeld, dat het stationair gedrag van het proces beschrijft. Door voor alle procesparameters en variabelen één voor één variaties te simuleren, zijn alle mogelijkheden tot het verminderen van het energiegebruik geïnventariseerd en gekwantificeerd. Op basis van deze "case-study" wordt een algemene, praktische procedure voorgesteld voor het ontwikkelen van simulatiemodellen van bestaande (industriële) processen. Behalve dat het de mogelijkheid biedt tot het systematisch afleiden van energiebesparingsmaatregelen, draagt zo'n model ook bij tot verbetering van het inzicht in het functioneren van het systeem in het algemeen.

Uit een beschouwing van concrete gevallen (o.m. de bovengenoemde papiercoating machine) blijkt dat de juiste keuze uit de verschillende maatregelen die in een bepaalde situatie mogelijk zijn (prioriteitsbepaling) niet eenvoudigweg gemaakt kan worden door economische criteria toe te passen op de afzonderlijke maatregelen. Dit, omdat dan volledig voorbij gegaan wordt
aan de interactie tussen verschillende maatregelen. Uiteraard is voor dit probleem een theoretische oplossing mogelijk op basis van een model (zie boven) van het desbetreffende systeem en een mathematische optimaliseringsmethode voor het bepalen van de gunstigste combinatie van maatregelen. Dit vergt echter een maximum aan "informatie" in de vorm van een model van het systeem. Meestal is dit niet beschikbaar en bovendien is in vaak gevallen het ontwikkelen ervan economisch gezien onhaalbaar. Vooral op grond van deze overwegingen is in dit onderzoek nader op het keuzeprobleem ingegaan. In de literatuur wordt een aantal methoden beschreven die zijn toegespitst op beslissingen t.a.v. het uitvoeren van maatregelen ten behoeve van energiebesparing. Enkele daarvan zijn ontwikkeld voor beschouwingen op macro-niveau (o.a. energie-politiek); andere zijn doelduidelijk gericht op het micro-niveau.

Kortom, in geen enkele bestaande methode is de interactie tussen verschillende maatregelen in één systeem en de gevolgen daarvan voor de door bedrijven te nemen beslissingen volledig geanalyseerd of verwerkt. Daarom is, in het laatste deel van dit proefschrift, dit keuzeprobleem uitvoerig en in algemene zin behandeld.

Ten behoeve van een vereenvoudigde theoretische benadering is uitgegaan van de veronderstelling dat elke maatregel tot vermindering van energiegebruik beschouwd kan worden als:
- of een vergroting van de weerstand tegen een ongewenste energiestroom (energieverliesstroom)
- of een vermindering van de weerstand tegen een gewenste (nuttige) energiestroom.

In bepaalde gevallen is het dan ook mogelijk het gedrag van het (geïntegreerde) proces te beschrijven met behulp van een elektrisch analogon. De resultaten van deze benadering zijn getoetst aan de hand van analytisch geformuleerde gevallen, alsmede aan de genoemde "case-study". Op grond van deze beschouwingen is ten aanzien van de fysische interactie tussen maatregelen een theorie ontwikkeld welke de mogelijke effecten van interactie bepaalt (definieert) en ordent, en die gericht is op algemene toepasbaarheid. Daarbij is er van uitgegaan dat elke energiebesparende maatregel terug te brengen is tot een verandering van een bepaalde, karakteristieke procesvariabele of -parameter en dat de energiebesparingen en de uitgaven van de maatregel beïnvloed worden door middel van algemene vergelijkingen beschreven kunnen worden als functie van deze karakteristieke variabelen.

Door aan de hand van bovengenoemde ordening het financieel resultaat van maatregelen, gerealiseerd in verschillende volgorden van uitvoering, te analyseren, kon worden vastgesteld dat de verschillen tussen deze resultaten bepaald worden door zowel de fysische en de financiële karakteristieken van de maatregelen zelf als door de fysische samenhang tussen de verschillende maatregelen. Dit betekent dat de prioriteit van maatregelen door deze aspecten bepaald wordt.

Ten behoeve van de analyse van de gevolgen van interactie tussen maatregelen is er van uitgegaan dat de maatregelen één voor één worden gerealiseerd (en voor de desbetreffende situatie worden geoptimaliseerd). De oorzaak van het feit dat verschillende uitvoeringsvolgorden van maatregelen leiden tot verschillende eindresultaten voor het hele project is hierin gelegen dat in het algemeen de bereikte besparingen van een maatregel afnemen - en daardoor het optimale punt van uitvoering verschuift - wanneer deze wordt gecombineerd met een andere maatregel. Daardoor veranderen voor die maatregel zowel de energiekostenbesparing als de uitgaven; deze twee echter niet in gelijke mate.

De analyse van de interactie-effecten toont aan dat de prioriteit van energiebesparende maatregelen ten opzichte van elkaar in 90 % van de gevallen bepaald kan worden aan de hand van gegevens betreffende de afzonderlijke maatregelen. De resterende 10 % zijn voornamelijk gevallen waarin de effecten verhoudingsgevijl gering zijn. Dit betekent dat prioriteiten bepaald en beslissingen genomen kunnen worden op basis van
beperkte informatie: nl. zonder combinaties van maatregelen door te rekenen. Dit is geïllustreerd met behulp van combinaties van maatregelen uit de eerdergenoemde "case-study".
Voor toepassing in willekeurige energiebesparingsprojecten is op basis van bovengenoemde onderzoeksresultaten een beslissingsprocedure opgesteld, welke gericht is op een, financieel gezien, zo gunstig mogelijke volgorde van realisering van de verschillende maatregelen. Deze procedure is gebaseerd op een prioritesgetal (Priority Decision Number; PDN), dat voor elke maatregel afzonderlijk bepaald kan worden. Dit prioriteitscriterium komt niet in de plaats van de gebruikelijke economische criteria, maar verschaft aanvullende informatie. Daarom wordt binnen deze procedure naast dit prioriteitscriterium een economisch criterium toegepast, als een "check" op de economische haalbaarheid.
Deze procedure is in aangepaste vorm ook bruikbaar in gevallen waarin alle maatregelen tegelijkertijd worden gerealiseerd (bijv. nieuwbouw), ten behoeve van versnelling van het -iteratieve- optimaliseringsproces.
CURRICULUM VITAE

STELLINGEN

behorende bij het proefschrift

PRIORITIES IN ENERGY CONSERVATION

A study on the interactive effects of energy conservation measures

van

Willem Willeboer

24 september 1985
De mensheid van de jaren tachtig, die in een eeuw van zich voortdurend versnелde -vooral technische- ontwikkelingen daarvan steeds meer wraak vruchten moest plukken is te vergelijken met een kind dat als joy-rider ver van huis een aanrijding krijgt, merkt dat de brandstoftank leeg raakt en bovendien de weg niet meer weet.

2

De vrede in de wereld wordt niet in de eerste plaats bedreigd door de aanwezigheid van wapens, maar veel meer door de houding van en de verhouding tussen mensen en volken. Vredespolitiek en vredesactiviteiten dienen zich daarom in de eerste plaats te richten op verbetering daarvan.

3

Meer nog dan economische aspecten of overwegingen van schaarste e.d. zullen in de nabije toekomst de gevolgen voor het milieu beperkingen opleggen aan de omvang van het energiegebruik.

4

De Nederlandse economie drijft al zo lang op de aardgasbel, dat ze het zwemmen verleerd heeft.

5

Voor energiebesparing in industriële produktiesystemen zijn principiële verbeteringen van de processen belangrijker dan de voor de hand liggende "standaard"-mogelijkheden zoals warmte-kraakhkoppeling, warmteterugwinning en thermische isolatie, die in feite slechts de "ins" en "outs" van de processen raken.

6

Zolang de huidige motorrijtuigenbelasting niet -geheel of gedeeltelijk- wordt omgezet in een extra heffing op de brandstoffen is het overheidsbeleid inzake energiebesparing en milieubescherming ongelooïerd.
Exergie-analyse is nuttig voor enkele specifieke toepassingsgebieden, maar het feit dat aan deze analysemethode grote waarde wordt gehecht voor elke beschouwing waarin energie een rol speelt, is onterecht.

(hoofdstuk 2 van dit proefschrift)

De prioriteit van energiebesparende maatregelen t.o.v. elkaar kan niet bepaald worden zonder ook rekening te houden met hun fysische samenhang.

(hoofdstuk 5 van dit proefschrift)

De pensioenen van weduwen en wezen van slachtoffers van verkeersongevallen e.d. dienen niet door de overheid (AW), maar door de desbetreffende schadeverzekeringmaatschappijen uitgekeerd te worden.

De achterstelling van weduwnaren met kinderen binnen het Nederlandse sociale bestel dient opgeheven te worden door voor deze groep een pensioen te schappen binnen de AW(n)W.

Teneinde valse verwachtingen en vergeefse sollicitatieprocedures te voorkomen dienen advertenties voor het werken van wetenschappelijk T.H.-personeel vermeld te worden onder de rubriek "vrijwilligerswerk".