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CONCEPTUAL APPROACH TO PROCESS INTEGRATION EFFICIENCY

Doctoral Dissertation

Mari Tuomaala

Helsinki University of Technology
Department of Mechanical Engineering
Laboratory of Energy Economics and Power Plant Engineering

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ABSTRACT OF DOCTORAL DISSERTATION

Author Mari Tuomaala

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Conceptual Approach to Process Integration Efficiency

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Opponent(s) Prof. Theodore Zhelev and Ph.D. Heikki Hassi
Supervisor(s) Prof. Pekka Ahtila and Prof. Markku Hurme

Abstract

Various types of models and methods are used to design and analyze industrial processes. Mostly their use deals with partial system efficiencies like utility system efficiency. A model for treating the entire system has been missing. An integrated industrial process consists of interconnected production processes of the process industry (e.g. pulp and paper, metallurgical, chemical and energy production industries).

The thesis presents a conceptual approach to the evaluation of integrated industrial processes. According to research results, efficiency can be categorized into material efficiency, energy efficiency and operational efficiency. These dimensions are described using criteria and case-specific indicators. The criteria and indicators sometimes represent certain perspectives of design, such as economy or environment.

The concept of efficiency can be attached to systems of varying physical scales. In its narrowest context the scale covers equipment and unit processes. In its largest context the scale covers complete production sites. The scale determines which criteria and indicators are emphasized in the evaluation: technical ones are emphasized on the equipment and unit process scale and strategic ones are emphasized on the site scale.

An important part of the proposed concept is the way in which the potential for improvement is dealt with. The potential for improvement is dependent on the life span phase of the mill, the physical scale of the problem and the number of priority criteria (potential in respect of one criterion versus potential in respect of several simultaneous criteria). The potentials are categorized into three groups: 1) structural (theoretical) potentials, 2) technical potentials and 3) economic potentials. The research also indicates that efficiency improvement activities have to be done in close cooperation with company's operational management. The connection is required to prioritize actions and to implement corrective actions.

The developed concept is qualitative and it is applied on case-by-case basis. The concept does not contain a quantitative analysis; it is used to formulate the problem and to select the correct and detailed tools for the work. The results of evaluation can be utilized e.g. to compare unit processes and process concepts against each other.

Keywords process integration, process industry, efficiency analyses

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VÄITÖSKIRJAN TIIVISTELMÄ

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Konseptuaalinen lähestymistapa prosessi-integraation tehokkuuden arviointiin

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Työn valvoja(t)	Professori Pekka Ahtila ja Professori Markku Hurme

Tiivistelmä

Teollisuusprosessien suunnittelussa ja analysoinnissa on käytössä useita erilaisia laskentamenetelmiä. Niiden käyttö painottuu osajärjestelmien esim. hyödykejärjestelmien hallintaan. Kokonaistarkastelun mallin puuttuessa integroitujen kokonaisuuksien hallinta on ollut vaikeaa. Integroiduilla tehdasprosesseilla tarkoitetaan prosessiteollisuuden (esim. massan- ja paperinvalmistus-, metallurgisen-, kemian- ja energiateollisuuden) tuotantoprosesseja, joiden osat ovat vuorovaikutuksessa toistensa kanssa.

Väitöskirja esittelee konseptuaalisen lähestymistavan integroitujen tehdasprosessien tehokkuuden arviointiin. Tutkimuksen mukaan prosessiteollisuuden tuotantoprosessien tehokkuus koostuu kolmesta osatekijästä, joita ovat materiaalitehokkuus, energiatehokkuus ja käyttötehokkuus. Näitä osatekijöitä kuvataan kriteereillä ja mittareilla, jotka ovat tapauskohtaisia. Kriteereitä ja mittareita voidaan asettaa myös tietyistä näkökulmista esim. talous ja ympäristö.

Tehokkuuden käsite voidaan liittää erilaisiin fyysisiin kokonaisuuksiin. Suppeimmillaan kokonaisuus käsittää laitteita ja osaprosesseja. Laajimmillaan se kattaa koko tehdasalueen. Laajuus määrittelee sen millaiseksi arvioinnin kriteerit muodostuvat: laite- ja osaprosessitasolla korostuvat tekniset tekijät ja tehdastasolla korostuvat strategiset tekijät.

Tehokkuuden arvioinnin ja parantamiseen työkaluksi kehitettiin lähestymistapa, joka avulla voidaan muodostaa käsitys parannuspotentiaalista. Parannuspotentiaalin laskenta on riippuvainen tehtaan elinkaaren vaiheesta, tarkasteltavan kohteen laajuudesta ja laskennassa huomioitavien kriteerien määrästä (parannuspotentiaali yhden kriteerin suhteen vs. usean samanaikaisesti huomioitavan kriteerin suhteen). Potentiaalit jaettiin kolmeen ryhmään, jotka ovat 1) rakenteelliset (teoreettiset) potentiaalit, 2) tekniset potentiaalit ja 3) taloudelliset potentiaalit. Tutkimuksessa havaittiin lisäksi, että tehokkuuden edistämisen ja sen arvioimisen on toimittava yhteistyössä yrityksen operatiivisen johtamisen kanssa. Tämä määrittää tehokkuuden painopisteet. Toisaalta tulokset toimivat johtamistyön apuna.

Väitöskirjassa kehitetty lähestymistapa on kvalitatiivinen ja sitä sovelletaan tapauskohtaisesti. Menetelmä ei sisällä numeerista analyysiä, mutta sen avulla luodaan numeerisen analyysin perusta ja valitaan oikeat laskentatyökalut. Tuloksia voidaan käyttää mm. vertailtaessa eri osaprosesseja tai prosessikonsepteja toisiinsa.

Asiasanat prosessi-integraatio, prosessiteollisuus, tehokkuusanalyysit

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Tuusula, April 2007

Mari Tuomaala

CONTENTS

DEFINITIONS

Concept is an idea of something formed by mentally combining all its characteristics in particulars (Webster's dictionary 1996).

Constraints are expressions that describe requirements or limitations affecting the range of alternatives available to the decision-maker.

Criterion is a characteristic attaching to a thing, by which it can be judged or estimated (Oxford dictionary, 2002).

Decision aid is a tool or process which helps the decision-maker to select one alternative from a set of two or more available alternatives to address a problem or opportunity.

Design method is a procedure, tool or technique for designers to use when designing.

Design methodology is a collection of design methods (procedures, tools and techniques) for designers to use when designing. According to this definition, the process integration methodologies cover all available process integration methods.

Design scale means the geographical size of a design task such as a plant or process.

Efficiency means competency in performance (Webster's dictionary 1996). More specifically e.g. energy efficiency can be defined as meaning the useful output of a process / energy input into a process (Patterson, 1996), or vice versa. Definitions vary in different domains.

Indicator is a measurable (quantitative) or descriptive (qualitative) variable. Each indicator has to be considered in relation to all the other criteria and indicators, and not separately.

Life cycle means consecutive and interlinked stages of 1) a product system, from raw-material acquisition or generation of natural resources to final disposal (SFS-EN ISO 14040; 1997) or 2) a process, from process creation to plant demolition. The term **Life span** is often used interchangeably to emphasize the linear sequence of events in time instead of cyclical nature of the life of an object.

Plant means the realization of the conversion process that takes place on a single site. It consists of equipment and processes.

Process is used to convert raw materials into products and covers the physical and chemical transitions required.

Retrofitting means modification of an existing process or plant. A retrofit design comprises the re-design of a process to improve its performance (Herder, 1999).

System means an organized or connected group of objects (Oxford dictionary, 2002).

Part 1: INTRODUCTION

1 PROCESS INDUSTRY TRENDS

In the process industry, raw materials undergo chemical conversion in a series of stages during their processing into finished products. This thesis covers the pulp and paper, metallurgical, chemical, petrochemical and energy industries.

The paper industry's operating environment has undergone many changes in recent years. One important milestone has been the action plan for sustainable development, the Agenda 21 from Rio Earth Summit in 1992, which encouraged the adoption and reporting of the implementation of codes of conduct promoting the best environmental practice (UN, 1992). The demands for sustainability pose requirements to produce cleaner and inherently safer process designs (Barnicki and Siirola, 2004). The new requirements are shown as e.g. an increasing number of companies issuing sustainability reports. The sustainability issues deal with health and safety, social and economic factors.

The process industry is a substantial consumer of materials and energy. The issues relating to their availability and prices have emphasized their strategic importance (Barnicki and Siirola, 2004; Westkämper et al., 2001). The International Energy Agency (IEA) has estimated that in 2030 the world's energy needs will be almost 60% higher than they are now, corresponding to an annual growth rate of 1.7% per year, and that climate-destabilizing carbon-dioxide emissions will continue to rise, being in 2030 more than 60% higher than now (IEA 2004). Global warming, which is said to be caused by the emission of carbon dioxide and other greenhouse gases, is one of the most discussed anthropogenic effects. The majority of climatological experts confirm that actions are needed to mitigate climate change (Westkämper et al., 2001). The Kyoto Protocol is one such action. Communities across the world are facing water supply challenges (Miller, 2006).

Production in the process industry has become more customer-driven. The trends indicate growing demand for new products with improved performance and shorter product life cycles. Conventional process design has expanded into product-oriented process synthesis and development (Li and Kraslawski, 2004). The supply chains have become more complex as all actors in the supply chain are organizing their operation. These have resulted in requirements such as just-in-time delivery and a requirement for minimized variability in product quality. There is also a tendency to require more technical support from suppliers. As a general consequence of these trends, process industry companies in developed countries are moving out of low-margin commodity and bulk production into specialty chemicals and high-value-added products (Ishii et al, 1997; Cziner et al., 2005b). Alternatively, manufacturing plants have been transformed into efficient and flexible plants satisfying quality requirements and complying with safety, health, and environmental legislation.

Along with these demands, the world of financial markets has changed. A major change has been the availability of international capital, which is searching for attractive investment alternatives. On the international financial market, investors are looking for industries and companies for which the expectation for profitability is high.

The processes in the background of these phenomena have been globalization and the industrialization. Globalization is a broad term dealing with aspects of economics, politics and culture. According to the International Monetary Fund (IMF), the term refers to the ‘increasing integration of economies around the world, particularly through trade and financial flows’ (IMF, 2002). One of the main facilitators of globalization has been the advance in technology of transportation and communication (e.g. Westkämper et al., 2001). Along with industrialization, many countries have developed from agrarian to manufacturing and service-based economies. This has increased the wealth and living standards of those countries. Their consumption of raw materials and energy has increased too, as have the risks of environmental degradation.

1.1 Challenges associated with the use of financial performance controls

Companies are benchmarked against traditional financial performance measures such as gross revenues, net profit, return on assets, and earnings per share. In addition, the measures include more industry-specific indicators such as market share, sales per area, percentage of sales from new products, etc. (Grant, 2002). The basic measures are compiled into financial statements, which provide shareholders with statutory financial information and keep them posted on the organization's performance. Standards exist about how to calculate these measures.

The problem associated with the use of financial measures in the process industry is explained in Figure 1, which presents the factors constituting the Return on Capital Employed (ROCE) in the paper industry. The figure shows which factors contribute to this measure, e.g. costs (like manpower) and uninterrupted operation at the time required. But the method of presentation does not establish a systematic or quantifiable connection between the factors, e.g. the effect of a lower raw material price on the net sales (potentially affecting outcomes such as product quality and thereby customer satisfaction) and on gross production (potentially affecting factors such as the number of breaks and the amount of broke).

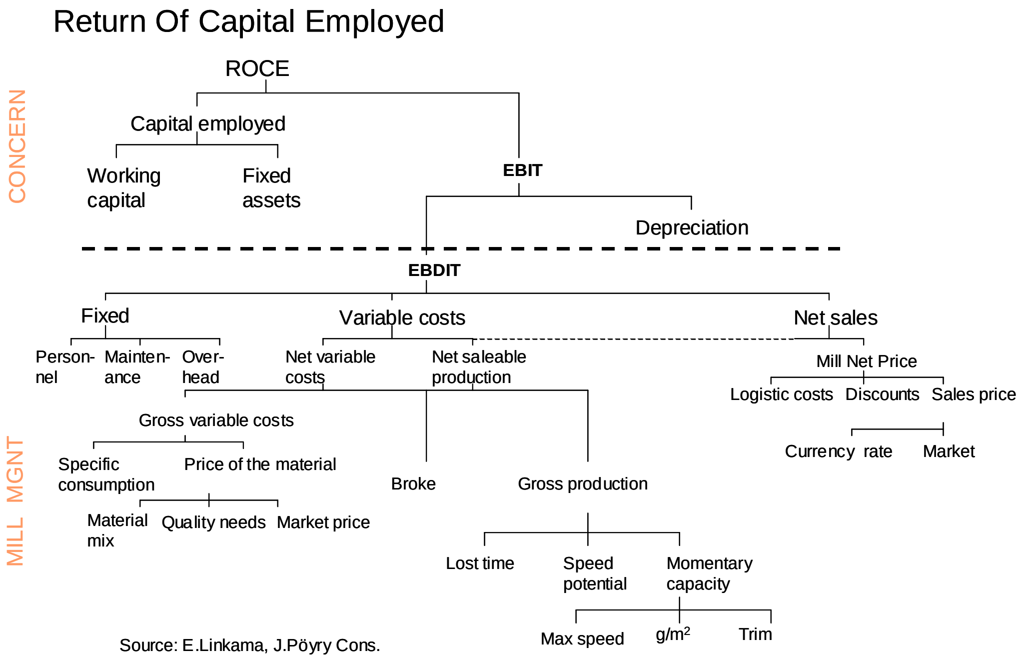


Figure 1. The factors affecting the return on capital employed in the paper industry (Linkama, 2003).

1.2 The challenge of measuring sustainability

Sustainable production from an environmental perspective is defined as *production where the throughput of materials and energy is reduced to a level where the regenerative and assimilative capacities of environmental sources and sinks are maintained* (Wellford and Starkey 1998). In the process industry, sustainable operation is usually understood as successful (economic) operation within the social, environmental and ethical framework. As a consequence, external pressure on companies has increased: the authorities set standards and guidelines and the customers impose demands concerning the consideration of environmental factors. This pressure is different in various parts of the world, and causes inequality among producers.

Environmental protection and increasing ethical discussion has created pressure to identify and report new, non-traditional, and 'non-financial' measures which could be used along side financial performance measures. In the process industry, this means e.g.

measures describing non-waste and resource-efficient production. An example of the movement towards these measures is the Dow Jones Sustainability Index, which tracks the financial performance of the leading sustainability-driven companies worldwide (Dow Jones, 2007).

1.3 The challenge of efficiency in materials and energy use

A part of the process industry is based on the utilization of non-renewable materials such as ore and chemicals. Another part of the process industry is based on utilizing virgin renewable raw materials such as wood logs. The industry is very energy-intensive, although big variations exist within its branches. The share of energy costs as a percentage of total manufacturing costs for some branches is:

Pulp and paper:	Up to 25 % (Paperonline, 2007)
Steel industry:	12-15% (EIA, 2007)
Chemical industry:	Wide variation, from a few per cent up to 85% (EIA, 2007).

Energy savings typically come along with investments and maintenance, and with new technologies. The location of non-renewable energy resources, the threat of climate change, and increasing energy prices have been the main factors driving the process industry to consider energy aspects more.

Another important area is water supply and use, which is leading to closed water circuits in mills. Wastes are recovered for use, and for obtaining a more efficient use of raw materials.

The requirements for cleaner processes have facilitated pollution control but the requirements for profitability and sustainability have facilitated resource-efficient production. This has resulted in the creation of inherently efficient processes and the re-use and recycling of materials and energy. For example, in the paper industry there has been a decrease of over 70% in the discharge of BOD per tonne since the mid-1990s, and the share of recovered fibers is estimated at 46.5% (Paperonline, 2007). The pulp industry’s dependence on natural, renewable raw material has boosted biomass-based electricity production on the same site.

The requirement of resource-efficient and non-waste production has increased the need for systematic analysis tools for energy and materials use in the mills. Process integration is a field of methodologies that was developed to carry out this task. Currently, process integration methods are applied throughout the process industry: chemicals, petrochemicals (including oil refining), pulp and paper, metallurgy, food and drink, and power generation (Natural Resources Canada, 2003). One example of such integration is in the production for heat for industry and society, whereby households utilize the excess heat from factories. Great challenges exist in promoting multi-perspective and large-scale integration in industry.

In parallel with the discussed phenomena, equipment purchases for production facilities have become larger and there has been a shift from single device purchases to larger functional units. In the pulp and paper industry, that has been reflected as increasingly large delivery projects. However, the strategies of the machine suppliers are still dominated by the traditional emphasis on machinery design and construction, rather than a focus on developing, designing or producing integrated process solutions (Kauppinen, 1999).

2 QUEST FOR A NEW APPROACH

2.1 External requirements

When a process plant is built, its expected lifetime is at least 20 years. The life span of mills and machines can be several decades. Over time, the plant equipment wears out, the requirements change and available technologies develop. It follows that at any given time there may a need for replacement.

Changes in the operating environment generate new demands for companies. For example, the demands for sustainable operation are somewhat different in different parts of the world at the moment. On the other hand, the demands create new opportunities. For example, effectively dealing with climate change requires deep technical changes. The main consequences have been the improvement in the efficiency of fossil fuel use and breakthroughs in the use of renewable energy sources.

The change trends (Chapter 1) have created a need for the process industry to see itself within the larger environment. It is expected that social factors such as sustainability, climate impact, impacts of operation over the whole life cycle, labor utilization, and human security will become ever more important in the future. For this, business leaders and strategic managers need new knowledge and new models that will allow them to guide their firms to economic success and simultaneously to minimize the stress imposed on the ecosystem. A generic unifying framework is needed to systematically assist decision-makers to make design/investment decisions in the presence of uncertainties throughout the process life cycle (Stead and Stead 1998; Cheng et al., 2003; Barnicki and Siirola, 2004).

2.2 Coping with design complexity

A process plant consists of several process units with complex piping arrangements between them (Figure 2). In the pulp and paper industry, there is a need to reduce local environmental impact through system closure and reduced water usage. However, water-system integration is just a partial solution to the problem as there are many other significant factors too. The general demands include: to reduce and plan capital, reduce operating costs, improve efficiency with regard to raw materials and utility consumption, minimize waste and increase throughput. Other notable aspects are operability, flexibility, controllability and safety (Gundersen, 1997; Natural Resources Canada, 2003.).

Enhancing one feature in a process plant may worsen another. For example, water systems are in complex interaction with energy systems, and reduction in water usage may lead to an increase in energy consumption. Also, water and its quality are closely coupled with the quality of the product. Good operability of a paper machine as such would not be compromised through any integration activity.

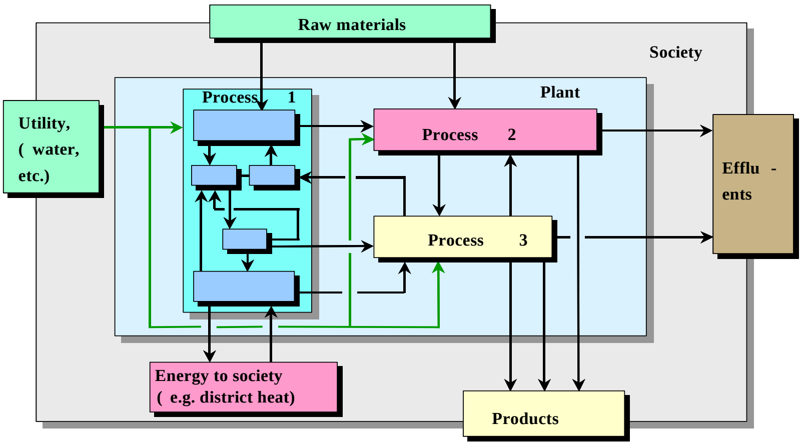


Figure 2 . Schematic presentation of a process plant (Söderman and Ahtila, 1998).

The larger the system is, the more difficult it becomes to evaluate how good it is. This is because increasing complexity increases the number of design and evaluation criteria, their interactions and the involvement of strategic aspects. According to Herder (1999), physical connections between sites exist mostly between their product and raw material flows. Heat integration between plants is seldom made since the plants are separately energy-optimized. Also, the distances between the process units are long or the vulnerability of the plants (as one plant goes down, the other will go down with it) is seen as critical.

Strategic outsourcing is one method in the search for new saving opportunities. Outsourcing is the purchase of a value-creating activity from an external supplier (Hitt et al., 2003). Companies are outsourcing those operations that are not considered to be their core businesses. Outsourcing is seen to increase the efficiency and flexibility of operation and to decrease costs. It is seen as one of the major contributors to the reduction of process plant personnel. In particular this means the personnel directly responsible for process development as well as mill personnel involved directly in searching for and developing fundamentally new process concepts.

2.3 Summary

Sections 2.1…2.2 delineated the conditions within which process design/evaluation is carried out. Many simultaneous factors have to be considered. Optimal balancing of the factors is difficult.

The existing engineering practices are capable of producing partial solutions for the problem. For example, the quantitative financial appraisal methods emphasize the monetary factors in decision-making, but do not emphasize qualitative factors such as operability of the plant. The mathematical methods are most useful in treating small-scale or simplified problems, but they are difficult to apply to large-scale industrial problems. In addition, the tools developed to serve engineering purposes are typically focused on solving specific problems. Pinch Analysis, which is a process integration tool (see Chapter 4), is one example of such an engineering tool. On the other hand, the tools developed for management purposes do not take the engineering aspect into account, e.g. the Balanced Scorecard by Kaplan and Norton (2001).

3 RESEARCH APPROACH

3.1 Research question

The objective of the research is to develop a conceptual approach to process integration efficiency. Consequently, the objective is to:

Develop an approach which supports the design of efficient integrated industrial processes and their efficiency evaluation. The approach should take into account the requirements of materials and energy use, the requirements of operation and the requirements posed by business management.

The approach would be used to develop and manage integrated processes in the process industry. The approach should take into account the opportunities and requirements posed by business management. It should be capable of considering a variety of design and evaluation criteria. A major feature should be the ability to indicate the potential for improvement. The approach must be applicable on various plant scales and on various life span phases, from process design to operation and retrofitting (excluding building and start-up).

The new approach aims to combine the existing practices and to complement them. It also aims to combine academic approaches and practical insights in order to serve the needs of the industry.

The research question covers the following:

Enhanced target-setting

A framework for operational efficiency from the business perspective is needed. It must incorporate those objectives that management has established for operation. The framework will be used to set priorities, and to allow faster responses for required changes.

Comprehensive design and evaluation criteria

1) Processes are described through criteria and indicators, which exist in both quantitative and qualitative form. Quantitative information increases towards the end of the process life span. As the amount of data increases, it becomes difficult to separate relevant information from the less relevant. The quantitative data is most emphasized due to its adaptability with the design methods and its convertibility into costs. 2) The criteria and indicators have interdependencies. The exact interdependencies are often poorly understood when it comes to the design of large complexes. 3) The layers of information are hierarchic. Different data is used in the design and evaluation of equipment, processes and plants.

An approach is needed to identify the relevant criteria for the design and evaluation of integrated industrial processes.

Enhanced use of process integration methods

Process integration is seen as an important means of progressing towards resource-efficient production. Its methods have developed greatly in recent years. Along with their development it has become difficult to see the fundamentals behind the methods.

The exact definition of process integration and its methods is needed in order to facilitate their development and their use in industry. A definition should describe the benefits of the methods' use.

Potential for improvement

Conventional process integration deals with the optimal use of raw materials, water and energy. In existing processes, savings have been made by using these resources in an optimal way. In practice, process integration results in increased re-circulation and recovery of mass and energy flows. Potential for improvement exists in areas such as secondary heat use, wastewater recovery and reuse, and utilization of waste flows.

The concept ‘potential for improvement’ needs to be clarified. This means e.g. how the potential for improvement can be quantified within a particular technical system. The information is needed in all phases of the process life span.

3.2 Research method

Research dealing with efficiency in industrial production processes is fragmented on many areas and the interdisciplinary nature of the study was acknowledged at the start of the research period. Thus, two concurrent processes were started: the literature surveys and the experimental work (the industrial case studies).

3.2.1 Theory reviews

To cover the main research objectives, the following theories were reviewed:

- The theories on process integration and the process integration methods. Since the process integration methods and process synthesis methods are partly overlapping, the theories of process synthesis were studied. The concept of process synthesis was opened by reviewing the theories of process design, retrofitting and investment practices (Chapters 4 and 5).
- The theories on existing design and evaluation criteria and indicators together with industry practices (Chapter 6).
- The theories discussing decision-making in complex systems (Chapter 7).
- The theories about business management. This was done to study the possible intersections between engineering efficiency and business operational efficiency (Chapter 8).

The method development was supported by findings from the case studies. These findings are referred in the theory chapters.

3.2.2 Experimental work

The experimental work consists of about six industrial case studies. Two of the studies were carried out in co-operation with a collaborating company. That determined the main scope and scale of the studies. More generally, the objectives of the case studies were formulated to capture the research question (Section 3.1). That covered areas such as differences among industry fields, differences within process life cycle phases and different problem scales. A matrix-type presentation of the case objectives is available in Table A1 in Appendix 1.

3.2.3 Method development

The work between theory review and the experimental work was interactive. The objectives of both works were revisited when needed (Figure 3). Conclusions from the case studies were derived to support the theory reviews and concept development. Two of the six case studies were carried out to validate the parts of the concept.

At the end of the research period it became evident that no single case study can validate the concept as a whole. The cases in Appendix 1 reflect the multitude of different process integration problems.

The findings from each case study are documented in the *Conclusions sections* of Appendix 1. Other observations, i.e. the ones supporting the particular research discipline (e.g. energy research), are not documented in the Appendix 1.

3.3 Structure of the thesis

The thesis consists of four parts:

Part I:	Introduction
Part II:	Theory
Part III:	Results and Conclusions
Part IV:	Appendix 1 (Industrial case studies)

Part I introduces the problem and the structure of the thesis. Part II contains a study about the relevant theories with references to case studies in Part IV (Appendix). Part III collects the findings into elements of the concept and presents how they are used together in the design and evaluation of integrated process systems.

The industrial case studies supporting the theory reviews are given in Appendix 1. This is to highlight the case findings.

The thesis consists of the following chapters (Figure 3):

Part I: Introduction

1. Chapter one introduces the research problem against the process industry trends.
2. Chapter two specifies the need for a new method.
3. Chapter three presents the research methodology and the structure of the thesis.

Part II: Theory

4. Chapter four introduces the history of process integration and discusses the various definitions for the term ‘integrate’.
5. Chapter five provides insights into design theories and their methods.
6. Chapter six is a study of design and investment criteria.
7. Chapter seven is a study about the ways of making decisions in complex designs.
8. Chapter eight discusses business management.

Part III: Results and conclusions

9. Chapter nine summarizes findings about efficiency in process design and presents new definitions for process integration and its methods.
10. Chapter ten collects the findings from Part II into elements of the concept.
11. Chapter eleven describes the methodological use of the concept.
12. Chapter twelve concludes the thesis.

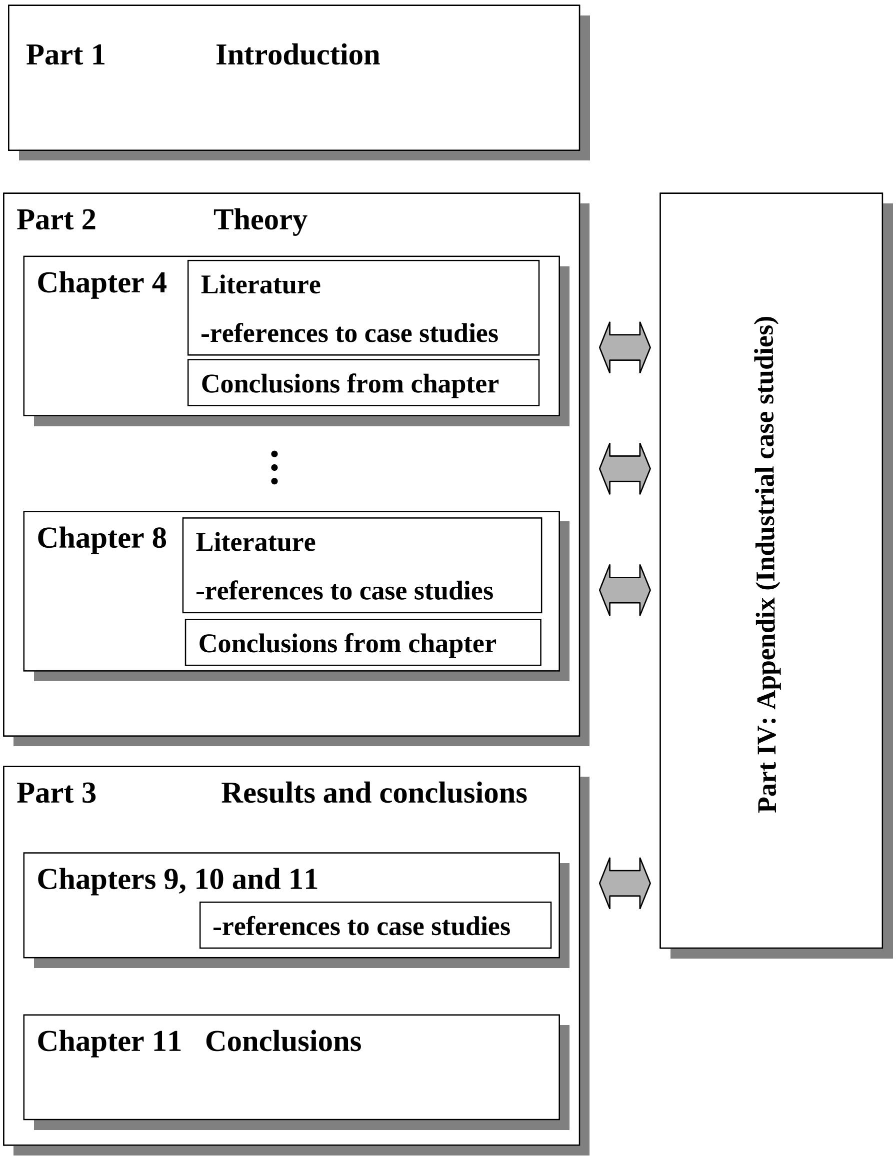


Figure 3. Outline of the thesis.

Part IV: Appendix

Appendix 1 contains all relevant data and findings from the industrial case studies, to which references are made in the theory (Part 2) and results (Part 3) sections. The cases include:

Case 1. Integration at the conceptual design phase. The study clarifies the opportunities for integration at preliminary process design phases especially in chemical process and plant design.

Case 2. Energy management. A survey is made of the concepts and methodological issues related to energy efficiency measurement in the pulp and paper industry.

Case 3. Paper mill water management. A new water integration management tool is analyzed and further developed.

Case 4. Steel mill process retrofit. A study is made to analyze the mill-wide effects of a process change.

Case 5. Bio-fuel drying in a power plant. A new concept for drying moist bio-fuel in a power plant is evaluated. A conventional approach is supported by applying the draft elements of the proposed concept.

Case 6. Business management material in design. Availability and applicability of the proposed business management material (Chapter 8) is discussed.

Part 2: THEORY

4 INTEGRATED PROCESS DESIGNS

4.1 Objective of the chapter

The objective of the chapter is to clarify the various interpretations of the term ‘integrate’.

The history of process integration began with the introduction of a fundamentally new concept of heat exchanger network synthesis in the 1970s. The pioneering work was a study by Hohmann (1971). That was followed by the discovery of Heat Recovery Pinch in the late 1970s. Process integration was seen as a synonym for heat recovery (Gundersen, 2002). Over the years, process integration methods have developed a great deal. They now cover a wide range and scale of applications. Along with the development it has become difficult to define what process integration means and what is gained by the use of the methods. In addition, the term ‘integrate’ is also used in other contexts. Mostly it is used in disconnection with the process integration design discipline. An example is an ‘integrated pulp and paper plant’.

4.2 The process integration design discipline

4.2.1 The Heat Recovery Pinch

The studies by Umeda et al. (1978) and Linnhoff and Flower (1978a,b) have been milestones in the systematic synthesis of heat exchanger networks using Pinch Analysis. The Heat Recovery Pinch was a new concept in the connection of unit processes and process flows to save energy. The development that followed the discovery of the Heat Recovery Pinch has been unique in process design (Westerberg, 2004; Sargent 2004).

In the Heat Recovery Pinch the process's external heating and cooling energy requirements are obtained from a temperature vs. enthalpy diagram (Figure 4). The 'Composite Curves' of the diagram give the cumulative cooling and heating requirements of a complete process in a single picture. The point where the two curves come closest is called the 'Pinch'. The overshoot of the cold composite curve represents the minimum requirement for hot utility Q_{Hmin}, i.e. the minimum external thermal energy requirement. The overshoot of the hot composite curve represents the minimum cold requirement for utility Q_{Cmin}, i.e. the minimum external cooling duty requirement. Pinch Analysis aims to identify heat recovery potential between process streams of different temperatures, eventually leading to the design of efficient heat exchanging networks. For more, see e.g. Linhoff (1994).

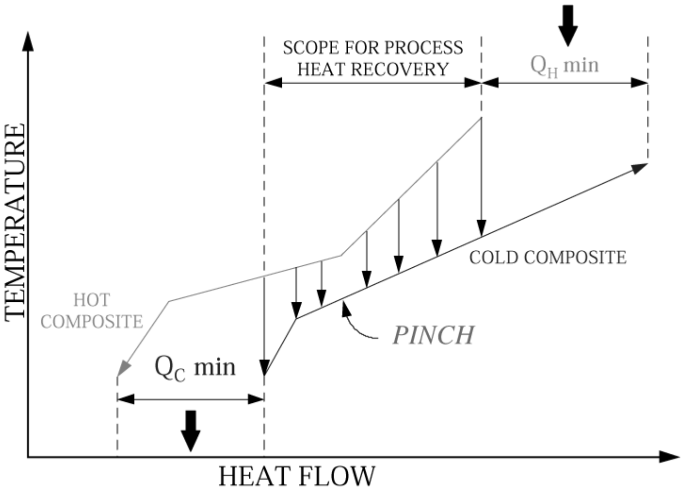


Figure 4. An example presentation of the Composite Curves.

Another early application was the 'Grand Composite Curve'. That presents a temperature enthalpy profile of the external heating and cooling utility requirements after heat recovery has taken place. For more, see e.g. Linnhoff (1994).

4.2.2 Other applications of the Pinch principle

During the late 1980s and the 1990s, through the use of analogies, the basic concepts of Heat Recovery Pinch expanded into Mass Pinch, Water Pinch, Hydrogen Pinch, Flue-gas Pinch and Oxygen Pinch (El-Halwagi, 1997; Gundersen 2002; Zhelev, 2005). A Network-Pinch was developed to overcome the difficulties in the use of the Pinch principle in a heat exchanger network retrofit (Asante and Zhu, 1996).

These methods have not gained as much popularity as the Heat Recovery Pinch. One of the reasons may be their limited applicability to industrial problems. For example, the realm of mass exchange includes process operations such as absorption, adsorption, extraction and ion exchange (El-Halwagi, 1997). Oxygen Pinch is developed for the biodegradation of organic waste through aerobic degradation (Zhelev, 2005).

4.2.3 Large-scale Heat Recovery Pinch applications

The concept of Heat Recovery Pinch is further applied to time-dependent integration (batch processes), to the combined heat and power analysis, including co-generation, and to the total site analysis, including utilities, heat and power, and flue gas (Zhelev, 2005; Zhu and Vaideeswaran, 2000).

The total site analysis means a thermal analysis of a site. Such sites involve several individual processes. In the total site analysis the heating and cooling requirements of each individual process are represented using a Grand Composite Curve. They can propose different steam levels and heat loads. The way forward is to compose total site source and sink profiles from the individual Grand Composite Curves. These profiles allow targets to be set for the utility requirements of the whole site. This is then used as e.g. a target for co-generation from steam turbines (Smith, 2000; Zhu and Vaideeswaran, 2000).

4.2.4 Combined resource management

In industrial processes, energy streams and mass streams are interconnected. In chemical processes, e.g. reaction rates and equilibriums are affected by temperatures. In a pulp mill, a stock carries water, fibers and energy. Attempts aimed at combined water and energy minimization are reported in many sources (e.g. Smith et al., 1997).

Many of the novel applications (see Section 4.2.5) deal with process integration at preliminary process design phases, where multiple resources must be considered at the same time. This was also discussed the Case 1 'Integration at the conceptual design phase'. It was found that process design is about dealing with multiple performance criteria throughout the design life cycle. Demand for efficient mass and energy utilization is only one subset of the requirements.

4.2.5 The state-of-the-art in integration

Pinch Analysis and heat recovery projects are still perhaps the majority of the process integration projects, although a wide range of other analysis methods exist for analyzing, simulating and optimizing energy and material flows in industrial processes. Scientific attempts are continuously made to develop industrial processes using the Pinch principle (see e.g. Nordman, 2005).

The modern methods combine different solution techniques. The insights of physics and thermodynamics are supported by mathematical methods and the use of heuristics. The Pinch principle is not necessarily considered in them. The combined use is seen in several new methods (e.g. Tveit, 2003) and noted by several authors (e.g. Smith, 2000; Zhu and Vaideeswaran, 2000).

The new process integration methods aim to identify the most appropriate flow-sheet structure, and to optimize process parameters such as flow rates, temperatures and pressures (Rossiter, 2001). As the methods have developed the applications have become wider and the tasks more complex. Continuous attempts have been made to consider multiple design criteria.

Recent achievements include energy saving and gas emission reduction, water saving and waste-water minimization; efficient raw-materials use; process de-bottlenecking; process operations and process optimization (Hallale, 2001; Smith 2000). According to Zhelev (2005) a recognized way in the late 1990s was to cover combined heat and mass transfer processes. Recent advances in raw material and energy integration are given in Table 1.

Table 1. Recent advances in process integration according to Hallale (2001).

Energy efficiency	Raw material efficiency
- design of complex distillation systems - dividing-wall distillation columns - separation of azeotropic mixtures - thermodynamic analysis of distillation - design of absorption separation systems - cogeneration and site utility systems - design of cooling-water systems - design of low-temperature systems - automatic design of heat-exchanger networks - retrofit of heat-exchanger networks - heat-exchanger-network design using intensified heat transfer - power station design	- design of novel reactor systems - design of reactor-separator-recycle systems - reactive distillation - design of solvent-based separations - hydrogen integration in petroleum refining - integrated combined cycle gasification processes

Many of the recent advances fall into the category ‘efficient operation’ of the processes. This covers applications for de-bottlenecking (e.g. utility system capacity increase), applications to improve process unit operations (e.g. reactor design) and applications to improve operation (Hallale, 2001; Smith, 2000). The last category includes applications for scheduling and operation of batch processes, applications to optimize operating conditions (feed, product price, shut-down periods, etc.) and applications to maximize profits in operation.

Advances in the field of efficient operation can be seen to overlap with the field of production control. There, its functions can be divided into four levels (Uronen, 1987): 1) Long-range planning (a time horizon up to 7 years), 2) Production planning (a time horizon up to some weeks), 3) Production control (a time horizon from hours to a few days) and 4) Process control (a time horizon from seconds to hours).

4.2.6 Motivation for process integration

An aim of process integration is to reduce operating costs. The other aims include debottlenecking for increased throughput and the reduction of emissions by using mass and energy more efficiently. More generally, the process integration methods are applied to explore the trade-off between capital costs, operating costs and environmental impact (Rossiter, 2001). For example, the heat exchanger network design involves optimization of capital and energy costs.

4.2.7 Benefits and drawbacks of the Pinch Analysis approaches

The Composite Curves and associated design rules establish performance targets before the actual design has started. The whole process is analyzed at a time. One of the reasons for the success of Pinch Analysis is in the method's simplicity and transparency.

Energy savings will be obtained by reducing intrinsic energy consumption. That provides an opportunity to reduce combustion-related emissions simultaneously. The Pinch Analysis approaches are seen to result in: 10%…35% savings in energy consumption, 25%…40% in water consumption and up to 20% in hydrogen consumption (Natural Resources Canada, 2003). Process integration is seen as a major development in comparison with the former practices, were mass and energy were optimized with a limited scope of considerations. For example, energy utilization was optimized in unit operations and heuristics was used to arrange the connections between them.

The drawback of the Pinch Analysis approaches is that they consider a limited number of criteria simultaneously, i.e. they mostly deal with the management of a single resource. Another drawback is in their methodological hierarchy. This leads to the approaches being incapable of considering later changes in process conditions, such as slight changes in stream temperatures that could lead to a more desirable solution.

Moreover, Pinch Analysis approaches are not flexible enough to treat large-scale industrial problems, where the number of possible matches between the streams increases exponentially.

In large-scale applications, like the total site energy analysis, it is important to note how the process parts interact with each other. E.g. changes made to the process may affect steam usage/ generation at a certain steam level and generates a change to the 'site Pinch' of the utility system configuration. A change in the site Pinch has a knock-on effect on the configuration of the existing utility system (Zhu and Vaideeswaran, 2000).

4.3 The history of process integration definitions

Over the years there have been several attempts to define process integration. A study of the most well-known definitions reveals that it has become difficult to describe the fundamental principle behind process integration:

In 1993 the International Energy Agency (IEA) defined process integration to include: *Systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and reducing environmental effects* (Gundersen, 2002). By this definition, process integration is seen as a group of methods to optimize the use of energy, but with concerns for environmental aspects.

In 1997 the IEA broadened their definition of process integration to mean *the application of methodologies developed for system-oriented and integrated approaches to industrial process plant design for both new and retrofit applications* (Gundersen, 1997). Along with this the optimum of the *system* became a goal, and a need for the method's applicability throughout the life cycle was recognized. Later, Natural Resources Canada (2003) defined process integration as *all improvements made to process systems, their constituent unit operations, and their interactions to maximize the effective use of energy, water and raw materials*. In the Finnish process integration technology program, process integration was defined to mean: *integrated and system-oriented planning, operation and the optimization and management of industrial* *processes* (Timonen et al., 2006). The operation and management aspects are emphasized in the Finnish definition.

The above definitions describe the objectivity of a process integration task rather than the principles through which the enhanced situation is achieved. Rossiter and Kumana (1995) state that process integration methods: *focus on ensuring that existing process technologies are selected and interconnected in the most effective ways rather than attempting to invent new types of equipment or unit operations*. This definition slightly touches the potential synergic effects which will be achieved by integration. According to the definition by El-Halwagi (1997), integration *emphasizes the unity of the process*.

4.4 The other uses for the term 'integrate'

Generally, the verb 'integrate' means putting or bringing together parts or elements so as to form one whole or to combine something into a whole (Oxford dictionary, 2002). Thus, an 'integrate' is made of separate parts or composites, now connected and belonging to a whole. This context is typical in the process industry. For example, coating and supercalendering can be integrated online into the paper machine. The larger-scale examples include (Diesen, 1998):

A) Vertical integration

- Vertical integration means that the end-product of one manufacturing unit is the raw material of another. Vertical integration is close and sometimes seen as being synonymous with geographical integration. Geographical integration means co-operation between different units located in close geographical proximity, usually on the same mill site.
- A vertically integrated iron and steel works consists of several unit operations, including agglomeration of concentrates, coke-making, iron-making in blast furnaces, steel-making in converters, ladle metallurgical treatments, continuous casting, hot rolling and other eventual finishing processes. The benefit from integration is achieved e.g. as dusts and scales returning to the sintering stage to increase material efficiency.

- A vertically integrated pulp and paper mill (chemical pulp production and paper production) consumes about 25% less energy per produced ton of paper than a non-integrated paper mill (Vanhatalo, 2002). The setup is beneficial because energy steam consumption is better optimized between the mills, and pulp can be pumped directly to the paper mill, requiring no drying before transportation.

Case 4 'Steel mill process retrofit' deals with vertically integrated steel manufacturing. Case 3 'Paper mill water management' deals with water management at a vertically integrated paper mill. Case 5 'Bio-fuel drying in a power plant' evaluates the benefits of drying moist bio-fuel (bark from a paper mill) using various sources of heat energies (e.g. secondary energies from a pulp mill) to increase efficiency in power production.

B) *Horizontal integration*

In horizontal integration, different units use the same raw-material base. An example is a sawmill and a pulp mill.

C) *Financial integration*

Financial integration means co-operation between geographically separated units based on common ownership. Objectives include: 1) efficient use of investment funds due to economies of scale, and better opportunity to direct investments where needed. 2) decreasing sensitivity to fluctuations in national and regional economies or fluctuations in demand for a certain product or grade. 3) improving efficiency by organizing operations on the basis of what is produced and where.

In these examples, an increase in efficiency is gained through optimized material and energy use and through decreased sensitivity to risks caused by price and availability fluctuations.

4.5 Chapter findings

Process integration is traditionally applied to increase efficiency in energy and materials use and to reduce emissions. The application areas have extended from traditional heat and utility network design at the green-field and retrofit design stages towards the process synthesis stage.

In a more general meaning, *integration* is understood as a means to combine process parts and production units into bigger entities. Motivations for that include minimized treatment of intermediate products. This is done in disconnection with the process integration design discipline.

A target in both approaches is to create systems in which the elements are interconnected, *integrated*. The integrated system is an aggregate concept, which emphasizes the unity of the process. Synergy is achieved through increased efficiency as compared with a situation in which the parts would perform the tasks separately. As applied to industrial processes, process integration increases re-cycling and re-use of energy and material streams. Process integration is generally seen to lead to more efficient and environmentally friendly processes. Integration of large industrial process sites is generally seen to lead to a more undisturbed operation (caused by factors external to the company) and to cost savings.

5 DESIGN PROCESS

5.1 Objective of the chapter

The objective of the chapter is to clarify the differences between process integration and process design, especially the synthesis part of it. This is done because many of the recent advances in process integration and in process synthesis have been reported from overlapping areas.

The reason for this is an overlap in the solution techniques of process synthesis and process integration. To capture the role of synthesis, an introduction to process design, retrofit and investment procedures is given. Examination of the subjects allows one to see how efficiency is created in process designs.

5.2 Introduction to process design

5.2.1 A green-field design process

A *process design* is defined to mean designing a new process or modifying an existing one. A *plant design* is defined to mean designing a complete plant including auxiliaries (OSBL systems). A plant design covers both process engineering and detailed engineering (mechanical, civil, electrical) and includes plant layout, service facilities and location factors.

Before starting the work the designer should obtain as complete and unambiguous a statement of the design requirements as possible. This is usually called a design specification or a Basis of Design (BoD). In that, the design requirements are categorized into real needs and ‘wants’. The wants are those parts of the initial specification that are thought to be desirable, but which can be relaxed if required as the design develops. Identification of quality demands for a design is discussed in e.g. in Herder (1999) and Smith (2005). The product specification plays a vital role in the formulation of a design problem. In chemical engineering, product and process design is carried out in parallel, except in the bulk product industry, where product design is not needed.

Process design (Figure 5) starts with idea generation, and continues until the process is built and tested. The design steps vary according to the scope and scale of the project. Additional steps may include a research phase or a development phase. A design process may involve multiple decision-making points and several iteration loops. During the design process, the designer is constrained by many factors, which will narrow down the number of possible designs. Some of the constraints are fixed and invariable (e.g. physical laws, codes and standards) and some are more adjustable (Sinnott, 1999).

In the *problem analysis* and *data collection* phases the design goals, constraints and evaluation criteria are defined and economic feasibility studies are performed. All relevant facts and data required (physical property data, information about equipment, patents, plant location, lifetime aspects etc.) are assembled in a relevant form. A *market study* will be carried out to estimate demand, price and quality development in the future. In the pulp and paper industry, that typically includes a supply estimate for 2-3 years as well as an analysis of competitors' medium and long-term supply behavior. A supply estimate deals with known investment and probable projects, expected shutdowns of paper mills and paper machines, and estimated total capacity increase through minor investments and improvements (Diesen, 1998). Production capacity and major costs are determined during the preliminary process development stages.

Design continues with the *conceptual design phase*, in which process alternatives are developed through process synthesis, analysis and optimization. At this stage all potential process alternatives are developed and feasible process alternatives are examined. This stage is also called the 'synthesis phase' or 'process creation phase' (Biegler et al., 1997; Peters et al., 2003). The conceptual design phase may result in several entirely different profitable processing alternatives (flow-sheets) with which the work continues. At the *process selection* phase the feasible process alternatives are examined in detail. Modeling, simulation and optimization are applied to evaluate selected process alternatives until the final flow-sheet is available. The plant designer may also use a superstructure optimization approach to accomplish this.

The designer then starts designing the supporting network, i.e. heat and other utility. Heat and utility network design is performed using simulation and optimization models. A careful examination of process conditions is made. The design continues with the *detailed design phase,* in which the process flow-sheet, process piping and instrumentation diagrams and process equipment drawings are completed.

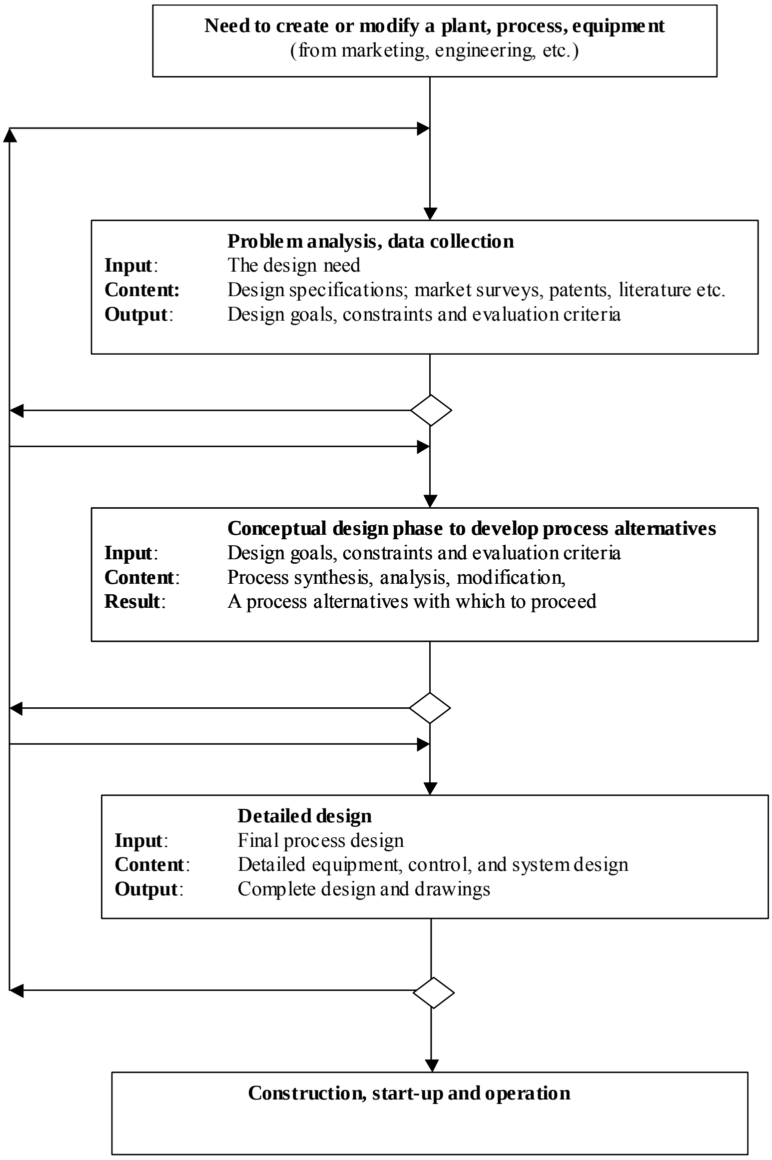


Figure 5. General design process.

5.2.2 Retrofit design project

The aim in a *retrofit* design project is to modify an existing process or plant. The number of process design and integration possibilities is limited by the existing plant, equipment and surroundings. The main process equipment, for instance, will not be changed. In most retrofitting projects, a part of the process is modified or re-built. For that part, the process design case is analogous to a green-field design, with options to integrate with the surroundings and with possibilities to synthesize that process part again. If the process chemistry remains untouched, a partial synthesis of the process is performed, e.g. changing the order of process equipment, connections or recycle flows. Typically, a retrofitting project has more constraints on the design process than a green-field design. Otherwise the same design principles and methods apply.

5.2.3 Investment design project – industry example

A typical investment project comprises (Diesen, 1998):

1. Pre-feasibility studies - a preliminary process and plant design for the purpose of carrying out a preliminary profitability and cost analysis. A market analysis is made and information such as raw materials prices is collected.
2. Basic engineering - a more detailed process and plant design, applications for necessary permits, inquiries and specifications for main machinery.
3. Feasibility studies – a reviewed profitability and cost analysis, construction schedule and financial plans.
4. Detailed planning.

The steps vary according to the scope and scale of the project. Iteration loops and decision points exist.

5.3 Process synthesis as part of the design process

The term synthesis means the putting together of parts or elements so as to make up a complex whole (Oxford dictionary, 2002). In the process systems engineering literature it traditionally means the first step of flow-sheet structure development, i.e. the (initial) selection of operations, their interconnections and the initial values for variables (Figure 6a). The next step after synthesis is *process analysis*, which involves solving the heat and material balances, sizing and costing of the equipment, and the *design evaluation*. The final design is obtained through *process optimization*. The process is optimized either by modifying the process parameters, i.e. temperature and pressure levels within a fixed flow-sheet, or modifying the process structure by changing the equipment type and/or interconnections.

More widely, synthesis means the flow-sheet structure development and all of its sub-tasks (Figure 6b). This interpretation is used more in algorithmic flow-sheet structure development.

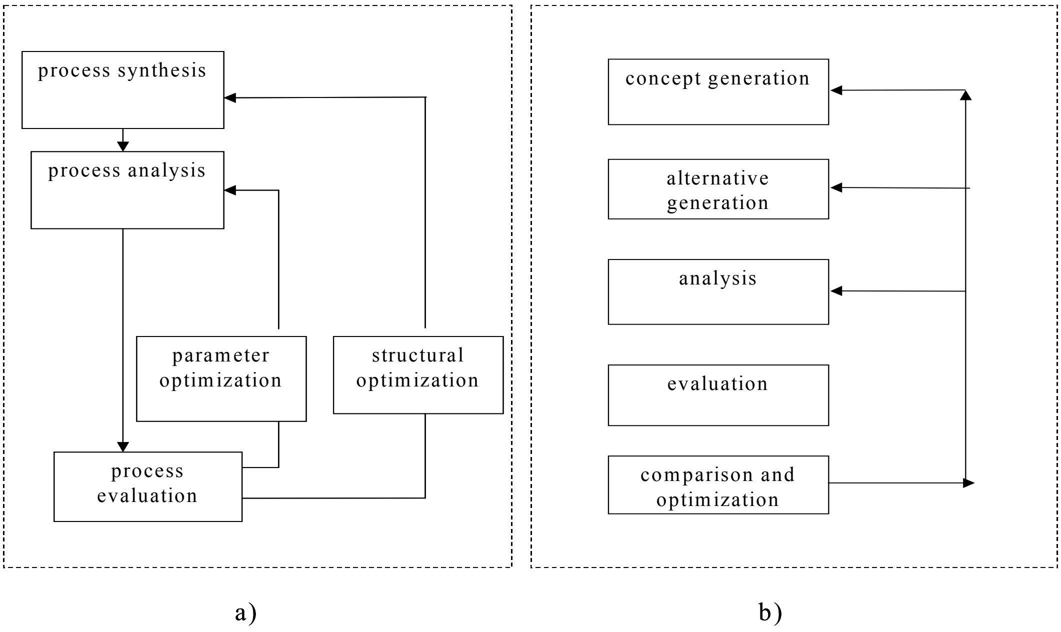


Figure 6. Two general approaches for the term synthesis: a) synthesis as the first step of flow-sheet structure development (Westerberg et al., 1979) b) synthesis as a procedure aimed at the complete flow-sheet structure (Biegler et al., 1997).

5.4 Process synthesis methods

The aim of process synthesis methods is to present a systematic way to construct a process. The synthesis methods have become more quantitative with the development of optimization and simulation software.

5.4.1 Heuristics and the hierarchical procedure

Heuristics methods rely on engineering experience. Heuristics mean design guidelines and rules of thumb and are thus aggregating the experience. Heuristics are used to make decisions about the structure of the flow-sheet and about the values of design variables. The problem with this approach is that many times no heuristics are applicable.

The hierarchical procedure for process synthesis developed by Douglas (1988) is a well-known approach:

Level 1. Batch vs. continuous
Level 2. Input-output structure of the flow-sheet
Level 3. Recycle structure of the flow-sheet
Level 4. General structure of the separation system
Level 5. Heat exchanger network

The basic idea is that one should solve design problems by first developing more basic aspects and then adding successive layers of details. The hierarchy is often represented symbolically as an ‘onion diagram’ (Figure 7, original version by Linnhoff, 1983). It presents the design process as a subsequent adding of layers of operations and functions to the core function of the process, i.e. the conversion of feedstock into products e.g. in a reactor. Each step is concluded with an evaluation by addressing the design quality factors (Herder, 1999).

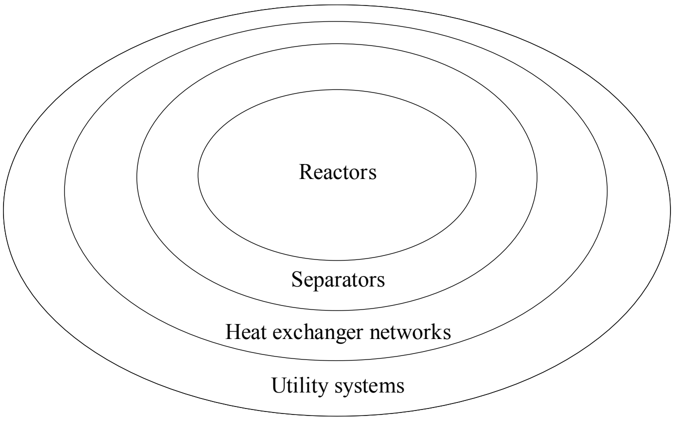


Figure 7. *The onion diagram.*

In hierarchical approaches, the design develops through a series of hierarchical levels. Additional details are added at each level. For example, the reaction system is specified before considering the separator system. Even the aim of the hierarchical approach is to simplify the synthesis by designing layers one by one. It may not be feasible to make final decisions until all layers of the hierarchy have been considered. This is in order not to create sub-optimal designs (Pennington, 2001).

5.4.2 Knowledge-based approaches

Knowledge-based approaches (or knowledge based systems, or expert systems) are a group of procedures that vary considerably in detail and sophistication. They range from simple lists of heuristics, through databases and hierarchical design procedures, to artificial intelligence programs (Rossiter, 1995). Knowledge-based approaches are built on accumulated proven knowledge.

Research in this area focuses on the development of computer programs that have specialized knowledge in a certain area. A knowledge-based system is not a distinct design approach. Instead, the structure or model is usually based on existing methods and approaches, like the hierarchical design approach or a superstructure approach (Herder, 1999).

Attempts have been made to systematize the heuristics but the result has been mostly applicable only to the conceptual design of large-scale fluid processes such as petrochemicals and organic bulk products. Solid, electrolyte, food, pulp, paper etc. processes often include details that are too specific to be treated by general methods (Virkki-Hatakka et al., 2003). Knowledge-based approaches are used to identify attractive designs alternatives and thereby narrow down the number of alternatives.

5.4.3 Algorithmic methods and process simulation

Algorithmic methods are mathematical procedures that include optimization techniques. They are generated using mathematical programming, i.e. linear programming (LP), non-linear programming (NLP), mixed integer linear programming (MILP) or mixed integer non-linear programming (MINLP), or genetic algorithms. In mathematical programming a superstructure containing all possible unit operations and interconnections is formed. The algorithm is used to solve the problem and to suggest the best combination. The main advantage over the heuristic and hierarchical approaches is that the mathematical methods have the ability to combine synthesis and optimization tasks in a reproducible way.

In the optimization-based methods the manual iterative design is replaced by mathematical optimization. The global optimum is found in the mathematical sense for the given objective function (equations, relationships) and in the defined design space (i.e. superstructure) (Cziner et al., 2005a). It aims to find the global optimum, i.e. the best solution to the problem. The objective function serves as a quantitative indicator of the ‘goodness’. A usual measure for it is the obtained profit. The values of the objective function are determined by manipulation of the problem variables (e.g. operation conditions such as pressure, temperatures, flow rates).

In Case 1 ‘Integration at the conceptual design phase’, a couple of problems associated with the use of mathematical optimization methods were found. First of all, the number of design alternatives is limited by the user because the definition of superstructure is a heuristic operation. This may leave out important alternatives from the optimization space. Secondly, practical aspects such as safety, operability, reliability, social aspects etc. cannot be easily expressed in an objective function. In addition, the optimization approaches are not interactive and the optimization cannot be adjusted or guided easily by the user. It may follow that the mathematical optimum is not the engineering optimum. The optimization also often leads to impractical or impossible solutions.

Process simulation (though missing from Table 2, see Section 5.5) is an essential process design tool. Simulation is used to understand the operating characteristics of a design. It is used to develop heat and material balances and physical properties data for a flow sheet. Process simulation packages are becoming more powerful, especially in the area of optimization (Rossiter, 2001).

5.4.4 The state-of-the-art and recent advances

The synthesis methods are typically hybrid methods combining several approaches. The knowledge-based systems combine heuristics, hierarchical design procedures and databases with thermodynamics and physics. Algorithmic problem solving combines heuristics and numerical methods. The promoters of the mathematical approach use heuristic methods for illustration and approximation to decrease the searching space. Modern methods aim to generate several process alternatives and to recommend one for selection. The majority of the synthesis literature understands that its task is to find the best configuration from among a large number of alternatives using well-defined unit operations (Westerberg, 2004).

In practice the use of optimization-based approaches is limited to small and well-defined problems. This is because the superstructure formulation becomes difficult and the computing time becomes long in large systems (Rossiter, 2001). For example, it is difficult to present a ‘complete’ superstructure for a mill-wide heat recovery problem.

The traditional focus in conceptual process design and synthesis has been in unit operations (meso-scale). Around 1990 environmental concerns focused the conceptual process design on constructing models of entire systems rather than of individual elements, bringing multi-criteria analysis into conceptual design, and developing techniques for better trade-offs between the multiple objectives (macro-scale). Around 1995 new unit operations and molecular design focused the conceptual design to combine intensive process knowledge, such as transport phenomena and molecular design (micro-scale) (Li and Kraslawski, 2004). Nowadays the discussion has shifted towards constructing processes at a more fundamental level, i.e. thinking of processes as combinations of transport phenomena (Westerberg, 2004). Environmental concerns brought extended system boundaries, inherent multi-objectivity, and more constraints (Yang and Shi, 2000).

Recent advances in process synthesis have been reported from conceptual design of complete (total process) flow-sheet systems and from specific design of sub-problems including heat-integration, heat-integrated distillation trains and multiple-effect distillation, separation trains, reactors and transport processes (Westerberg, 2004: Li and Kraslawski, 2004). These are the same advances that have been reported from the area of process integration.

The general tendency in future work in the area of process systems design at the macro-scale will be in the combination of methods towards multiple industrial resources management (Zhelev, 2005). This would result in treating the design problem as part of a larger entity. The further widening of the scope of process systems engineering involves considering management issues for the whole company, as well as the supply chain (Sargent, 2004).

Case 1 ‘Integration at the conceptual design phase’ indicated that future research is likely to emphasize simultaneous product development and manufacturing processes development. Knowledge and methodologies are needed to discover new products at the micro-scale, to invent intensified equipment at the meso-scale, and finally to synthesize and design manufacturing processes at the macro-scale.

5.5 An overlap between process integration and process synthesis methods

Process integration solution techniques overlap with process synthesis solution techniques. Two ways to categorize process integration methods are given in Table 2 as an example.

Table 2. Two example categories of process integration methodologies.

Rossiter and Kumana (1995)	**Gundersen (1997)**
Knowledge-based approaches	Artificial Intelligence / Knowledge-based Systems
	Hierarchical Analysis / Heuristic Rules
Pinch Analysis	Thermodynamic Methods (Pinch Analysis and Exergy Analysis)
Numerical optimization approaches	Optimization (Math Programming, Simulated Annealing, Genetic Algorithms)
	Possible Hybrid Methods

Of the categories in Table 2, the principles of the three main groups (thermodynamic analysis methods, mathematical programming and optimization methods and knowledge-based approaches) are summarized below:

1) Thermodynamic methods: A thermodynamic analysis of a process is needed to obtain physical insights into the process. This is gained by the use of the First and Second Laws of Thermodynamics. The most widely applied thermodynamic method is the Heat Recovery Pinch.

2) Mathematical programming and optimization methods: Mathematical programming and optimization are typically used to generate economically optimal process concepts. Mathematical optimization is best suited to process integration applications where a

limited number of well-defined design options require evaluation. In complex processes the programming effort and calculation time can become too extensive (Rossiter, 2001).

Such an example is Case 4 ‘Steel mill process retrofit’, which deals with process integration in a large steel manufacturing plant.

3) Knowledge-based approaches: Knowledge-based approaches for process integration are build on proven ideas, e.g. for waste minimization and pollution prevention. In those approaches experience is transferred from one user to another. The experience is used to develop new designs or to identify retrofit options (Rossiter, 2001).

A knowledge-based design theory was used in Case 3 ‘Paper mill water management’ to integrate a paper mill’s water system. The theory (the K-value theory) was based on knowledge about water COD values, which are found to correlate with good water management.

The featuring elements can be summarized as follows:

- The ‘thermodynamic methods’ consist mostly the Pinch method and extensions of it and feature an element to define a theoretical performance targets before the design starts. The drawback is that they consider rather limited design perspectives, e.g. energy alone.
- The group of ‘Mathematical optimization methods’ is capable of solving multi-criteria problems. Their use is difficult in large and complex processes since the programming effort and calculation time easily becomes too extensive. Dynamic models are needed to model process operation.
- The group of ‘knowledge-based approaches’ is built on a knowledge base of proven ideas, e.g. waste minimization and pollution prevention. The knowledge-based approaches are used to identify attractive designs alternatives and to narrow down the number of alternatives.

The methods in the basic categories have partly different areas of application. In the novel process integration methods they are used together to yield results which are complementary to each other. For instance, heuristics and the hierarchical approach are needed to formulate and solve problems that would otherwise be too difficult to converge and too large to search. This means decreasing the design space by e.g. making design approximations first. Heuristics and hierarchy are also used to develop step-wise problem-solving structures and to proceed between the steps. Mathematical tools are used to obtain a global optimum.

The group of ‘thermodynamic methods’ characterizes the ability to calculate (theoretical) performance targets before the design starts. In the Pinch Analysis, this means the requirement for the minimum external heating and cooling. In more complex applications like in Tveit (2003) this is normally approximated. In the final solution, the first performance target becomes somewhat relaxed as other design aspects are considered.

5.6 Chapter findings

Process synthesis methods traditionally focus on the systematic way to construct a process. The synthesis methods have become more quantitative with the development of simulation and optimization software.

Process integration is traditionally seen as a task of calculating a minimum utility requirement and designing heat exchanger networks, but current applications cover the whole process design life cycle. Simultaneously, the scope and scale of the applications have increased. This explains why advances in process synthesis and process integration are reported from the same area.

The study indicates that there is an overlap between the solution techniques of process integration and process synthesis. One fundamental difference between the two was found: whereas process synthesis focuses on the systematic way to construct a process, process integration (its traditional methods, especially for the group ‘thermodynamic methods’) usually focuses on enhancing specific feature(s). This is explained by their featuring an element to calculate performance targets, towards which the design proceeds.

The various solution techniques are capable of considering a different number of design criteria. For example, the mathematical methods are able to consider multiple criteria. The various solution techniques also differ in their flexibility for different problem scales. For example, the mathematical methods are applicable to equipment or unit process design problems. The various solution techniques also have a varying capability to consider the synergic effects of integration. Especially the traditional Pinch approaches feature this element.

6 DESIGN CRITERIA

6.1 Objective of the chapter

The objective of the chapter is to provide an overview of the process design and evaluation criteria and to verify how the general criteria apply to the design and evaluation of integrated processes.

The criteria and indicators play an essential role in the design and evaluation of industrial processes. The criteria and indicators exist both in quantitative and qualitative form. Many times their use is case specific. Also, industry-specific indicators exist.

6.2 General process and plant design criteria

A primary concern in *process design evaluation* is project economics in terms of profitability. The factors affecting it directly are considered. Other considerations include the safety of the plant personnel and public, as well as health and environmental impacts. Considerations over the operational phase of the life span include plant maintainability and operability. Operability refers to factors such as flexibility for variations and ease of control (Westerberg, 2004; Barnicki and Siirola, 2004; Peters et al., 2003; Biegler et al., 1997). According to Cziner et al. (2005b) integrated processes should be evaluated from three perspectives: economy, technology and EHS (environment, health, safety).

Plant design criteria are similar but factors such as layout and location-specific aspects come in addition. Location-specific aspects include land size, market area, raw material availability, utility availability (power, fuel, water), climate, transport facilities, waste disposal service, labor supply, political and legal issues (taxation, restrictions, permits) and fire protection. (Peters et al., 2003; Sinnott, 1999).

6.3 Economic criteria

Profitability calculations are based on capital and operating cost evaluations and product price and demand forecasts. In preliminary stages, when no accurate design and cost data exists, only preliminary (approximate) estimates can be made. They are used to study the feasibility of the project. More detailed and more accurate estimates can be made at later stages. The 'order of magnitude' estimates range between –30…+50%, the 'budget' estimates range between –15…+30% and 'definitive' estimates range between –5…+15% (Humphreys, 1991).

The standard techniques of quantitative investment appraisal used by companies are Payback Time, Internal Rate of Return (IRR) and Net Present Value (NPV) (see e.g. Graham and Harvey, 2001). The calculation can be based on non-discounted or discounted cash flow (DCF) analysis. The non-discounted cash flow analysis methods include Payback Time. The discounted cash flow analysis methods include NPV and IRR. NPV is defined as the difference between the present value of the estimated net cash inflows and the present value of the estimated net cash outflows. According to the NPV approach, the project should be accepted if its NPV is positive (or zero) with the required rate of return of capital.

Life Cycle Costing (LCC) is the process of economic analysis used to assess the accumulated costs of an asset over its life span, i.e. acquisition, ownership and disposal of a product (IEC, 2005). Life Cycle Costing is a tool used to find the cost-wise best solution for an investment over the whole life span of an investment by analyzing the arising life cycle cost.

Case 4 'Steel mill process retrofit' and Case 5 'Bio-fuel drying in a power plant' compared alternative process designs. In both studies the final decision-making was based on profitability analyses. Both studies confirmed that problems exist in expressing all criteria in numerical form. Both cases also revealed that the financial analysis is not explicit. The analysis results depended on the chosen balance boundary and the accuracy of estimates, among other factors.

6.4 Aspects of sustainability, environment, health and safety

The environment, health and safety aspects are commonly grouped into ‘EHS aspects’. A ‘sustainable’ design fulfils economic, environmental and social requirements (e.g. Burgan and Sansom, 2006). Explicitly describing sustainability and the factors affecting it is problematic, so its connectivity with design is difficult.

A traditional way to incorporate the EHS aspects into a process synthesis has been through the introduction of various impact metrics as target values or constraints on a list of design requirements. Another approach is through compliance-based reviews, where each of the EHS disciplines is well considered by reviewing it separately during the design process. The trend today is towards the latter approaches (Little, 2001).

According to researchers, tools for evaluating environmental performance should be more general or qualitative in the preliminary design stages (e.g. risk assessments) and more quantitative in the detailed design phase (e.g. optimization of total emission release rates) (e.g. Allen and Shonnard, 2002; Freeman, 1994).

Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product (SFS-ISO 14040). Recent literature suggests applying it in process selection, design and optimization (Azapagic, 1999) and in estimating environmental impacts associated with products, processes and services (Khan et al., 2002).

All process plants are to some extent hazardous when it comes to dangers from rotating and cutting machinery, falls, falling objects etc. Especially in chemical processes there are additional hazards associated with the use of chemicals and the process conditions. The safety of a process plant can be divided into intrinsic (inherent) safety and extrinsic safety. Inherent safety means that the process concept and materials are safe. Extrinsic safety must be engineered in (alarms, control systems etc.). A process engineer should always aim for an inherently safer process design (Heikkilä, 1999). Hazard assessment methods are used to evaluate the potential risk from the process. They are used in the preliminary stages of process design. The traditional techniques for evaluating the level of safety include index-based methods such as the Dow Fire and Explosion Index and the Mond Index. Systematic techniques for identifying hazards and operability problems and analyzing hazardous events include HAZOP (Hazard and Operability) studies and What-If safety reviews (Nolan, 1994). Because of its specific characteristics, neither the subject 'safety in process design' nor its criteria are discussed further in this thesis.

In Case 4 'Steel mill process retrofit', the process alternatives were evaluated from economic, environmental and technical perspectives. The environmental aspect was evaluated through CO_2 emissions. It was noted that other criteria could have served the same purpose in the study, e.g. a waste amount.

6.5 Design operability, controllability and flexibility

Process operability is a wide concept. Examples of definitions and contents are given in Table 3 and 4.

Table 3. Operability definitions.

Definition	**Source**
The ability of the plant to provide acceptable static and dynamic operational performance.	Kheawhom and Hirao, 2002
Ability of the process to change effectively and quickly from one steady state to another so that a different production rate is achieved or a different product is made while rejecting process disturbances.	Subramanian and Georgakis 2001
Term is used to define all the criteria that a chemical process needs to satisfy to be able to operate smoothly.	Gollapalli et al., 2000
The ease with which a process is operated and controlled is referred to as operability.	Bahri et al., 1996
Considerations that account for a plant's life cycle.	Vassiliadis and Pistikopoulos (1998)

Table 4. Contents of the term operability.

Content:	
Flexibility, controllability and reliability and safety.	Pintarič and Kravanja, 2004
Optimality, stability, flexibility and controllability. Risk and environmental issues are becoming increasingly important.	Blanco and Bandoni, 2003
Controllability, flexibility, resiliency and safety.	Gollapalli et al., 2000
Flexibility, reliability and maintainability	Vassiliadis and Pistikopoulos (1998)
Flexibility and controllability.	Vu et al., 1997

Most of the contributors understand operability as the ability of a process to perform an operation or series of operations in order to produce products. Flexibility and controllability are considered as major concepts. Controllability is associated with stability, resiliency, selection of measurements and manipulations, and accounting for disturbances. Flexibility is associated with the 'size of an operating window' and accounting for uncertainties. Sometimes flexibility and controllability are collectively referred to as switchability.

Researchers have made several attempts to consider operability and control design together with process design, and to develop rigorous mathematical models for that purpose (e.g. Sakizlis et al., 2004; Pintarič and Kravanja, 2004; Vu et al., 1997; Subramanian and Georgakis 2001). Quantitative operability measures can be found from the literature. For instance, Kheawom et al. (2002) present a complex mathematical presentation for a *deviation ratio*, where the basic idea is to investigate how the cost of, for example, environmental impact increases when fluctuation of input occurs. Another example of an operability measure is the *operability index* approach by Georgakis et al., 2003.

Research on flexibility is fragmented across many disciplines. For example, strategists deal with ‘strategic flexibility’, meaning a capability which aids repositioning when conditions change. Examples of design flexibility definitions from process systems engineering perspective are given in Table 5.

Table 5 . Example definitions of flexibility.

Definition	
Flexibility implies ensuring feasible regions of steady state operation in the face of disturbances and parametric uncertainty.	Blanco and Bandoni, 2003
The capability that a design has of having feasible steady state operation for a range of uncertain conditions that may be encountered during plant operation.	Biegler et al., 1997
Flexibility is concerned with the problem of ensuring feasible operation of a plant for a whole range of conditions, in both steady-state or dynamic environments.	Bahri et al., 1996
Flexibility means the ability to operate under different conditions such as differences in feedstocks and product specification.	Smith, 1995

Difficulties in the use of controllability metrics are reported by Sakizlis et al., 2004. They include 1) a difficult relationship between the value of the measure and the design itself, 2) conflicts between different measures and 3) difficulties in modeling real conditions with steady-state or linear models. Controllability measures include ‘the minimum squared error between the set-point and the output’ and ‘the minimum time needed for the closed-loop system to reach the steady state’ (Bahri et al., 1996). Examples of design controllability definitions are given in Table 6.

Table 6. Example definitions of controllability.

Definition	
Controllability is the ability to achieve an acceptable performance within various limitations on process operations, despite external disturbances and uncertainty in design parameters, by using available input and manipulated variables.	Ekawati and Bahri, 2003
Controllability has mainly to do with dynamics in the face of disturbances.	Blanco and Bandoni, 2003
Controllability deals with the ability to operate the process satisfactorily while undergoing dynamic changes from one operating condition to another, or while recovering from disturbances.	Biegler et al., 1997
Controllability is the ability of the plant to move efficiently from one operating point to another as well as dealing effectively with disturbances.	Bahri et al., 1996

The thesis divides process operability into controllability and flexibility. The literature associates controllability with stability, resiliency, selection of measurements and manipulations. It means the process's ability to keep the set point operation, i.e. a capability of adapting to required and unexpected changes. Flexibility is associated with optimality of the design. It accounts for variations in inputs (feed qualities and utility temperatures and pressures), in output requirements and in process-related variations such as fouling and aging. In other words, flexibility considers a fixed range of variations in normal operating conditions.

6.5.1 Practical limitations

The 'normal operating conditions' are usually specified for process design purposes. These include the product rate and quality, process operating conditions (flow-rates, temperatures, pressures) and ambient conditions. However, the conditions change during operation time, e.g. due to plant aging and process modifications. Variations occur e.g. in utility ranges, feedstock compositions and in product quality and flow quantity.

The computer-aided design of operability requires a model of a process, i.e. a process superstructure. In the literature, computer-aided operability design is typically demonstrated for rather simple processes like a small-scale heat exchanger network or a mixing tank. The quantitative operability measures are developed to help process design decisions. The challenges associated with their use were discussed above (Section 6.5).

These findings indicate that there is still a substantial gap between the currently available computer aids and the practical demands. This is mostly due to the fact that quantitative determination of operability is difficult. Evaluating its impact on investment costs and operational costs therefore carries significant uncertainty.

6.6 Process availability

6.6.1 Standard definitions

The term ‘process availability’ is used to describe whether a process is performing its intended action as planned. According to SFS-IEC 50-191:

Availability (performance) is *the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.*

This ability depends on the combined aspects of reliability performance, maintainability performance and maintenance support performance (Figure 8). According to this definition, external resources other than maintenance resources do not affect the availability performance of the item. According to SFS-IEC 50-151:

- reliability (performance) *is the ability of an item to perform a required function under given conditions for a given time interval.* Here it is assumed that the item is in the state to perform this required function at the beginning of the time interval.
- maintainability (performance) *is the ability of an item, under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.*
- maintenance support performance *is the ability of a maintenance organization, under given conditions, to provide upon demand the resources required to maintain an item under a given maintenance policy.* Here, it is noted that the given conditions are related to the item itself and to the conditions under which the item is used and maintained.

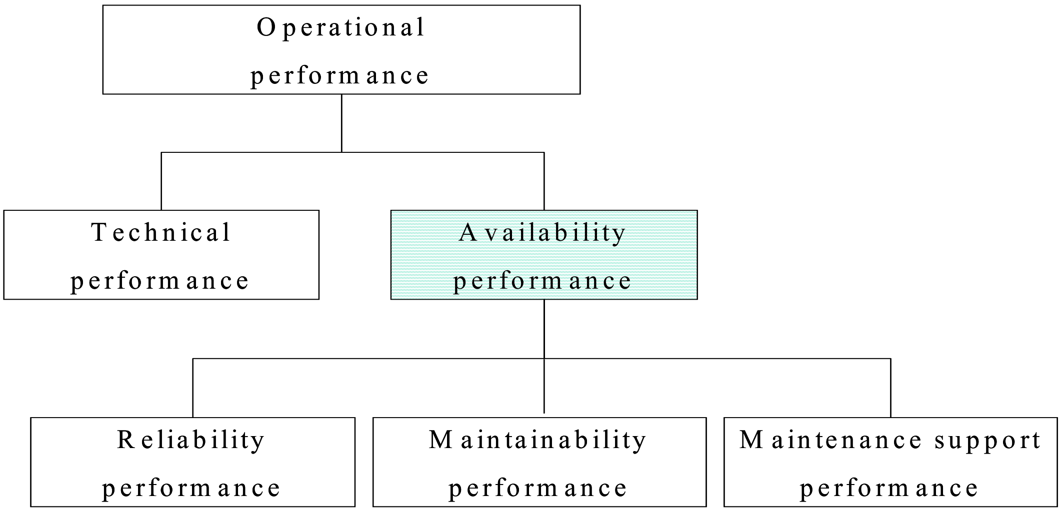


Figure 8. Availability performance (Lyytikäinen, 1987).

The term *dependability* as a general and non-quantitative term is used to describe availability and its three influencing factors (SFS-IEC 50-151). ANSI/IEEE (1987) defines reliability and availability without positioning them in a hierarchical manner.

Here, reliability stands for the ability of units to perform their intended function. Availability measures are concerned with the fraction of time a unit is capable of providing service.

Researchers have tried to introduce system optimization frameworks to account for availability already at the preliminary design stages. Mathematical programming is used to study availability in design and operation, typically by addressing equipment (process) reliabilities and maintenance (policy). The models typically optimize benefits, i.e. increased availability and production, with costs. Computer-aided design requires mathematical descriptions for component reliabilities, cost characteristics of components as well as type and cost of different maintenance policies (Pistikopoulos et al., 2000; Goel et al., 2003). The term availability is also seen as ‘the number of operating hours per year’ (Smith, 1995).

6.6.2 Availability performance measurement

Availability measurement is based on the measurement of time. Availability (A) is defined as:

$$A = \text{Availability time} / \text{Reference time} \tag{1}$$

Normally, the *reference time* is a planned utilization time such as the maximum period of usable production. The *availability time* is the actual production time. This means that availability is a relationship between realized and planned production times. The definitions for reference time and availability time are case specific (Lehtinen, 2002).

The item states need to be categorized in order to measure availability (Figure 9). The categorization should take all interruptions and shutdowns into account. The reasons for interruption are diverse: failures, maintenance actions and lack of resources. Unplanned shutdowns are usually caused by mechanical defects. Shutdowns are planned to allow cleaning (machine, heat exchangers, piping), replacement of worn mechanical parts, and the like.

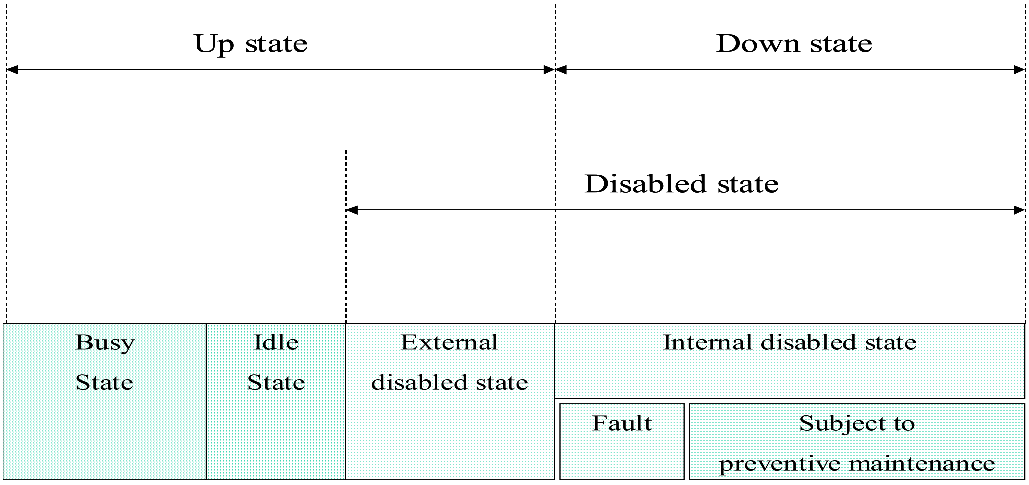


Figure 9. Classification of item states according to SFS-IEC 50-151.

Measures for reliability include: Mean Time Between Failure (MTBF) and Mean Time To Failure (MTTF). Measures for availability include: Mean Up Time (MUT) and Mean Down Time (MDT) (SFS-IEC 50-151)

6.6.3 Availability performance modeling in production systems

The availability performance analysis of a production system is based on a hierarchical model of a logical structure of the system, while defining connections between sub-functions and the storage capacities between process stages (Figure 10). At the lowest level, the availability model comprises the sub-function's hardware. The data for calculation consists of hardware item failure rates and repair times, preventive maintenance actions and the corresponding information on other shutdowns. Failures are divided into critical and non-critical ones. Critical failures prevent system functioning. Non-critical failures do not necessarily prevent functioning but result in reduction of the production quality or quantity (Pursio et al., 1999, Kortelainen and Pursio, 2001).

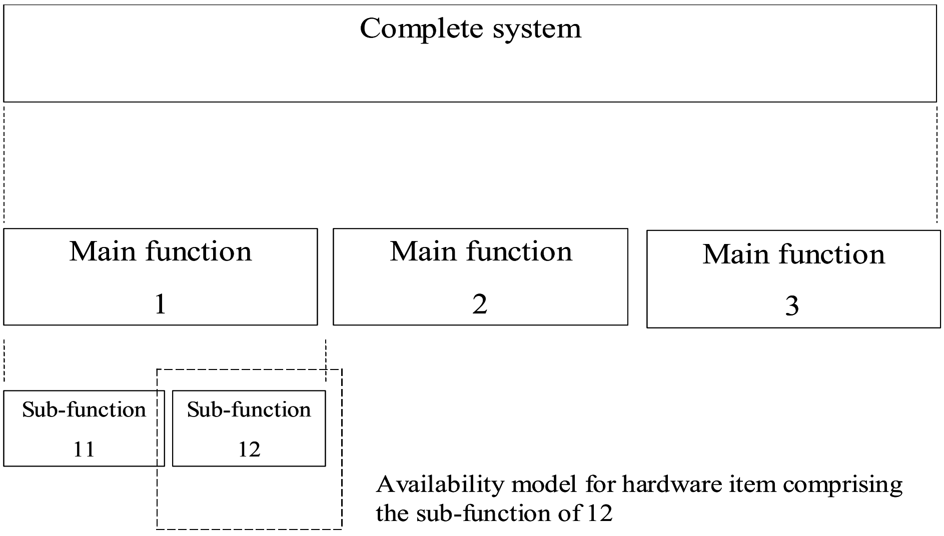


Figure 10. Hierarchical model of system performance. Adapted from Pursio et al. (1999).

Many mills collect shutdown and failure data systematically. Availability models utilize this information. Once the model exists, availability can be calculated analytically or by simulation. The logical structure offers information about how the availability of a hardware item influences the system availability performance. Models are used to see the production bottlenecks and items causing most interruptions. They are also used to direct improvements, test operation strategies and compare different process alternatives (Pursio et al., 1999, Kortelainen and Pursio, 2001).

Kortelainen and Pursio (2001) studied availability performance modeling in the pulp and paper industry. They stated that intermediate storage capacity has a positive impact on the system level availability performance but a diverse impact on production efficiency and product quality. Lehtinen (2002) made an availability performance study on three optional ways to pre-treat a slurry in a pigment manufacturing plant. Two of the alternatives got the lowest scores for availability performance but were estimated to yield the best combined effect of availability, production capacity and product quality. These studies indicate that it is hard to measure availability performance alone, but easier when grouped together with production quality and quantity considerations.

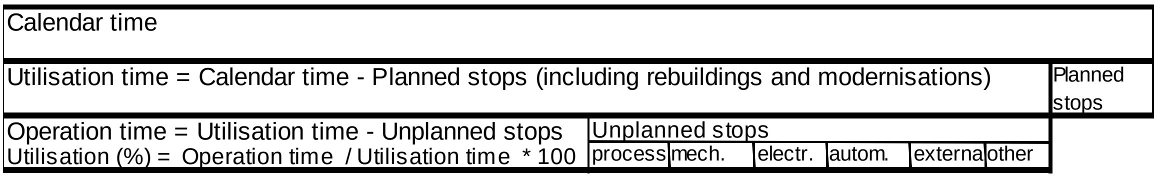
6.6.4 Industry practices

Example from the steel industry

Sintering plant

The European steel industry has established calculation guidelines for the efficiencies of sintering plants. The specified time categories for a sintering plant are seen in Table 7:

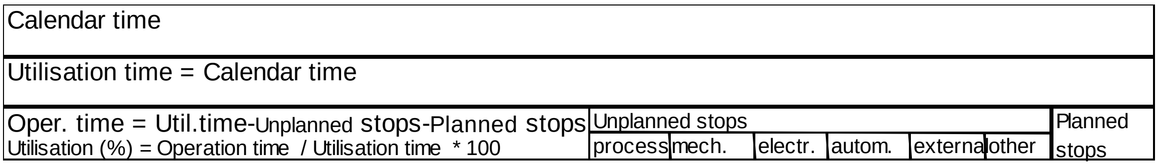
Table 7. Example standard time categorization for a sintering plant (Rautaruukki, 2002a).



Calendar time							
Utilisation time = Calendar time - Planned stops (including rebuildings and modernisations)							Planned stops
Operation time = Utilisation time - Unplanned stops	Unplanned stops						
Utilisation (%) = Operation time / Utilisation time * 100	process	mech.	electr.	autom.	externa	other	

Kekkonen at al. (2005) studied a steel mill process retrofit (Case 4 in Appendix 1). A review of the time efficiency measures was made for comparison. The time categories specified in the case plant are seen in Table 8:

Table 8. Time categories for calculating sintering plant utilization rate in a case plant (Rautaruukki, 2002a).



Calendar time							
Utilisation time = Calendar time							
Oper. time = Util.time-Unplanned stops-Planned stops	Unplanned stops						Planned stops
Utilisation (%) = Operation time / Utilisation time * 100	process	mech.	electr.	autom.	externa	other	

A comparison of the Tables 7 and 8 shows that the capacity 'utilization time' in the case plant is equal to the calendar time. In the method used by the European steel industry the capacity utilization time is calendar time minus the planned stops. The difference in utilization time will affect the results when calculating efficiencies.

Blast furnace

The European steel industry has established calculation guidelines for the efficiencies of blast furnaces. The specified time categories for blast furnaces are seen in Table 9.

Table 9. Example standard time categorization for a blast furnace (Rautaruukki, 2002b).

<table>
<tr><td colspan="8">Calendar time</td></tr>
<tr><td colspan="7">Utilisation time = Calendar time - Planned stops (including rebuildings and modernisations)</td><td>Planned stops</td></tr>
<tr><td rowspan="2">Operation time = Utilisation time - Unplanned stops
Utilisation (%) = Operation time / Utilisation time * 100</td><td colspan="6">Unplanned stops</td><td rowspan="2"></td></tr>
<tr><td>process</td><td>mech.</td><td>electr.</td><td>autom.</td><td>externa</td><td>other</td></tr>
</table>

Kekkonen at al. (2005) studied a steel mill process retrofit (Case 4 in Appendix 1). A review of the time efficiency measures was made for comparison. The time categories specified in the case plant are seen in Table 10.

Table 10. Time categories for calculating the blast furnace utilization rate in a case plant (Rautaruukki, 2002b).

<table>
<tr><td colspan="8">Calendar time</td></tr>
<tr><td colspan="8">Utilisation time = Calendar time</td></tr>
<tr><td rowspan="2"></td><td colspan="6">Unplanned stops</td><td rowspan="2">Planned stops</td></tr>
<tr><td>externa</td><td>process</td><td>mech.</td><td>electr.</td><td>autom.</td><td>other</td></tr>
<tr><td colspan="2">Operation time = Utilisation time - Time for internal stops
Utilisation (%) = Operation time / Utilisation time * 100</td><td colspan="6">Time for internal stops</td></tr>
</table>

A comparison of the Tables 9 and 10 shows that the capacity ‘utilization time’ in the case plant is equal to the calendar time. In the method used by the European steel industry the capacity utilization time is calendar time minus the planned stops. Another difference is in the calculation of operation time. These will affect the results when calculating efficiencies.

Example from the paper industry

In the paper industry there is a need to benchmark production efficiency and harmonize companies' internal calculation methods. The paper technological committee of Zellcheming has published 'Production indices for the papermaking industry' to calculate the key production data of any machine line producing paper or board, where every machine line's efficiency is the sum of losses in any sub-process included in the production line (Figure 11) (Airola et al., 2005).

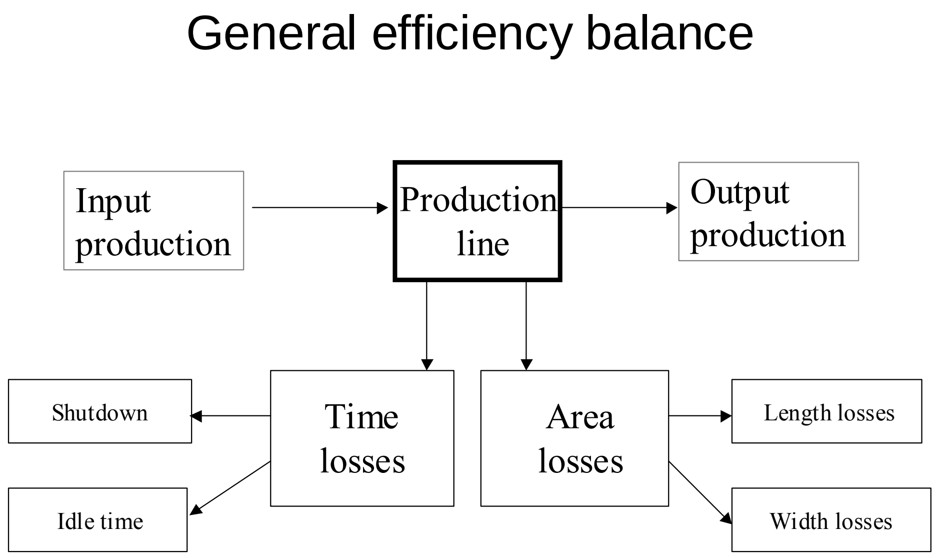


Figure 11. General efficiency balance (Airola et al., 2005).

The standard defines the calculation of Time Related Efficiencies, Area Efficiencies and Overall Efficiencies. Time categories (Figure 12) have to be specified in order to calculate Time Related Efficiencies.

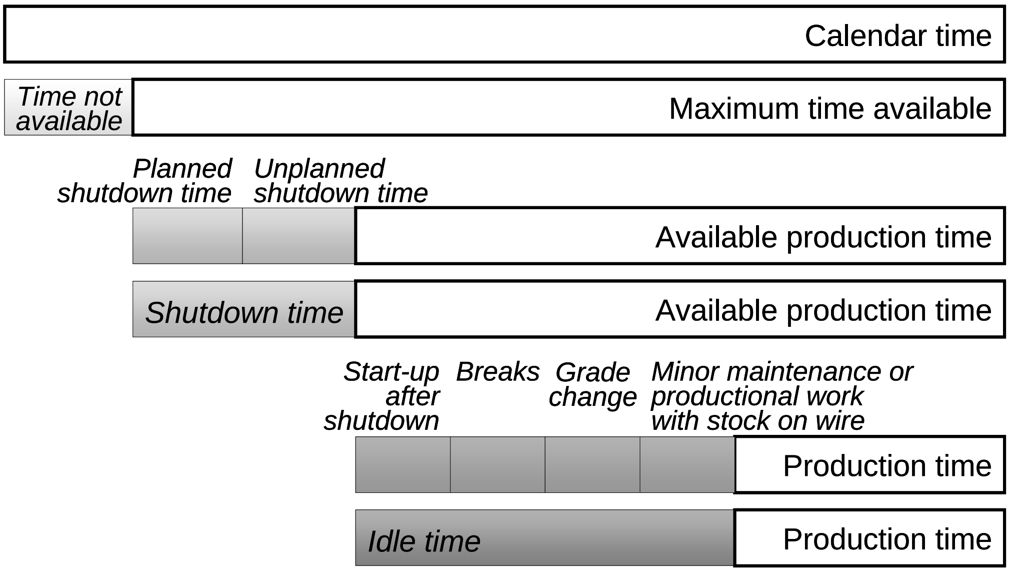


Figure 12. Time analysis overview (Airola et al., 2005).

The overall efficiency is a way to monitor how efficiently the capacity is utilized. It is more developed than a single time efficiency measurement.

6.6.5 Practical limitations

The SFS-IEC 50-191 standard is focused on electro-technical products. It applies well to systems where the item states are easily defined. Such is the situation e.g. in a computer system. Further on, a failure in a computer system may cause a shutdown of a mechanical system. An example is an automation system causing an interruption in district heating service. In the process industry, the item states categorization is more complicated. The situation is difficult when the system is performing a grade change operation, or producing off-spec quality or operating below nominal capacity. For example, a failure in a tank feed pump or a recovery from a failure may result in partial production.

Researchers are looking for quantitative techniques to model availability in process synthesis (e.g. Pursio et al., 1999), which requires an expression for each term in mathematical form. Complex modeling involves e.g. expressing how to share equipment for multiple purposes. Information about new hardware and systems is difficult to obtain, and its validity is open to question until test data exist.

An availability performance calculation is based on time measurement. The models are based on a hierarchical structure of a production process. The models allow the calculation of availability from low hierarchical levels (hardware item) to aggregate levels. The models can be used to see the production bottlenecks and items causing most interruptions, or to plan process modifications. These models do not, however, exist in all process plants. Also, if they do, they monitor current situation and might not be applicable to the design of process changes.

Availability performance measurement in the process industry also has a couple of other difficulties: One is a difficulty to categorize time, as was discussed above. Another is a difficulty to take into account the effects of chemical interactions, e.g. an increased risk of paper web break as concentrations get higher in the water system, as was seen in Case 3 'Paper mill water management'.

Ongoing trends in the process industry have increased the need to evaluate the economic viability of processes and production sites. That has facilitated the development of production performance indices and industry-specific guidelines. They are used to benchmark production units, process plants and branches of industry. Standardization is needed since in the paper industry for example, some mills run 365 days per year where some others run 330-350 days per year due to holidays etc. (Diesen, 1998). Also typically, variations exist in practices in monitoring the time spent on scheduled maintenance. That is either included or excluded from the maximum available time. The availability performance of a production process/ plant can be called the 'overall efficiency', 'technical availability performance' or 'efficiency of production', depending on the calculation principles (Kortelainen and Pursio, 2001; Diesen, 1998). Availability performance calculation is well developed in the paper industry. There the total efficiency (called the overall efficiency) encompasses time efficiency calculation and area efficiency calculation.

6.7 Chapter findings

Efficient operation of a process

An optimal selection of a process must allow its *efficient utilization*. Operability and availability studies try to capture these features into designs. Process operability can be further divided into controllability and flexibility. The following definitions are applied in the thesis:

- Process *operability* is 'the ability to perform an operation or series of operations in order to produce products'.
- Process *controllability* is 'the ability to operate at various set-point values over a feasible operating range', i.e. keep the set point operation and adapt to required and unexpected changes.
- Process *flexibility* is 'the feature to account for variability in normal operating conditions', i.e. to allow the manufacture of certain products in spite of variations in output demand, feed temperatures and pressures, etc. This thesis simplifies the idea of flexibility to mean the designed variability in (input and output) flow quantities and qualities as well as in the other main equipment design parameters used.
- Process *availability* is 'the time that the process is performing its intended operation'.

Process operability and availability was studied in Case 4 'Steel mill process retrofit'. Studying 'operability' and 'availability' turned out to be difficult. It was noticed that changes in process operation led to changes in production quality and quantity, and in operation time. This data was available in the mill information management system. Using this approach it was possible to take the operability and availability aspects into account in the profitability analysis.

The thesis proposes to study operability and availability through:

1. Process output quantity and quality characteristics
2. Process operating time characteristics, i.e. as time during which the process operates.

The characteristics are given for equipment/ unit process/ process or plant. The approach allows monitoring how efficiently capacity is utilized. This is schematically presented in Figure 13. It describes the relationship between flexibility, controllability and availability affecting the 'degree of functioning'. The degree of functioning is measured either as quantity or quality. The flexibility contributes by specifying the operating limits. The controllability contributes to the ability to operate within these limits. If not, partial production (in respect of quality or quantity) or a down state will follow. Recovery from deviations or transitions from one state to another depend on operating limits (flexibility) and capabilities of the control system.

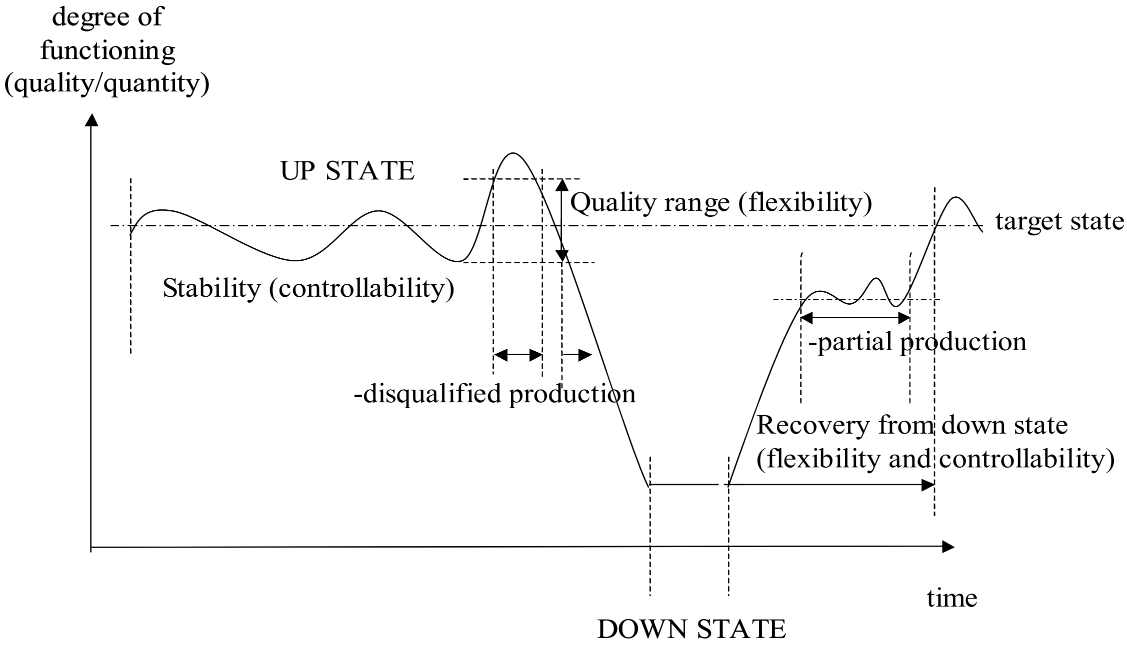


Figure 13. Schematic presentation of controllability and flexibility affecting the 'degree of functioning' and 'operation time'.

Industrial guidelines are used to compare production units and process plants. One of the most developed one was found in the paper industry. It tries to capture the ‘overall efficiency’ of the production process. That includes the time efficiency of the process, and the quality and quantity of the production, thus being analogous to the principle of Figure 13.

Design perspectives

The primary concern in process design evaluation is project profitability. The factors affecting it directly are considered. Other considerations include aspects of safety, health and environmental impacts. They are commonly grouped into ‘EHS criteria’. Usually, data which is readily numerical and/or convertible into costs is used.

Case 4 ‘Steel mill process retrofit’ indicates that the various perspectives of design represented different projections of equipment and process data. The mass and energy balances and basic equipment data were derived from the information ‘mass’. The *technical evaluation* was based on numerical data, consisting of main mass and energy flow values etc. Design aids use this data. Data for *EHS evaluation* was also derived from the basic data source. The problem with EHS information is that it cannot always be expressed or interpreted implicitly. In the Case 4, the data having the most affect on costs was included in *economic evaluation* together with the investment cost.

References to best performance

The potential for improvement in respect of a single criterion is seldom a target. Usually, many criteria have to be taken into account.

In Case 1 ‘Integration at the conceptual design phase’ it was found that process improvements are made through process synthesis, through process analysis, or through optimizing process operation. In process synthesis it is possible to make more fundamental changes in the process. Best theoretical practices are often used as references.

In Case 3 'Paper mill water management' the k-value theory was tested and developed further. The k-value theory is developed to calculate an improvement potential in respect of one criterion, water. The potential in a sequentially integrated system can be analyzed.

In Case 4 'Steel mill process retrofit' two process concepts were compared. Improvement potentials were calculated in respect of several criteria by comparing the old and an enhanced process. The potential calculation was guided by the process design objective: the maximum waste reduction potential was the difference in performance between the old and enhanced processes designs.

The balance boundary

In Case 5 'Bio-fuel drying in a power plant' a couple of optional approaches to select a balance boundary for calculation were identified. In Case 4 'Steel mill process retrofit' the numeric evaluation of the results got new dimensions as the calculation balance boundary was altered: the CO_2 emission increased on the plant level but decreased on the world level.

The design balance boundary is linked with the design opportunities and constraints, and with the available design tools. Also the decision-making criteria are different, depending on the level on which the problem is studied.

7 DECISION-MAKING IN PROCESS DESIGN

7.1 Objective of the chapter

The purpose of the chapter is to identify different approaches to make decisions about integrated process designs.

A modern process development is done together with product development. The whole product and process design life cycle can be understood as a chain of decisions. Each decision consists of the following steps: 1) information gathering, 2) criteria selection and processing this information with different design methods and 3) making the final decision. (Cziner et al., 2005b). The decisions are made based on many, often conflicting, criteria. In addition, the decisions are often made under uncertainty. Aids for making decisions have been available on the market for many years, but process experts still tend to make their decisions based on only their expertise and personal intuition (Cziner, 2005).

The emphasis in decision-making is on profitability analysis. In the pulp and paper industry, sensitivity analyses of investment are tested against variations in production rate, sales price and investment cost. Specific feasibility assessment criteria include wood-paying capacity (an estimate about how much wood can cost) and cost competitiveness (an estimate for a minimum sales price). Equipment selection criteria later during the design process include: performance according to specification, controllability, reliability and maintenance, price as well as guarantees and references (Diesen, 1998). These criteria are very different and difficult to compare.

Approaches to decision-making are available mostly in the process design literature. In addition, they are discussed as part of investment theories and in theories dealing with single goals, like cleaner production.

7.2 Standard quantitative decision-making

7.2.1 Quantitative profitability analysis methods

The primary concern in process design evaluation is project profitability. The standard quantitative profitability analysis methods and the factors affecting them were discussed in Chapter 6.

Traditional methods of treating uncertainty include Sensitivity Analysis, which is a calculating procedure used to predict effects of changes in input data on output results of one model (Jovanović, 1999). It is used to determine which factors can jeopardize the future of the investment. The engineering examples typically include changes in raw material prices, utility prices, product cost, etc. The reliability of the result depends upon the accuracy of the deterministic cash flows (revenues and costs) and their timing. A problem in the use of this method is that users mostly assume a certain (predetermined) operating strategy, or consider a limited number of uncertainties, like the discount rate and economic life.

7.2.2 Mathematical design and optimization

The use of mathematical methods in design was discussed in Chapter 5. In an ideal case, the competing parameters (criteria and indices) were reduced to an impact on a single measure of process economy (Westerberg, 2004). This means expressing the competing factors in costs and benefits using an economic objective function and making trade-offs between competing ones (Barnicki and Siirola, 2004).

Final design selection typically involves multi-criteria optimization and evaluation of Pareto sets. For multiple objectives, optimization theory can ‘only’ tell us how to establish which alternatives are in the so-called trade-off or Pareto set (Westerberg, 2004). The final selection is based on a priority setting among the criteria.

Quantifying and rationalizing the factors into numeric and financial terms is problematic. This is due to the fact that incompatible indices are often used. In addition, the designer makes (consciously or unconsciously) trade-offs among them (Westerberg, 2004; Barnicki and Siirola, 2004). For example, optimization may reduce buffer storage and over-design. This will affect the plant operability.

7.3 Treating uncertainty

7.3.1 Literature regarding investment theories

In the real world, the realization of cash flows from an investment will most probably differ from what was initially expected. In general, it is difficult to incorporate different levels of risks into a profitability analysis. A common way to overcome this is to increase the minimum acceptable rate of return for a risky project. Stochastic simulation can be used to evaluate different uncertainties or strategies and test different levels of risks.

Current research has highlighted the importance of considering the timing of investment expenditures and the expected returns, and has facilitated the development of the field *Investment under uncertainty*. According to the literature review by Laurikka (2005), the central argument towards the standard techniques of quantitative investment appraisal is claimed to be the inability to capture management’s flexibility in adapting and later revising its decisions with regard to market development.

A real options theory tries to address this shortcoming. Real options provide a way to link two disciplines together: the strategy and corporate finance (Amram and Howe, 2002), thus allowing operational and strategic flexibility since changes are possible along the project. A real option is the right, but not the obligation, to take an action concerning an investment project: for example, to alter the scale of operation (i.e. to expand or to contract) or to switch inputs (e.g. fuels) (Laurikka, 2006). Successful implementation of the method requires to model the physical process with relevant details.

7.3.2 Literature regarding design and planning

A need to cope with the dynamic and uncertain environment throughout the process life cycle has facilitated the theoretical development of *Design and planning under uncertainty*. According Cheng et al. (2003), this class of problems should involve decision-making of different types (capacity, technology, etc), at different levels (investment, production, etc) and at different times (now, future). Attempts to simulate uncertainties include: a stochastic optimization framework for conducting process design under uncertainty, taking explicitly into account process robustness and product quality issues (Bernardo et al., 2001); simulation of the synthesis problem using a set of described scenarios with a given probability (Bhatia and Biegler, 1999); designing an environmentally benign process under uncertainty (Kheawhom and Hirao, 2004); simulation of sequential decision problems, involving decisions at different hierarchical levels being made sequentially throughout the process life cycle as a variety of uncertainties are incorporated in the operating strategy (Cheng et al., 2003). The applicability of the algorithms is still limited to small-scale problems, and approximations are needed, as noted by the authors.

7.4 Other approaches to decision-making

7.4.1 Decision-making and concurrent product and process design

The design of a new plant or a retrofit of an already existing plant is usually carried out in a hierarchical manner (Section 5.4.1). This practice is considered time consuming. Another drawback is that not all the factors affecting the design are taken into account simultaneously. This may cause iteration loops and difficulties later in the design process (Herder and Weijnen, 2000).

The concurrent process design, originally developed from the concurrent engineering concept, has been developed to overcome the problems of a hierarchical approach. According to Herder and Weijnen (2000): *Concurrent process design engineering implies that - in addition to the basis of design - all external factors of possible relevance to the process design are being considered in all stages of the design process.*

The authors define external factors as *factors that influence the design process or the design of the plant, but cannot be manipulated by the process design engineer, thus posing either constraints or opportunities to the designer*. Herder, 1999 divides external factors into physical/technical (e.g. site infrastructure, utility system), economic (e.g. raw material price and availability), social or public (e.g. legislation).

7.4.2 Decision-making and emphasis design criteria

Early consideration of individual design aspects is seen as enabling the search for more innovative and cost-effective solutions. Common examples are from the field of:

Process operability. A traditional process design is most concentrated on the steady-state economic optimality. This will later lead to difficulties in operating the process. Processes must have an inherent ability to move from one state to another, i.e. the operability of the process must be considered early in the design process (Blanco and Bandoni, 2003; Georgakis et al., 2003). Simultaneous consideration (also called 'integration') of process design and control in order to optimize the operability and economic performance of the plant is emphasized in many sources, e.g. in Sakizlis et al., 2004; Georgakis et al., 2003; Blanco and Bandoni, 2003).

Process safety. The safety aspect should be involved early in the design process. Inherent safety is a means to manage hazards and risk. It aims to reduce or eliminate the hazards by modifying the design through selection of inherently safer process technology (Heikkilä, 1999).

Cleaner processes. The debate in environmental protection has shifted towards waste minimization through waste reduction and pollution prevention, i.e. towards inherently cleaner processes by structural changes. To accomplish that, a designer must consider waste reduction and pollution prevention already at the first steps of process design. The primary target is to create processes that do not generate waste (Figure 14). The process synthesis or conceptual design stage is the key stage in pollution prevention and environmental impact minimization (Yang and Shi, 2000).

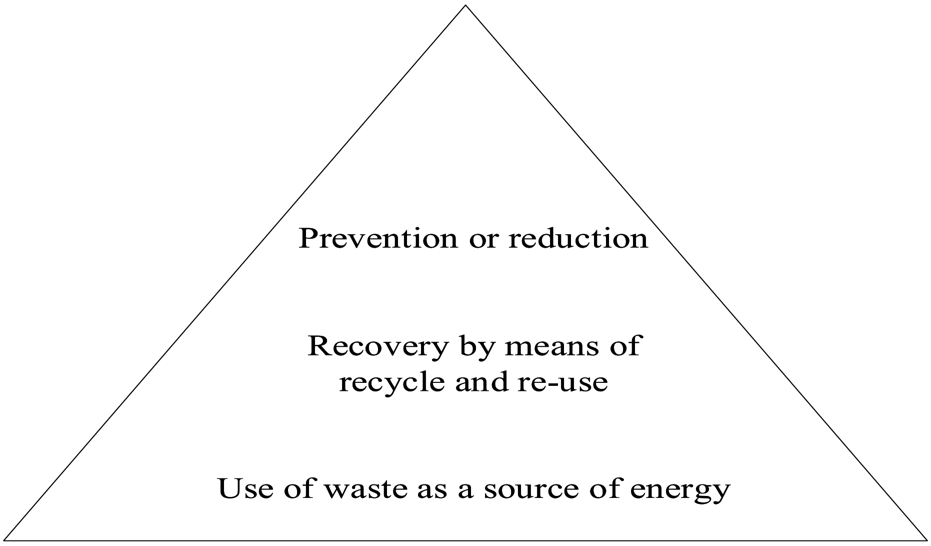


Figure 14. Priorities for pollution prevention (Council Directive, 1991).

An example of a proactive approach in EHS issues is the MERITT approach (Maximizing EHS Returns by Integrating Tools and Talents). It emphasizes the concurrency of environmental, health and safety thinking in a unified perspective and proposes practical means to apply them in business processes. The thinking covers a number of partially overlapping EHS paradigms: pollution prevention, design for the environment, green chemistry, green technology, and inherent safety. Instead of considered these at different stages of the project, they should be incorporated into the earliest stages of development (Little, 2001).

7.5 Chapter findings

In the basic quantitative investment appraisal techniques, investment sensitivity is tested assuming a range of uncertainty in each parameter in turn. The trend in design and decision-making is towards the use of mathematical methods and methods that treat uncertainty. The use of mathematical methods involves multi-criteria optimization and evaluation of Pareto sets. The modern methods deal with a quantified (mathematical) expression of the design object, e.g. a power plant.

The underlying difficulty in the use of mathematical methods is to quantify and rationalize the factors into numerical and financial form. Before this, the critical data must be identified and extracted from the plant's information system. The design/evaluation object must be described as an integral part of the plant's processes. In practice, the designer has to make approximations of the different factors, like the structure, and of the interrelationships between process parts.

The larger the design scale, the more emphasized these features will become. An example is a large process plant where changes are made to some of its unit processes. The mathematical models typically concentrate on dealing with some specific factor, like the effects of market changes on production. Though models are very specific, they harbor the risk of a sub-optimal design. According to Laurikka (2005), managers tend to prefer more qualitative tools as uncertainty increases.

Authors have proposed approaches to tackle the complicated design requirements by treating the design problem sequentially. In Case 1 'Integration at the conceptual design phase' the use of a 'decision map' was suggested. The case also introduced the 'decision-based method' which suggests studying the decision-making situations in detail by identifying: a) the purpose and timing of the decisions, and b) the content of the main decisions versus questions: what, why, who, criteria used, what the info is and documents are needed, what methods are used.

In general, hierarchical design methods are used to decrease the level of complexity in design. This means that design decisions are made in sequences where each decision will have a different priority setting.

8 BUSINESS MANAGEMENT AND ENGINEERING

8.1 Objective of the chapter

This chapter discusses business management theories on a general level. The objective is to find out how efficiency from the technical perspective is connected with efficiency from the business management perspective.

The expected lifetime of a process plant is at least 20 years. The lifetime of mills and machines can be several decades. The process design objectives are specified at the start of design. The typical background material at the start is a market study (Section 5.2.1). At later design stages, the design is evaluated using multiple evaluation criteria (Chapter 6). Real investments involve a substantial amount of capital. Investments e.g. in power systems are likely to involve a higher degree of strategic decision-making in the future, due to the trends in the power sector (Laurikka, 2005). As the process is started-up and commissioned, measuring efficiency becomes a part of all the other routines of the company.

8.2 Principles of business management

8.2.1 Purpose and general structure

A firm strives to maximize a shareholder value, which is the surplus of revenues over costs (Grant, 2002). Companies also look for above-average returns. These are returns in excess of what an investor expects to earn from other investments with a similar amount of risk (Hitt et al., 2003).

For this they create strategies. A strategy ‘is an integrated and coordinated set of commitments and actions designed to exploit core competencies and gain a competitive advantage’. Furthermore, the strategic management process is ‘the full set of commitments, decisions, and actions required for a firm to achieve strategic competitiveness and earn above-average returns’. It determines how the company carries out the strategy-related activities (Hitt et al., 2003).

Strategists have created several strategic management process structures. They have evolved from fundamentally different perspectives on how the strategy formulation and strategy implementation should be carried out. The way of formulating strategies is one of the major areas of debate within strategic management (Grant, 2002). For example, Mintzberg et al. (1998) proposes ten schools of thought on strategy formation, where each has a unique perspective that focuses on one major aspect of the strategy-formation process. Each of the perspectives is narrow and overstated but insightful and clarifying.

Conventional strategic management is a top-down process, where strategy results from a formal planning process that is decomposed into distinctive steps and brought down into an organization. More modern approaches to the strategy formulation process introduce bottom-up and vertical dynamics (e.g. Hamel, 2000).

The top-down strategic management process starts by establishing the organizational mission (purpose), vision (future scope) and objectives. The objectives are converted into specific performance targets, i.e. the results and outcomes the company wants to achieve. The objectives are shaped by and targeted to match the company’s external and internal environmental forces. External environment forces represent either new opportunities for the firm or threats to its present way of doing things. The internal forces reflect the organization’s capabilities to respond to those opportunities and threats. Due to developments in external circumstances and internal capabilities, strategy formulation becomes an ongoing process. Strategy execution involves development of competencies and capabilities, budgeting, policy-making, motivating, leadership etc. Organizational performance controls guide the use of strategy. They are necessary to help ensure that the firm achieves its desired strategy. The measures are used to monitor the achieved performance and verify results against targets. The objectives and strategies of firms are aligned to cope with the needs of organizational stakeholders. (Hitt, et al., 2003; Thompson and Strickland, 2001; Wright et al., 1998).

8.2.2 The external and internal analyses

The external environment analysis is divided into macro-environment (or general environment) analysis and industry environment (or competitive environment) analysis. These are not under the direct control of the organization. Hitt et al., 2003 defines an *industry* as a group of firms producing products that are close substitutes. The analysis of macro-environment forces includes (Wright et al., 1998; Hitt et al., 2003):

1. Economic forces such as the general state of the economy (depression, recession etc.), interest rates, inflation rate, unemployment rate and some costs like energy costs. This is often considered to be the most significant area.
2. Political, legal and regulatory forces such as the outcomes of elections, legislation, etc. These are considered either restrictive or conducive for the operation of business.
3. Technological forces mean scientific improvements and innovations that provide opportunities or threats for business, such as inventions, techniques, materials and knowledge. The rate of technological change varies considerably from one industry to another. Technological developments can significantly alter the demand for an organization's or industry's products or services.
4. Social forces include traditions, values, societal trends, and a society's expectations of business. For example, the society may have concerns about the environment or the ethics of business. Societal trends can influence the demand for an organization's products and services.

The analysis of environmental forces affecting industry focuses on the factors and conditions influencing a firm's profitability and on predicting the dynamics of competitor's actions, responses and intentions (Hitt et al., 2003). These forces can be quite intense in industries such as the steel industry, where returns are generally low (Wright, 1998). The industrial environment is typically studied through use of Porter's model about 'forces driving industry competition' (Porter, 1980). They can be summarized as follows:

- Competitive changes meaning new competitors, new products and price changes – i.e. *potential entrants* and *substitutes*
- Supplier changes meaning input costs and suppliers' capability to provide material and energy – i.e. *suppliers*
- Market changes meaning new markets and new uses or demands of products – i.e. *buyers*.

The analysis of internal environmental forces focuses on the determination of a firm's strengths and weaknesses that are constituted by its resources. The internal environment factors are to a large extent controllable by the firm. They can be categorized into tangible and intangible resources (Grant, 2002):

- Intangible resources are assets that cannot be quantified, such as human aspects (education, experience, skills etc.) and organizational aspects (structure, culture, etc.).
- Tangible resources are the easiest to identify and evaluate, e.g. financial resources and physical assets.

The analysis of external and internal forces should reveal current conditions and future trends and changes. Forecasting and making long-range plans is important, even though they contain many uncertainties. Scenarios are constructed to study the future. For most authors, scenarios identify plausible future environments that the firm might face (Schnaars, 1992).

8.3 Organizational aspects

Strategy formulation occurs at various levels: the corporate level, the business unit level and the functional level (Figure 15).

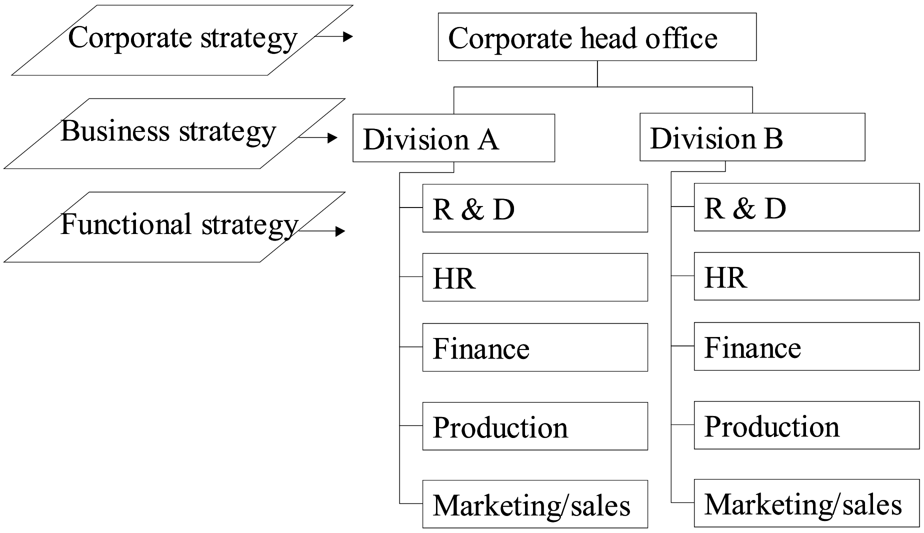


Figure 15 .Levels of strategy and organizational structure (Grant, 2002).

Corporate level strategy is concerned with building and managing a portfolio of business units by making acquisitions, strengthening existing business positions and making divestment decisions, establishing investment priorities and steering corporate resources towards most attractive opportunities. Business strategy is concerned with forming responses to changing external conditions, uniting the strategic initiatives of key functional departments and taking action to address company-specific issues and operating problems. Functional strategies are focused on moves and approaches to support business strategy and on achieving functional/operational performance requirements. In addition, operating strategies are created to craft narrower and more specific approaches/moves aimed to support functional and business strategies and to achieve operating-unit objectives (Thompson and Strickland, 1998). In reality, a strategy process is often less structured. Managers may be measured by their departmental efficiency, or by their own functionally derived perspectives and goals. This may lead to trade-offs that are sub-optimal for the business as a whole (Hill 2000, Grant 2002).

According to Porter (1980) a firm's strategy ultimately falls into one or two categories: cost advantage and differentiation. These can be applied within either a broad or narrow scope. Based on this, three generic strategies result: cost leadership, differentiation and focus, and they are applied at the business unit level.

Strategic issues relating to technology generally appear in a fragmented manner as part of other functional strategies. Most typically they appeal to production management, operations management, and research and development. Sometimes separate technology strategies are formulated. For example, the selection of a bleaching technology is a matter of technology strategy in the pulp and paper industry. A significant relationship has been found between manufacturing strategies and the performance of the firm: strategic linkages are clearer among good performers than poor performers (Williams et al., 1995; Sun and Hong, 2002; Ward and Duray, 2000). Models have been proposed to guide the development of process capabilities and to better integrate technology into the business planning process (e.g. Bessant, 1997; Probert et al., 1999).

8.4 Operational performance management

The activities of creating, producing, selling, and delivering can be the basic sources of competitive advantage. Operational effectiveness means performing these activities better (i.e. faster, with fewer inputs, with fewer defects) than the competitors (Porter, 1996).

Attempts to increase productivity, quality and speed have created a number of management tools and techniques, e.g. total quality management, benchmarking and outsourcing (Porter, 1996).

The TQM (Total Quality Management) is 'a philosophy of managing a set of business practices that emphasizes continuous improvement in all phases of operations, 100 %

accuracy in performing activities, involvement and empowerment of employees, team-based work design, benchmarking and fully satisfying customer expectation' (Thompson and Strickland, 2001). Quality awards such as the Malcolm Baldrige National Quality Award are seen as currently the most demonstrative philosophies of the TQM discipline (Kujala, 2002). According to Choi and Eboch, 1998, there have been conflicting reports about how TQM practices lead to the expected performance results of a firm. The negative findings indicate that the quality gains and operational results are less than expected. The authors state that TQM practices have a stronger impact on customer satisfaction than they do on plant performance. Technical Committee 207 of the ISO has published several guidelines and standards for product and production integrated management (*Westkämper et al., 2001*). Peura (2001) analyzed the use of environmental indicators in environmental performance evaluation in Finnish certified companies. The study reveals that current indicators belonging to environmental programmes mainly measure the achievement of operational objectives and targets, i.e. the load generated or the consumption of energy and water, which is only one aspect of environmental performance.

A key element in the company's strategy implementation is the use of performance controls. They are used in each part of the organization, e.g. product lines, functional areas and departments. In general, the performance controls exist to ensure that firms achieve the desired strategy, to compare actual results with expected results, and suggest corrective actions when a difference between an actual and an expected result is unacceptable. Also, the objectives set for operation should generally be stated in quantifiable terms and contain a deadline for achievement.

8.4.1 General approach to performance controls

Operational performance controls can be roughly divided into two main categories: financial and strategic (Thompson and Strickland, 2001; Hitt et al. 2003). Most companies have few problems establishing financial performance controls. In the Balanced Scorecard by Kaplan and Norton (2001) organizational performance is measured in four key areas: financial performance, customer satisfaction, internal business processes, and learning and growth. A principle in development has been to avoid exclusive reliance on financial measures, which might sacrifice long-term value creation, and to balance between the ‘lag’ and ‘lead’ indicators of organizational performance.

8.4.2 Theoretical approaches to performance controls

According to Sink and Tuttle (1989) the term ‘performance’ is a function of seven criteria, which are 1) effectiveness (dealing with a ratio between expected output and actual output), 2) efficiency (dealing with a ratio between expected resource consumption and actual consumption), 3) quality, 4) productivity, 5) quality of work-life, 6) innovation and 7) budget ability/ profitability.

Productivity can be understood as an indicator for a company’s production capability. Productivity is the relationship between the amount produced by a given system during a given period of time, and the quantity of resources consumed to create or produce those outputs over the same period of time. The term ‘productivity’ can be defined as (Rantanen, 2005):

$$\text{Productivity} = \Sigma\ \text{Outputs} / \Sigma\ \text{Inputs} \tag{2}$$

Productivity can be understood as total productivity or partial productivity. Total productivity is a measure of total output in relation to the sum of all impact factors. It is expressed either as physical or financial measure. ‘Total productivity’ (TP) can be given in the terms of (Rantanen, 2005):

$$TP = O / L+C+M+E+X \tag{3}$$

Where O is total output, L is labor input, C is capital input, M is material input, E is energy input and X is other inputs. Sometimes partial productivity measures are also used. They indicate a ratio between the total output and one class of input. For example, energy productivity P_E would be written as (Rantanen, 2005):

$$P_E = O / E \tag{4}$$

According to Rantanen (2005), partial productivity measures indicate the effects of change on each of the partial productivity measures individually. For example, investing in production equipment may increase labor productivity but decrease capital productivity. Productivity improvement actions can be made at the factory floor level with machines, working cells, and activities, thus reflecting the performance of a real process. The complexity increases as several hierarchical layers of organization are discussed and as different units are used for measuring, e.g. financial and physical. Productivity improvement is an important part of profitability improvement. However, as the actual relationship between the two is not very clear or easy to establish, many models have been developed to analyze this relationship.

Helminen (1998) studied widely the various interpretations of the terms efficiency and productivity. She found that the two terms are very much related and often used interchangeably. According to the study, the difference between efficiency and profitability is not clear cut. Tangen, 2002 claims that productivity should be expressed in physical units instead of monetary units. The matter seems to be the subject of ongoing academic debate. As Helminen (1998) concludes, efficiency is more a physical concept and means producing goods with minimum resources, whereas productivity is an economic concept.

8.4.3 Other origins for operational performance controls

Environmental and sustainability factors are becoming more important, and information is requested on these areas. Many networks, charters, agreements and guidelines are created to help communication between a company and its stakeholders. For example, environmental reporting has become an important part of a company's management system for external communication (Törnroos, 2005). The EC's EMAS (Eco-Management and Audit Scheme) is a voluntary European Union scheme to register sites that have established an environmental management system. It expects companies to produce periodic statements about their environmental performance (EMAS, 1996). The ISO (The International Organization for Standardization) has published the standard: Environmental management – Environmental performance evaluation – Guidelines, which deals with environmental reporting (SFS-EN ISO 14031, 1999). ISO 14031 divides indicators into environmental condition indicators (ECI) and environmental performance indicators (EPI). ‘Responsible Care’ is a commitment by the chemical industry to continuously improve its EHS performance. The CEFIC guidance on the reporting of distribution incidents covers 18 parameters, e.g. Hazardous waste for disposal (CEFIC, 2002). Industries may have their own benchmarking system and indexes, e.g. the Solomon Energy Intensity Index (EII) in the oil industry.

8.5 Other relevant literature

According to Martin and Eisenhardt (2001a) cross-business synergies are *the value that is created and captured, over time, by the sum of the business together relative to what it would be separately*. The promise of synergies is the primary logic behind strategic moves like acquisitions and alliances. Martin and Eisenhardt (2001a) stated that the capture of cross-business synergies originates from 1) the active role of business units instead of corporate headquarters, 2) planned and unplanned experimental work rather than planning process, 3) general managers’ self-motivation rather than corporate initiatives or collaborative financial incentives 4) resource reallocation and loose organizational structures rather than incremental resource movement and extreme levels of coordination. According Martin and Eisenhardt, 2001b, these cross-business synergies should be examined according to an external measure (e.g. ROI) and internal measures (e.g. net present value, knowledge transfer) to acknowledge the importance of the relationship between the internal and external environment of the corporation. Although the findings are from a different field of expertise, most findings apply to process integration, which is characterized by multi-objective resource usage over business units or incorporated functions.

Much research deals with organizational goal-setting. According to Boyer and McDermott (1999) it is important that the various levels of employees within an organization agree on what is most important for the organization to succeed at. That means that there should be a consensus on the relative importance of factors such as costs, quality, delivery and flexibility to key operational goals. In this, the manufacturing executives have an important role to play. Better business performance is achieved through the involvement and influence of manufacturing executives and their affect on organizational and manufacturing strategies. Organizations that develop mechanisms for manufacturing managers to participate in strategy formulation obtain competitive capabilities and better performance (Papke-Shields and Malhotra, 2001; Tracey et al., 1999). Emphasis must also be placed on creating managerial language, frameworks and processes to support the effective integration of technology into strategy (Hamilton, 1997).

Joshi et al. (2003) studied the importance of aligning strategic priorities between the functional level and business level. They tested whether the performance of the manufacturing unit is enhanced when general managers and manufacturing managers agree on strategic priorities. The study revealed no direct relationship between alignment of manufacturing priorities and performance of the unit except in certain conditions (e.g. in the case of new employees). According to Chang et al. (2003), compatibility between a business strategy and manufacturing flexibility is critical to business performance. Joshi et al (2003) further states that the studies focusing on the alignment or strategic consensus are classified into two categories in operations strategic literature, i.e. internal fit and external fit. Internal fit means consistency between the manufacturing task and manufacturing policies and practices. External fit refers to aligning operations strategy with business and corporate strategies. Smith and Reece (1999) state that the external fit has a significant, positive and direct effect on business performance.

Schroeder et al. (2002) analyzed a firm’s manufacturing capabilities. They stated that a competitive advantage in manufacturing results from proprietary processes and equipment. That is driven by external learning (learning from customers and suppliers) and internal learning (suggestion systems, cross-training). Several manufacturing performance variables were used to measure the performance, e.g. costs as a percentage of sales and conformance quality. Financial performance measures, such as sales and profits, were not used since ‘many factors external to the plant may distort them’. Later, Ray et al. (2004) stated that distinctive advantages observable at the process level are not necessarily reflected in performance at the firm level.

8.6 Chapter findings

Studies like the ones by Schroeder et al. (2002) and Ray et al. (2004) analyze the sources of superior firm performance. Although they indicate factors that lie behind organizational efficiency, their applicability in process engineering problems is limited. This is because the information they provide is difficult to connect with engineering problems involving complex systems, physical and chemical property data and numeric tools. The research dealing with the mechanisms of cross-sectional efficiency (Section 8.5) is insightful. It encourages the search for cross-sectional efficiency ‘from bottom to top’ and ‘in vertical directions’ in an organization, and points out the role of process specialists as a source for superior operational performance.

The external and internal analyses represent a potential source of new information for engineers. This information would be of most use in supporting process improvement initiatives, while incorporating additional design and performance criteria into target-setting. Their use would promote proactive technology development instead of reactive development as the design perspective is widened. The problem is that the analyses as such are only one type of background material in the business management process. From that the strategists continue into *strategic positioning to achieve a sustainable competitive advantage by preserving what is distinctive about a company* (Porter, 1996). That involves creating a valuable position and a set of activities, making trade-offs in competing and creating a ‘fit’ among a company’s activities.

The research surrounding operational performance management and controls indicates that while the engineers aim at creating physical or chemical efficiency, the management literature emphasizes the economic perspective. Traditionally, operational performance controls are used to communicate the targets and priorities ‘from top to bottom’ in an organization. A way forward is to enhance a two-way-communication. Engineering metrics (Chapter 6) can be further developed to cope with the requirements of operational performance management.

Case 6 ‘Strategies in design’ evaluated the availability and applicability of the proposed material. The study confirmed that the performance measurement at a low hierarchy level emphasizes the technical functioning of unit operations, whereas the performance measurement at high hierarchy levels emphasizes key aspects of strategy dealing with technology, economy and customer relations.

Several business units or incorporated functions may exist in a process plant. In Case 5 ‘Bio-fuel drying in a power plant’ the importance of different balance boundaries was noted. The wide design/evaluation balance boundary prevents from one from making a sub-optimal design or evaluating within too narrow a scope. For example, a certain design solution may be optimal from a process unit perspective but sub-optimal from the perspective of a whole plant. Strategic priorities determine which factors become emphasized. Prioritizing is needed to balance with different process development initiatives. In Case 5, two optional design priorities were identified: decrease in CO_2 emission and improvement in a power-to-heat ratio.

Part 3. RESULTS AND CONCLUSIONS

9 EFFICIENCY IN INTEGRATED DESIGNS

9.1 General

This chapter assembles the first part of the theory findings. It presents how efficiency is created during the process life span (Section 9.2). Then the chapter proposes new definitions for process integration and for its methods (Sections 9.3. and 9.4). The new definitions are developed to clarify the role of process integration in industrial design and to facilitate their practical use. The findings presented in this chapter can be considered as background material for Chapter 10, where the elements of the new approach are explained.

9.2 Efficiency in the process life span

The thesis divides the process life span phases into process development, process design, construction, start-up, operation, retrofitting and closure (Figure 16). The thesis focuses is on the process design (conceptual stage), operation and retrofitting phases.

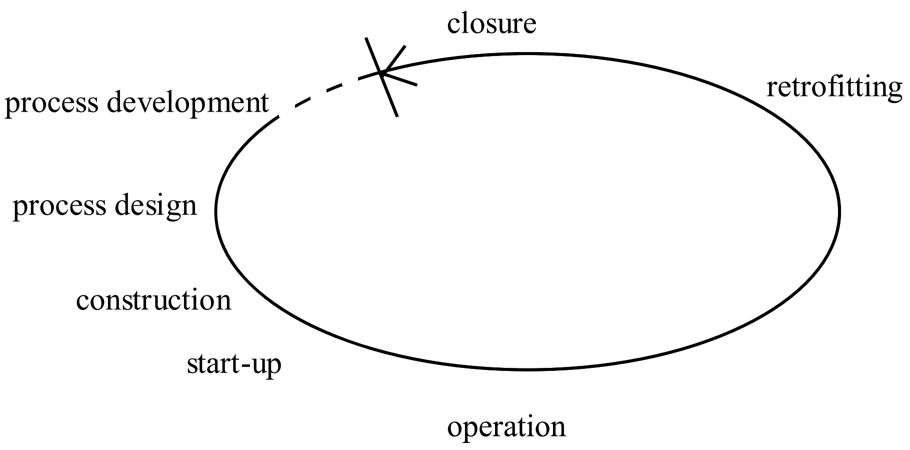


Figure 16. Process life span phases.

The perspective on integration efficiency is slightly different in each of the three phases:

- Processes are created in the process design phase. The chances of increasing efficiency are greatest during the design synthesis stage, where the process structure is formed and connections to the process surroundings are determined. During the design analysis stage, it is possible to optimize the process parameters.

- The operation of a process is monitored and/or optimized during the process operation phase. Limited possibilities exist to improve efficiency. Efficiency is mainly increased through adopting better operating practices.

- An increase in efficiency in the retrofitting phase is dependent on the degree of replacement. The number of design alternatives is limited by the existing plant, equipment and surroundings. For the part being modified, the process design case is analogous to a green-field design. If the process chemistry remains untouched, a partial synthesis of the process is performed, e.g. changing the order of process equipment, connections or recycle flows. The retrofitting phase is therefore a combination of the design and operation phases.

Process integration occurs on different design scales. At the site/plant level, the process is connected with its surroundings. This aspect is considered either at the start or at the final stages of design. A typical site level integration is heat integration between a plant and its surrounding society, i.e. district heating. Then, integration exists within the unit processes as a preliminary process concept has been designed. Integration between unit processes concerns heat exchanger and utility network design. These are shown in Figure 17. The sequences are similar to the retrofitting phase. The details of the task depend on the degree of replacement.

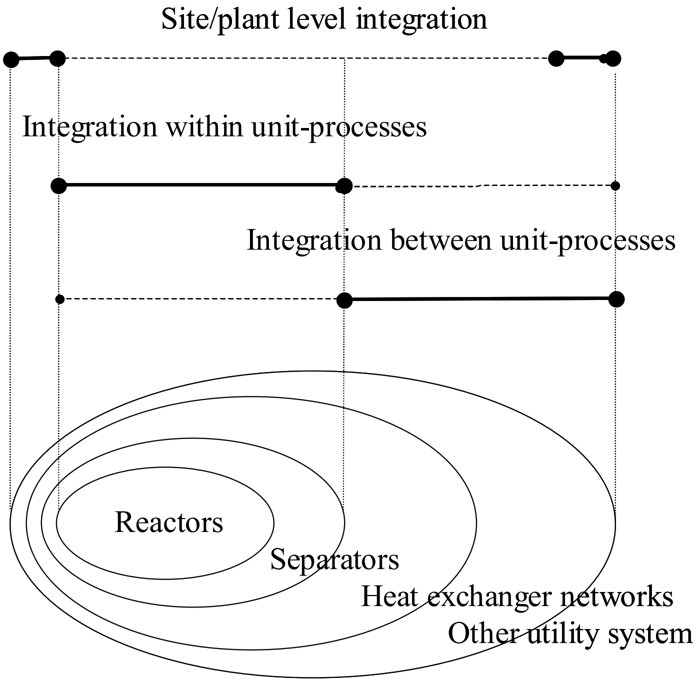


Figure 17. Process integration at various stages of design.

9.3 A new definition of process integration

Process integration is traditionally applied to the design of heat exchanger and utility networks. The primary objective has been to create an energy-efficient process. Nowadays, integration applications exist for all process design and process life span phases, including the operational phase. Process integration methods in the operational phase deal with production optimization.

Integration as a term has multiple uses. An ‘integrated process plant’ means a plant where production units or complete processes are made to operate in connection with each other, and usually they constitute a large process site. The intended benefits are typically financial, e.g. less packing and storage and less transportation, or more strategic, e.g. better material availability.

A new definition for process integration was created in order to clarify the objectives of process integration. The following definition of process integration serves both of the above-mentioned approaches:

Process integration means creating efficient systems. On a variety of scales, the system consists of a physical and/or chemical process(es) and its connections to surroundings. In process integration, the system parts are combined to obtain synergic benefits as compared with the situation where the parts would perform their tasks separately.

9.4 A new categorization for process integration methods

Consistently with the new definition of process integration:

Process integration methods are developed for the design, analysis and optimization of integrated process systems. Their featuring element is an ability to quantify the synergy obtained from integration.

The purpose of the new definition is to clarify the fundamental feature of process integration methods. The new definition allows the methods to be categorized into their own group, separately from other engineering methodologies. Their major featuring element is the ability to quantify the synergic effect, i.e. the potential for improvement obtained by integration.

The existing process integration methods differ in their ability to quantify the synergic effect. The capabilities of the methods in dealing with the synergic effect range from theoretical, to technical and economic (see Chapter 10). Then, the methods differ in their ability to deal with the problem scale. A rather small-scale problem is dealing with equipment or with a unit process. Some methods are capable of dealing with a site scale problem. Many (most) methods deal with steady state conditions. Some are able to consider dynamic conditions. Finally, the methods differ in their procedural approach to problem-solving. Some methods are highly interactive, whereas others are automatic.

To summarize, the process integration methods differ in four dimensions:

1. System synergic effect quantification i.e. calculation of process integration potential
2. Design scale management
3. Design state management
4. Procedural approach to problem-solving.

The methods focused on quantifying the theoretical potential include the Pinch analysis and Exergy analyses. On the other hand, an Exergy analysis has a limited capability to consider other than steady-state conditions or to treat large-scale design problems. The mathematical methods are capable of considering many design aspects simultaneously but they exploit more approximated integration synergy quantification. In addition, they are not well suited to large-scale industrial problems. The dynamic process integration methods consider dynamic process behavior as well. The flow-sheet programs are most applicable in site-scale industrial applications. They usually consider a steady-state condition. On-line plant simulation and optimization programs (mill management systems) consider large site scales, and the problem-solving is highly automatic. Mostly, they consider a certain process structure but with slight possibilities to alter a process, e.g. to add an additional electricity-consuming device as production exceeds a certain limit. They can be said to deal with the economic potential.

The four dimensions with an example are presented in Figure 18.

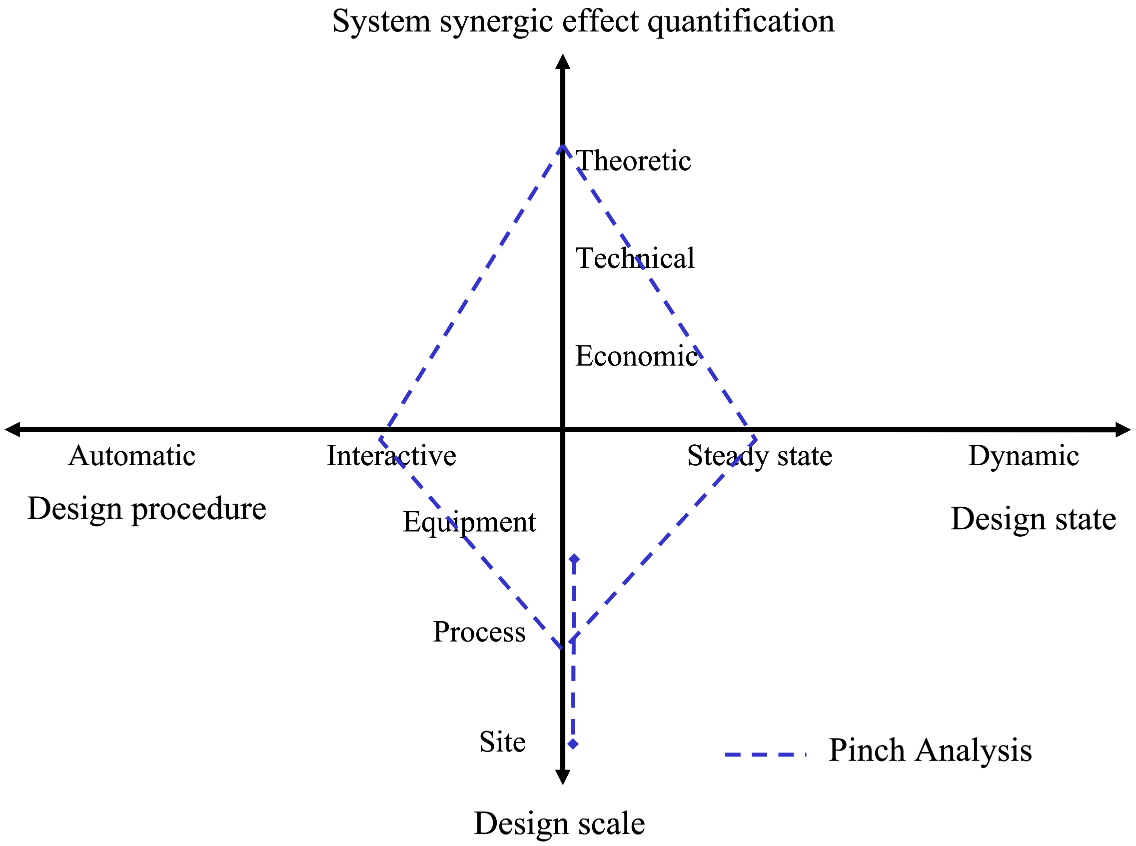


Figure 18. The four dimensions of process integration methods with an indicative example.

Use of a flow-sheet program was demonstrated in Case 4 'Steel mill process retrofit'. The method was used to calculate steady-state technical potentials. Case 3 'Paper mill water management' applied a steady-state interactive process integration method to calculate the potential for water integration.

Novel applications typically combine different problem-solving techniques to complement each other. For example, mathematical methods are combined with heuristics to make complex problem-solving and simulation easier, and to widen the design scale.

10 ELEMENTS OF THE CONCEPT

10.1 General

This chapter assembles the second part of the findings. It presents the findings as ‘elements of the analysis approach’. These elements are referred to in Chapter 11, where their methodological use is explained.

The conceptual approach to integration efficiency consists of 1) methodological elements that support a numeric process integration problem analysis and 2) supportive elements that create conditions for a numeric process integration problem analysis. Process (design) efficiency evaluation is always a case-specific task. It follows that the analytic methods and tools are also case-specific.

1) Methodological elements supporting a numeric process integration problem analysis:

- The efficiency design/ evaluation must be comprehensive from the criteria and index point of view. Altogether *three efficiencies* have to be taken into account i.e. the material efficiency, energy efficiency and operational efficiency. The final design and decision-making criteria and indices should cover all these three dimensions. Indicators sometimes represent certain perspectives of design, e.g. economy or environment.
- A primary interest in efficiency design/ evaluation is to know what *the potential for improvement* is. Improvement potentials are calculated to point out the benefit that comes from studying systems instead of studying individual parts of it. The potential for improvement is analyzed against the most important criteria.

2) Supportive elements creating conditions for a numeric process integration problem analysis:

- Usually, several alternatives exist to choose a *problem balance boundary*. Its determination affects the problem definition (goals and constraints). In addition, its determination affects the evaluation of results. The reason for this is that the balance boundary determines which of the design/ evaluation factors are used and emphasized. The boundary, eventually affecting the problem size, also influences which of the design methods and tools are applicable.

- In companies, operational performance controls are used to guide the activities towards strategic goals. The *performance controls* should drive the development in key aspects. A connection between operational performance controls and engineering metrics should be established.

10.2 Potential for improvement

10.2.1 Theoretical, technical and economic potentials

The field of process integration started with the discovery of the Heat Recovery Pinch. The success of the method comes from its ability to calculate the potential for integration already at the start of the design. The potential is calculated in respect of one design criterion, which is the minimum required external heat energy (or the minimum required external cooling energy). According to the new definition (Section 9.3) process integration is about creating efficiency *systems*.

The thesis divides the process integration potentials into theoretical, technical and economic (Figure 19). The *theoretical potential* represents the maximum improvement available through structural arrangement of the process. As the target theoretic value is found, the design work continues to find a suitable technical solution. At this point, the designer must consider the other perspectives of design. It follows that the initial performance target will be relaxed to some extent. The remaining potential is called the *technical potential*. The economic constraints and requirements may reduce the potential still further. The potential maximizing the economic requirements is called the *economic potential*.

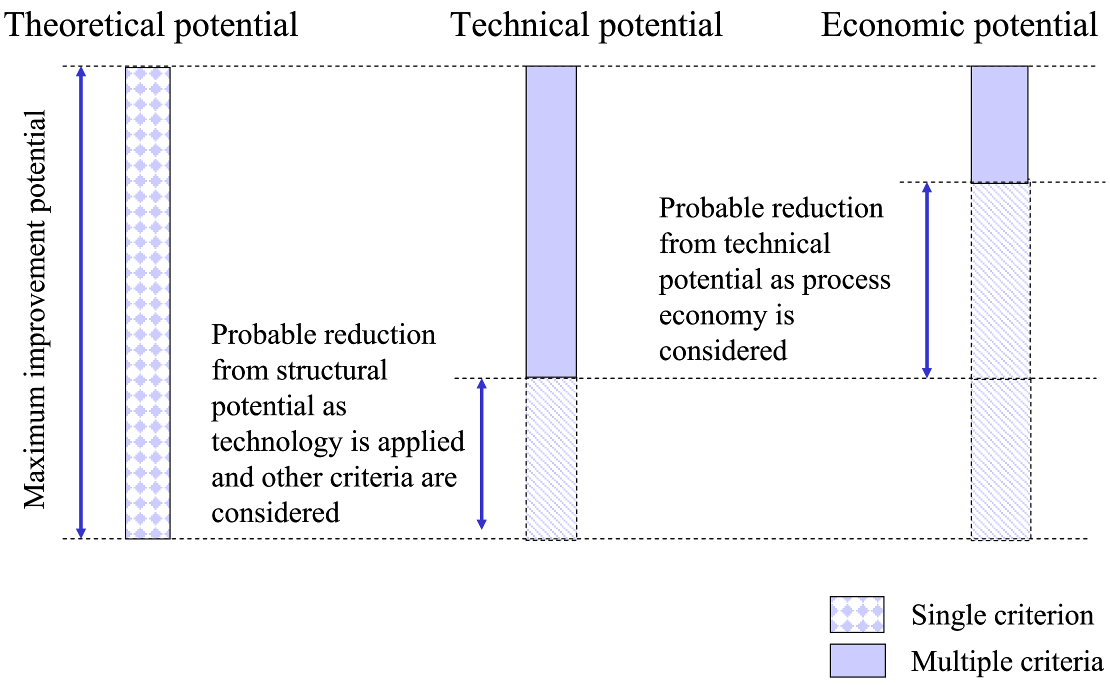


Figure 19. Potential for improvement in integration.

The theoretical potential is calculated for one criterion at a time. If several theoretical criteria are of interest, they are calculated one at a time.

Usually several optional process alternatives exists. This means that several technical potentials exist for the same design problem. If the theoretical potential is calculated for another criterion, a number of new technical potentials follow. The same logic applies to the calculation of economic potentials: the number of economic potentials equals the number of calculation cases.

A way to calculate theoretical and technical potentials was demonstrated in Case 5 'Bio-fuel drying in a power plant'. In the case example, the theoretical potentials were calculated separately for a power-to-heat ratio and to a level of CO_2 emission. The technical potentials were calculated for five optional design cases. Case 2 'Energy management' discussed the difficulties in calculating the energy efficiency improvement potential. Sometimes the calculation of potentials is circumvented using the Best Available Techniques (BAT) or using theoretical reference values.

Heuristics covers a wide range of engineering practices. Many times they are formalized into guidelines and into rule-of-thumb approaches, which are then used to identify possibilities for improvement. The use of heuristics was demonstrated in Case 4 'Steel mill process retrofit'. In that case 'only' engineering heuristics was used to identify a feasible process alternative. This was then taken as a basis to calculate the technical potentials. The result described the difference in performance between the two design cases i.e. the existing process and a new design.

10.2.2 Potential for improvement at different stages of process life span

Process design

The potential for improvement is greatest at the start of the process life span, when the structure of the process is created and connections to surroundings are determined. The aim in that phase is to create efficiency in respect of several criteria. Therefore calculation of the theoretical best performance is difficult, except small-scale designs like equipment. The technical potential (and the economic potential) can be obtained by making comparisons to similar or old designs. The potentials are, however, difficult to distinguish as the design usually proceeds in an iterative manner (synthesis, analysis, evaluation).

The theory on process potentials starts to apply as part of the process is fixed and some criterion/ criteria can be chosen for a basis of calculation. This is the case e.g. in the heat network design. See Table 11 for a summary.

Operation

The efficiency of an operating process is improved mainly through adopting better operation practices. No theoretical potential can be given for a process at this stage (otherwise considered a process retrofit). It follows that the technical potential is usually not available either. The economic potential is therefore of the most interest at this stage.

The economic potential can be obtained by using process analysis tools such as production optimization tools. Sometimes they are capable of considering minor technical changes while optimizing the production i.e. they are capable to realize the known technical potentials. Another example of a technical potential is the trial runs that are carried out to find out more feasible operating conditions. Sometimes the Best Available Techniques (BAT) or theoretically calculated values are used as references see e.g. Case 2 ‘Energy management’. See Table 11 for a summary.

Retrofit

If structural changes are made to the process, the theory follows the one for *Process design* above. If only operational optimization is performed, the theory follows the one for *Operation*. See Table 11 for a summary.

Table 11. Possibilities to quantify the potential for improvement (theoretical, technical and economic) in design, operation and retrofitting.

Design phase	**Operation phase**	**Retrofit phase**
Theoretical potentials - Difficult to apply to systems at concept design phase (a multicriteria circumstance) since no reference design exists. Applied for equipment or for known unit processes (e.g. Carnot cycle). - Principle applicable after a preliminary process concept exists.	Theoretical potentials - Not applicable (no structural changes made). - Calculations of theoretic performances can be made.	Theoretical potentials - As in design phase. - In addition: the approach is most relevant at this stage. Best applicable when the target enhancement criteria are clear and their number is low (1….3 pcs).
Technical potential - Difficult to apply to systems at concept design phase (as above). - Principle applicable after a preliminary process concept exists (as above). - Sometimes BAT, calculated references, etc. are used as references and a technical potential can be calculated in relation to those.	Technical potential - Not applicable (no structural changes made) except than: 1) many times possible to consider minor technical changes while optimizing operation, 2) new technical potentials possibly available after analyzing pilot trials.	Technical potential - As above.
Economic potential - Economic potential can be calculated for selected case designs after a preliminary process concept exists.	Economic potential - Economic potential can be calculated for special cases explained above.	Economic potential - As above.

10.3 The three efficiencies

An optimal design (Figure 20) is efficient with regard to its resource usage. In addition, it allows an efficient operation. The former is emphasized more during design stages, and the latter during the operational stage.

The process design aids are developed to treat numeric data, like equipment data (e.g. a heat transfer area), design coefficients (e.g. reaction constants) and physical property data of mass and energy flows. The physical property data of mass and energy flows have quantity and quality characteristics, like a biomass flow has a mass, moisture, density, energy content (see e.g. Case 5 Bio-fuel drying on a power plant). The material and energy balances are usually given in a steady-state condition.

Good process operability allows the maintenance of the set-point operation in a steady-state condition. Good process operability also allows fast transitions from one state to another. Process operability can be further divided into flexibility and controllability. They are both taken into account in dynamic modeling. Sometimes stepwise steady-state modeling is used (dotted line in Figure 20). Process availability considers the availability of parts and components.

As noted and discussed in Case 3 'Paper mill water management', the operational aspects of the process are determined by the complexity of factors such as raw materials, products, control system and the history of use. The outcome of the synthesis of the factors is unknown when new processes are designed. Some information is gained by studying existing processes, but the magnitude remains unknown. Based on the findings of Case 4 'Steel mill process retrofit', it is proposed that the outcome is described through the process operation time and the process output, usually the product, quantity and quality parameters.

The thesis proposes that process integration efficiencies are divided into three categories: efficiency in materials use, efficiency in energy use and efficiency in process operation.

The material and energy efficiencies are efficiencies in respect of process material and energy use. Several technical design/ evaluation criteria and indicators can be used to describe materials and energy use. They include the *yield* and consumption per ton of product etc. The material and energy efficiencies can be calculated for various input/output relationships and at various process integration scales (site/ plant/ process/ unit/ equipment).

Operational efficiency describes the goodness of operation. The term operational efficiency captures the complex interactions within the process. It follows that the operational efficiency is case-dependent as the processes are unique. The operational design efficiency encompasses process flexibility, controllability and availability. The outcome of operational efficiency is seen as and monitored through:

- Process output (quality and quantity)
- Process operating time.

Process flexibility means ‘the in-designed parameter ranges’, such as the allowed utility ranges or allowed deviation in product quality. The controllability of the process determines whether the process is capable of operating within these limits. If not, partial production in respect of quality or quantity or a reduction in operation time will follow. Recovery from deviations or transitions from one state to another are dependent on the operating limits (flexibility) and capabilities of the control system.

The approach provides a means to treat operational efficiency in numeric (and economic) terms. This is an alternative approach to the use of dynamic tools, which in most cases are not available in industrial design/ evaluation. The approach can be used to sharpen the design scope as in Case 5 ‘Bio-fuel drying in a power plant’.

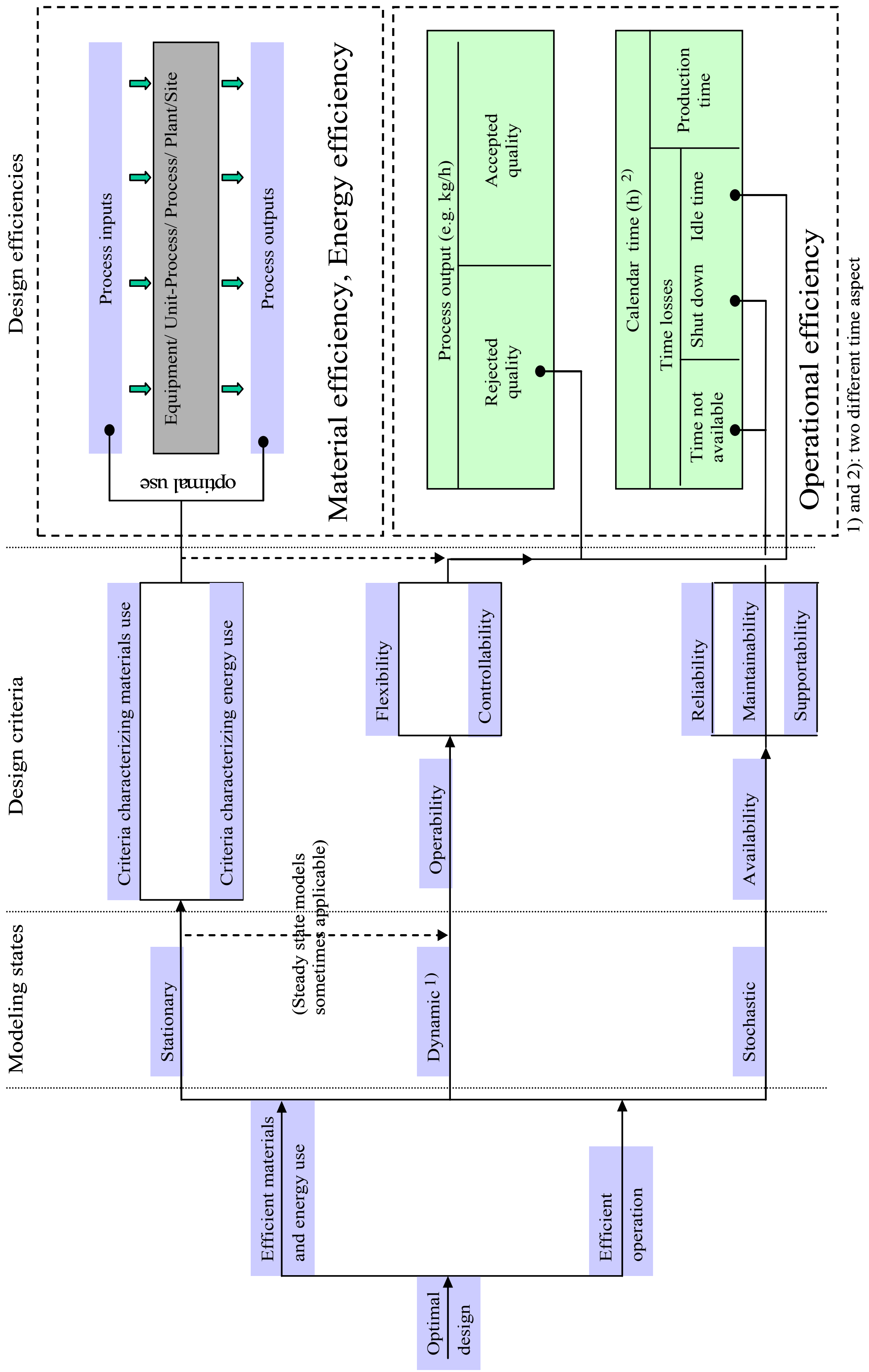


Figure 20. Schematic presentation of factors affecting the three design efficiencies.

10.4 Supportive elements

10.4.1 Balance boundary definition

Small-scale problems concern equipment and unit processes where problem-solving is mainly focused on technical issues such as physical phenomena. Large-scale industrial problems concern total site issues, and many of the design criteria are strategic, e.g. the raw material type and the amount of waste. This was demonstrated in Case 4 ‘Steel mill process retrofit’ and Case 5 ‘Bio-fuel drying in a power plant’. Case 5 also demonstrated that design problem target setting becomes fairly different at different design scales. An attempt to treat the problem from too a wide perspective may result in difficulties in applying design tools or balancing between detailed and generalized source data. Also the process must be modeled in order to use mathematical methods. This is challenging in large industrial applications.

Figure 21 schematically presents the hierarchical structure of a production plant and depicts the alternative balance boundaries.

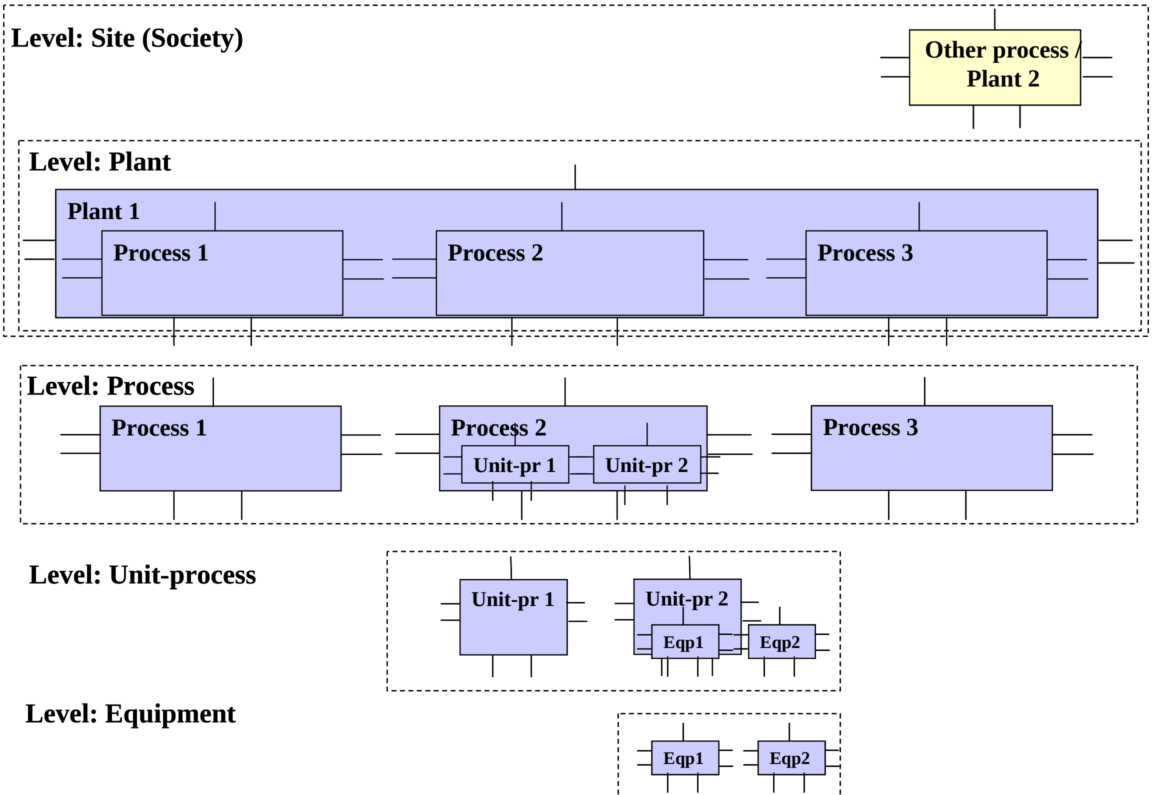


Figure 21. Various problem scales at a mill.

Modular thinking helps to structure the problem. In the module in Figure 22, the process flows are categorized into seven input and output flows. The number of flows in an industrial application is always case-specific. An analysis can be performed for one module or for a combination of modules. A module can be equipment, a unit process, a process, a plant or a site, depending on the problem. Operational efficiency describes the functioning of the module.

The effects of process changes should be analyzed on various hierarchical levels. Case 5 'Bio-fuel drying in a power plant' is an example of this. In Case 5 the bio-fuel drying was to become a part of CHP (Combined Heat and Power) power production. In CHP production, there must be a certain load for the steam in the process. A reduction in the steam load may affect a mill's ability to produce the full electricity potential. A change in the steam load occurs, for instance, when the type of paper drying is changed from cylinder drying to infrared drying.

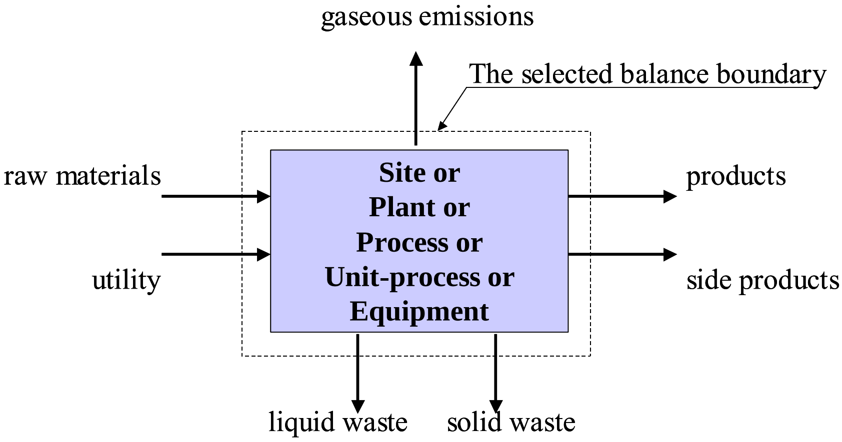


Figure 22. An example of a module. Each flow has quality (e.g. moisture -%) and quantity (e.g. kg/h) characteristics. The categorization into seven flows is demonstrative.

To summarize, the determination of a design balance boundary influences the process (design) problem definition and evaluation. It determines which factors are used and emphasized. The chosen balance boundary also influences which of the design methods and tools can be applied. A concise problem scope results in more accurate problem-solving but may lead to a sub-optimal solution. Too a large scale may lead to problem-solving on too general a level.

10.4.2 Connection to business management

Operational performance controls are used in companies and in operating mills to guide the activities towards strategic goals. Basically, the controls should drive the development in key aspects, and the potential for improvement should be analyzed against them.

A link between engineering criteria and operational performance controls

Traditionally, operational performance controls are used to communicate the targets and priorities 'from top to bottom' in the organization. A way forward is to enhance two-way communication. In general, the operational performance controls of mills should not compromise process development towards the principles presented in this chapter, i.e. development towards a balanced approach between all three efficiency categories and development towards realization of the physical and chemical improvement potentials.

The measures indicating process integration efficiency seem to be well adaptable to those management controls that try to capture the efficiency of the production process. For example, the three efficiencies are close to the term 'productivity'. These types of intersections with management controls should be taken into account in process (design) target-setting and evaluation. Along with balanced measures, the persons responsible for process development become more systematically aware of operational goals. The management is better able to interpret the results of engineering work.

Business management perspective in the design start-up

The process design objectives are specified at the start of design. A typical engineering background material is a market study. That is used to formulate the target of the design task from a business management perspective. The market study is focused on products and markets.

Strategists carry out ‘external and internal environment analyses’ that are used as one of the background materials in a business management process. The external and internal analyses contain more comprehensive strategic information than the market studies. This information combined with the technical design criteria would sharpen the design/ evaluation scope and broaden the understanding of the goals and constraints of the (future) work. The practice would promote proactive instead of reactive development. However, the subject requires more research in order to specify the required actions on a more detailed level.

11 METHODOLOGICAL USE OF THE ELEMENTS

11.1 General

The principles of the proposed concept can be applied in a variety of engineering tasks. The contents of those tasks are always case-specific. The case formulation is affected by the branch of industry, life cycle phase, scale of the study, availability of design/ evaluation methods, operational priorities, etc. Thus, no single case example can be carried out to validate the whole concept.

Methodological use (or a combined use) of the elements is clarified by two examples:

1. An application example of a generalized problem-solving procedure, while introducing complementary industrial data (Section 11.2).
2. A case-specific industrial application example of how to formulate an evaluation problem (Section 11.3).

11.2 A generalized application example

In this example, the elements of the proposed concept (from Chapter 10) are brought to support a general problem-solving procedure. That is schematically presented in Figure 23. The left side of the figure depicts the generalized procedure. The right side of the figure depicts the elements of the concept.

A design /evaluation starts by problem analysis and data collection. It continues with goal-setting. These are unique in each engineering problem. The theories related to general design stages (synthesis, analysis and evaluation) were discussed in Chapter 5. The evaluation criteria were discussed in Chapter 6, and the ways of making decisions in Chapter 7.

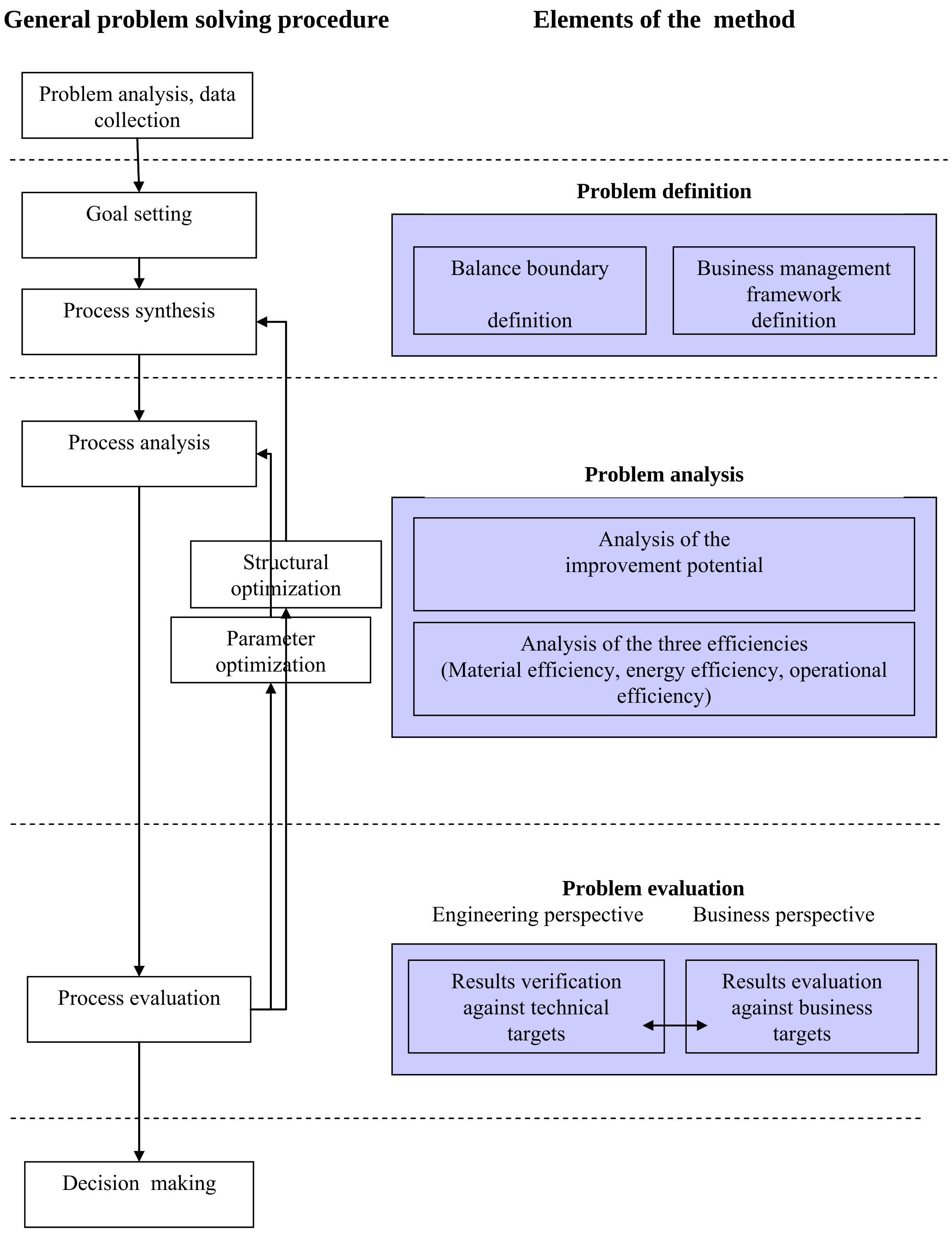


Figure 23. Elements of the proposed concept in a general problem-solving procedure.

General

The concept aims to support both design cases and evaluation cases. A design case is considered to be one having an objective to improve the process performance (process efficiency) in respect of a certain criterion (criteria). In such a case the design reference is either the existing (old) design or some other known reference design. An evaluation case is considered to be one having an objective to quantify the potential for improvement or to quantify the performance against a known reference. After that, a design step may follow.

Problem definition phase

The goals and constraints of the work are defined first. Example industrial goals include: energy efficiency improvement (as in Case 2 and Case 5), water savings (as in Case 3), waste reduction (as in Case 4), yield improvement, better production control (e.g. less breaks), better quality, etc. Example industrial constraints include: maximum deviation for quality parameters (e.g. brightness, purity or strength), minimum and maximum utility pressure, minimum production speed, etc.

The developed concept highlights first the importance of the balance boundary definition. The boundary influences which type of design/ evaluation criteria the case is dealing with and what are the aspects that have to be considered in decision-making. Furthermore, the balance boundary influences which analytic methods and tools are suitable for use. Different methods can be used to quantify the potential for improvement. The principle applies in problems dealing with both integrated and non-integrated processes.

The concept also encourages the consideration of process (design) evaluation criteria and constraints from the business management point of view. In practice, this means prioritizing the process input and output parameters, e.g. an output quality. The improvement potential is quantified against the most important criteria. The principle applies in problems dealing with both integrated and non-integrated processes.

Example 1

Figure 24 presents a simplified module, a paper machine. Example goals and constraints, and the strategic objectives are drawn on the module. One of the goals is to reduce CO_2 emission by 10%. An example constraint is that a share of softwood cannot exceed 51%. The emission reduction and reduction in water use were set as main goals for the task.

A real design /evaluation case is more complicated, as the module consists of several sub-modules. Also the number of streams is larger. In such cases it is more difficult to see the inter-relations within the module and its sub-tasks. A comprehensive approach to problem-solving becomes more important to avoid sub-optimal solutions.

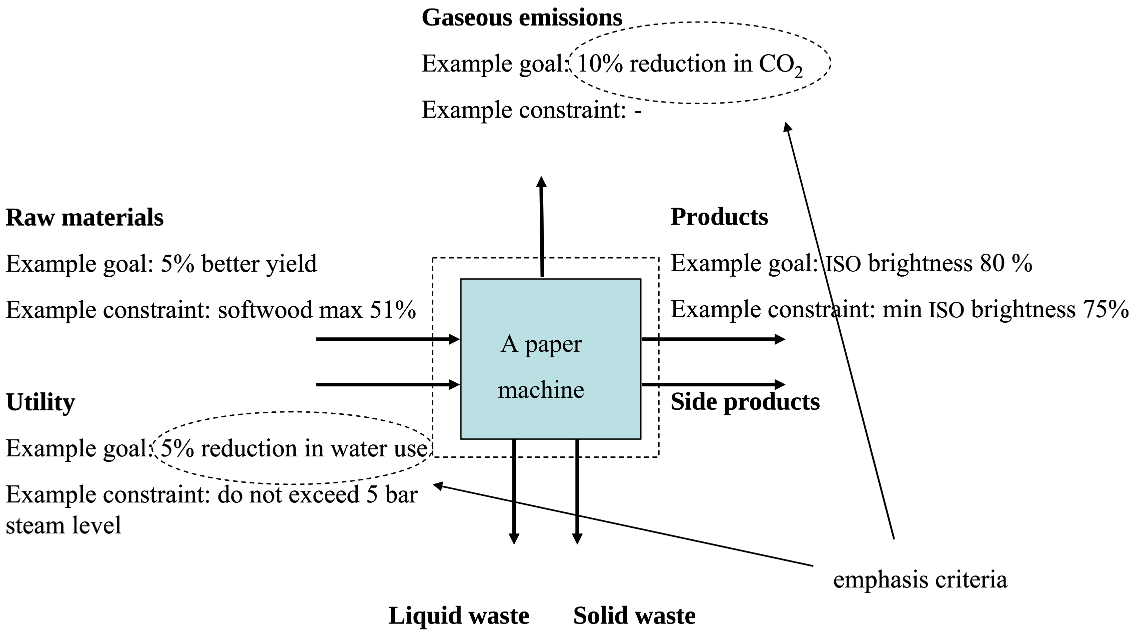


Figure 24. A simplified module and its strategic emphasis criteria together with example goals and constraints. The goals, constraints and emphasis criteria are only illustrative.

Problem analysis

The efficiency of a process with regard to its materials and energy use is usually emphasized during the first stages of design. The simulation and optimization of operations is difficult before the design details have been decided. Efficient operation of systems is more emphasized as the process is built and connections to the surroundings are determined. A difficulty is to combine quantitative and qualitative information. Typical qualitative information is process operability.

The concept discusses the total system efficiency, which can be divided into energy efficiency, material efficiency and operational efficiency. All three dimensions are taken into account simultaneously. The final criteria and indicators for the task are chosen so that all the three dimensions and their contributing factors (Figure 20) become covered. The approach allows the description of systems in numeric terms and facilitates numeric treatment of the problem.

The selected balance boundary influences which type of criteria are used. The efficiency is analyzed within a selected system boundary. The approach is similar for all system boundaries.

Example 2

Figure 25 clarifies the systematic balancing of the criteria. Only examples of criteria and indicators are given. In an ideal case, information is obtained about how far the situation is from ideal, i.e. what is the potential for improvement.

Operational efficiency is traditionally described through the criteria of *flexibility*, *controllability*, and *availability*. Different indicators are used to describe these criteria, but their industrial (process industry) use is problematic. Example indicators include such as Mean Time Between Failure for availability (Chapter 6). The thesis suggests that the criteria for operational efficiency are encountered through considerations about operation time, and production quality and quantity. After that, the indicators can be tailored to meet this objective. The flexibility, controllability and availability criteria are affected by case-specific factors such as machine construction and component features.

The criteria and indicators can be named and tailored in different ways. This makes it sometimes difficult to draw the line between the criteria and indicators. In principle, the criteria describe the general objectives of measuring. The indicator describes the same objective in a more case-specific way. An ideal indicator includes information on the potential for improvement, e.g. the Energy Efficiency Index (Case 2: Energy management). All three efficiencies contribute to costs and profits.

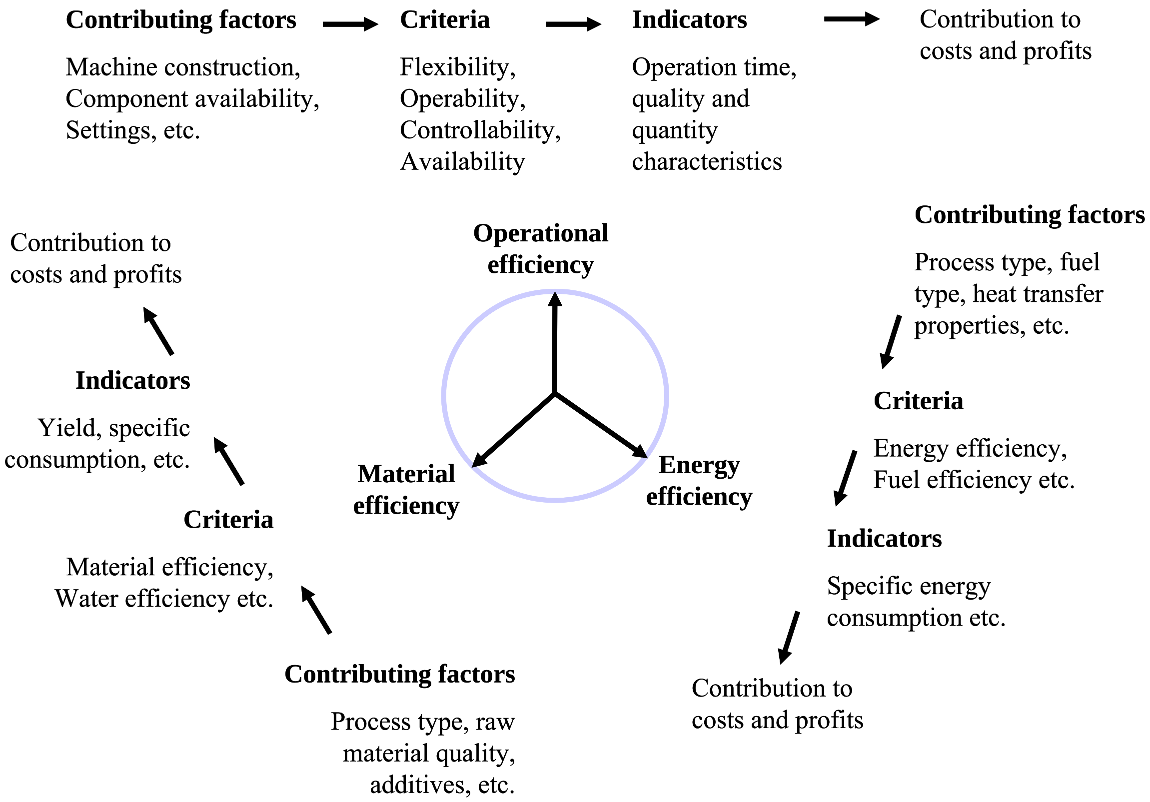


Figure 25. A balanced selection of criteria.

The potential for improvement is analyzed within the chosen system boundary. The potential for improvement should be analyzed against the key operational performance targets.

The analysis of the improvement potential is different in different design/ process life span phases (Table 11, Chapter 10). In addition, the analysis is different in various plant scales (Example 3). To analyze systems, one needs an analytic integration tool to quantify the potential for improvement.

Example 3

The procedure for obtaining reference values (best performance values) for energy efficiency improvement is dependent on the problem scale:

- The reference values can usually be calculated on the *equipment leve*l. References are also available in the literature.
- The reference values are industry-specific on the *unit-process (process) level*. References are also available in the literature. Benchmarking organizations try to track these references.
- On the *process and site levels* (system scales), one needs an analytic integration tool to quantify the potential. The references are often process/mill-specific. Benchmarking organizations try to track these references, too.

Figure 26 presents an example of the theoretic improvement potential with respect to CO_2 emission reduction. The potential is calculated as a function of the final bark moisture (data from Case 5 Bio-fuel drying in a power plant, Appendix 1). The maximum CO_2 reduction was achieved with completely dry bark.

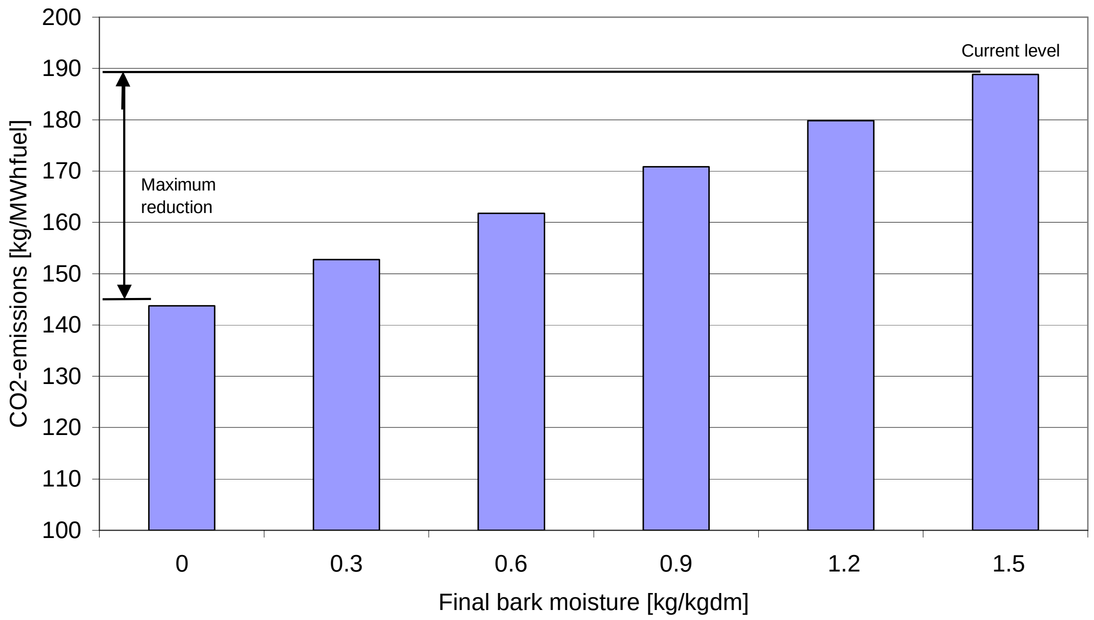


Figure 26. Theoretic potential for CO_2 emission reduction as a function of final bark moisture in Case 5 'Bio-fuel drying in a power plant' (Appendix 1).

Problem analysis

The concept supports existing design, evaluation and investment practices (review in Chapters 5…7). For example, investments are commonly evaluated using tools such as the Net Present Value (NPV), like was also done in Case 5 'Bio-fuel drying in a power plant'. In that study, aspects such as net income cash flows, total number of years over which cash flows occur, annual operating hours of the dryer and investment cost were taken into account. It is also a current practice to decide whether to optimize current operation or to consider future requirements as well. Life Cycle Costing (LCC) is one means of capturing this aspect.

Considering the elements of the concept prevents sub-optimal design and decision-making. The problem analysis becomes more comprehensive. The concept establishes a link to operational business management (see Example 4). Conventional links to business control exist, for example, as the profitability of the project is evaluated through the IRR (Internal Rate of Return).

According to research, process integration means creating efficient systems. One should therefore analyze the *system* behavior. Duration curves are used in industry to monitor production efficiency (Figure 27). The principle of its use could be applied to analyze the total system efficiency, too. This is discussed more in the Example 4.

Example 4: Process durability curves and integration efficiency

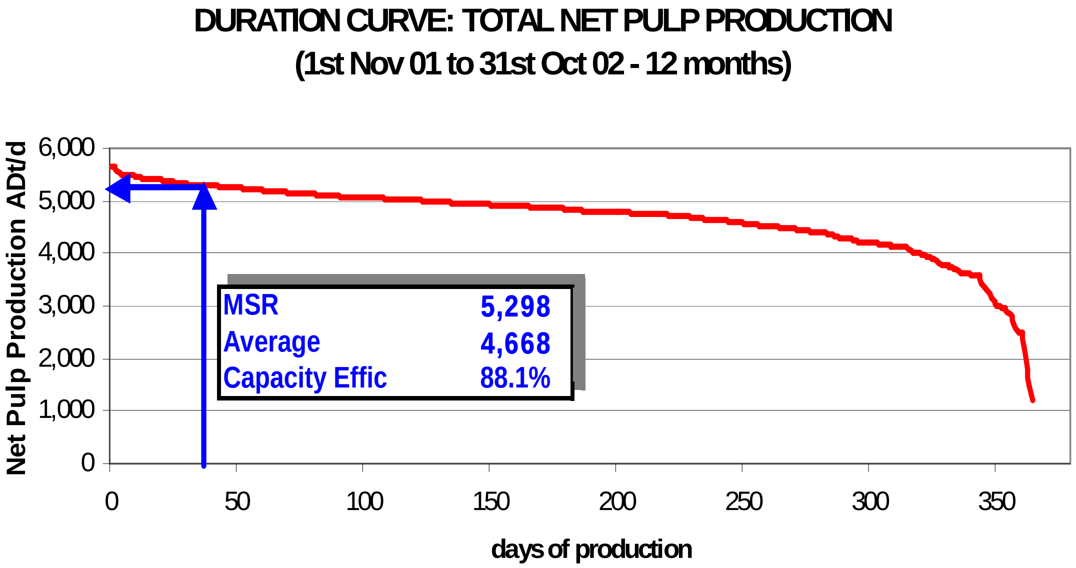


Figure 27. A pulp mill duration curve (Pöyry Oyj, 2007).

Figure 27 depicts the durability curve of a pulp mill, where the Net Pulp Production is monitored against days of production. The data behind the curve is used to calculate a Capacity Efficiency. The Capacity Efficiency is the ratio between a maximum sustainable rate of production (MSR) and an average production (Average). MSR can be calculated in different ways. It can be an average of the best 10% of days in a year. Alternatively, it is calculated from monthly data: the best three-day period is chosen from each month and an average is taken from all the three-day periods of the year. The latter practice tends to give lower MSR values. Using that as a basis of calculation, a good Capacity Efficiency for paper mills is 90% and for pulp mills somewhat less.

In an optimum theoretical situation, the Capacity Efficiency can reach 100%. This would mean that the unit produces the required quality during all days of production (assuming that the system operates close to its design values). From the concept point-of-view, the operational efficiency would then be regarded as maximum. To ensure undisturbed operation, the rest of the production, such as other unit processes, utilities and storage, would need to be dimensioned to support this operation. This would eventually return the discussion to costs and profits, and to questions about making compromises in design and in operation. Also the performance in respect of the energy and material efficiencies would probably fail. This is because an optimal indicator e.g. for energy efficiency contains information about how far the situation is from ideal, i.e. what is the potential for improvement (see Example 2). Over-dimensioning and careless operation would be seen in these indicators.

Based on the above speculation, the duration curve seems a way to monitor the operation of an integrated mill taken that similar charts are provided on energy efficiency and material efficiency, too. Also, the measurement of operational efficiency should be complemented by the aspects of quality and time efficiency. Here it should be noted that different industry practices exist to calculate the production time, see Chapter 6. The planned shutdowns were taken into account in the example mill above.

Problems in production result in a decrease in the production rate, and thus in a lower Capacity Efficiency rate. In these circumstances, all the three dimensions of efficiency are present. In other words, problems in operational efficiency may be caused by a malfunctioning of an energy system or by problems in material systems. Similarly, the layers of hierarchy are part of the analysis: the poor performance of one unit may be caused by the malfunctioning of another unit (equipment, unit process, process).

11.3 Case-specific example of an industrial application

This application example highlights how the elements of the concept are used to formulate a process evaluation study.

11.3.1 Introduction to the study

Borealis Polymers Oy is an integrated production plant manufacturing and selling petrochemical products such as olefins (ethylene, propylene and butadiene), aromatics (benzene, cumene and phenol) and polyolefins (PP, LDPE and PE2). The ethylene production capacity of the plant is 330 000 tonnes p.a. and the propylene production capacity is 230 000 tonnes p.a. The plant is integrated in many ways: the manufacturing units of the plant are material and energy integrated with each other. The plant is also material and energy integrated with the neighboring oil refinery and a CHP (Combined Heat and Power) power plant. The plant is capable of manufacturing the products from different raw materials.

A company policy is to make continuous improvements in the plant energy efficiency. A current issue was to ameliorate the way of measuring the energy efficiency. The existing method was based on the figure ‘specific energy consumption’, which is the energy consumption divided by tons of production. The current method of energy efficiency measurement and monitoring was filling the requirement of the European Bref guidelines, and the external benchmarking needs for olefins (Solomon Energy Efficiency Index) and energy efficiency follow-up for polyolefins (Phillip Townsend Associates, Inc).

The concept presented in this thesis was applied to analyze the problem. The following sections clarify how the problem was approached.

11.3.2 Objective of the study

Energy consumption of the plant is affected by factors such as raw material type and quality, outdoor temperature and operational aspects. Accurate efficiency monitoring would require knowing these factors well. In addition, the energy efficiency of the plant is only one dimension of process efficiency and should be evaluated from multiple perspectives, as discussed in the thesis. The research aim can be divided in the following sub-objectives:

1) Finding the factors affecting energy consumption.
2) Finding the potential for improvement with regard to energy consumption.
3) Verifying and possibly suggesting new indicators, which monitor and control the use of energy most efficiently in multicriteria circumstances.

The factors affecting energy efficiency were known on a general level. The objective was to define the factors more specifically.

The potential for improvement can be studied in different ways, as discussed in the thesis. This study was, however, focused on finding the potentials based on the analysis of sub-objective 1. The aim was to quantify the correlations.

The idea behind sub-objective 3 was to study which operational performance controls monitor the energy efficiency most efficiently. Therefore, the overall performance controlling system of the company was verified. The monitoring and control aims were better follow-up of energy costs, allocating energy and CO_2 to products, and monitoring the energy consumption trends on the site.

11.3.3 Methodological considerations

Firstly, the alternative balance boundaries were defined. As the aim is to find the factors affecting energy consumption, one must consider the use of an analytical tool. Use of these requires treating specific process data. On the other hand, the plant is integrated together with two neighboring plants, i.e. the refinery and the CHP plant (Figure 28). Detailed data treatment on this level becomes difficult. To carry out the study, the problem was organized on three hierarchical levels:

- The Process level constituting the olefin production, the aromatics production and the polyolefins production.
- Borealis Plant level constituting the processes and the site infrastructure such as storage, offices and utility production facilities such as cooling water stations, compressed air production and electricity transformers.
- The Site level constituting the Borealis plant, the refinery and the CHP plant.

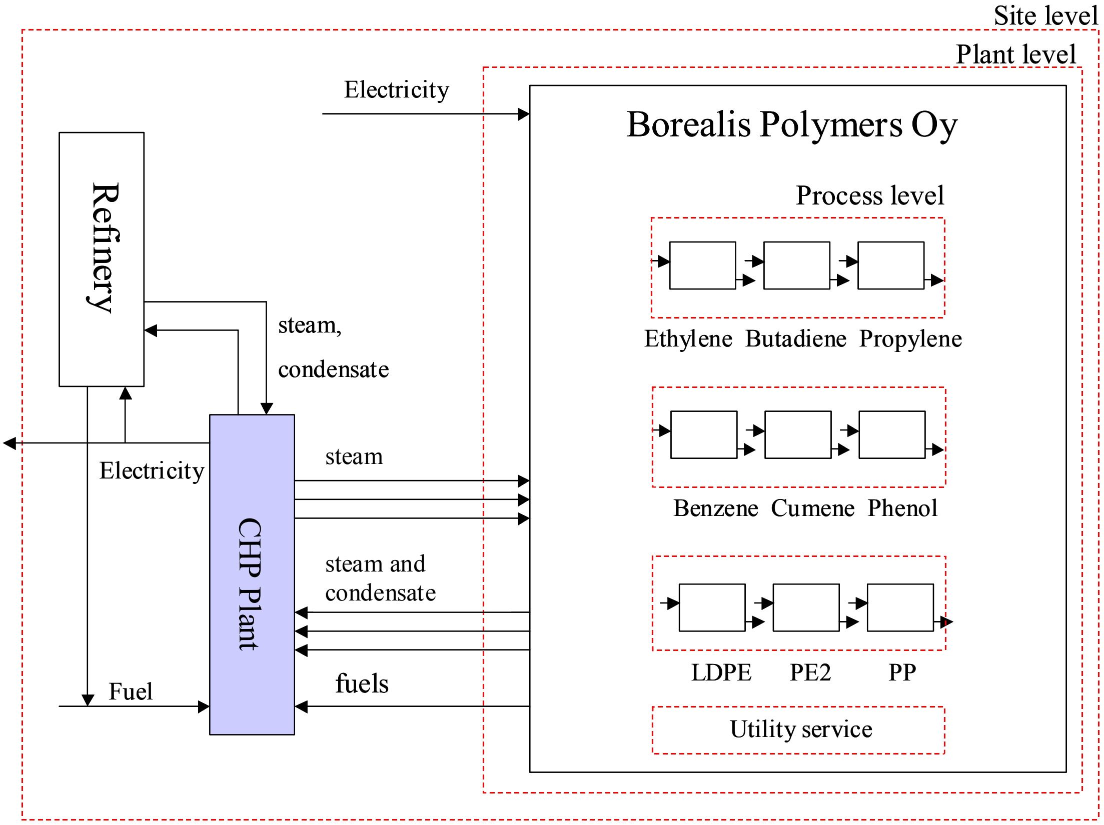


Figure 28. The balance boundaries in the example study.

Sub-objective 1

To find the factors affecting energy consumption, the theory about total efficiency and its categorization into energy efficiency, material efficiency and operating efficiency was applied. This approach ensured that all the important criteria and indices were taken into account.

The three process levels studied were carried out one after another, i.e. the olefins, the aromatics and the polyolefins. The correlations between energy-contributing factors were studied using a multivariate data analysis tool. The study focused on correlations between criteria characterizing: 1) energy, 2) raw materials, 3) production volumes and product qualities (if relevant), 4) important side recycle flows (secondary energies, side-products), 5) capacity utilization rate(s) and 5) failure rates. All the important flows crossing the balance boundary were taken into account. Also, other possible contributory factors such as outdoor temperature were considered.

The data was collected from the mill data management systems over the past 6 years. The data was collected into a spreadsheet, where it was developed further. The data specification and the data collection were made together with plant personnel.

Sub-objective 2

An important part of efficiency monitoring, control and development is to know where the potential for improvement lies. That is different in different plant life span phases.

In the operational phase, there are only limited possibilities to improve efficiency. The potential for improvement is obtained (mainly) by optimizing operating parameters (a multicriteria circumstance). This is where the multivariate data analysis comes in. The purpose was to take the results into the plant optimization system to ensure that energy efficiency becomes one of the optimization parameters.

The Borealis Polymer Porvoo plant is a plant in the operational phase but with possibilities for retrofit improvements. The ways to define the potential for improvement are therefore a combination of the one for the operational phase and the one for the retrofit phase. One improvement potential is gained by studying reference technologies such as the BAT (a multicriteria circumstance). The calculation of potentials is sometimes standardized within measurement systems, as in the Solomon Index. The company had carried out a Pinch Analysis (potential for a single criterion). The different potentials were analyzed in order to compare them against each other.

Sub-objective 3

The aim of this sub-objective was to study which operational performance controls are needed to indicate the energy efficiency. An aim was to establish these indicators as part of the overall controlling system of Borealis Polymers Oy.

The aim was to indicate the differences in the various balance boundaries. These were shown in Figure 28 (dotted lines).

- The Process level indicators indicate the consumption that is strictly related to the manufacturing of the products. On the basis of multivariate analysis, the energy consumption (and thereby the CO_2 load) can be allocated to each of the products.
- The Plant level indicators indicate the efficiency of the whole plant, including storage, site logistics and buildings.
- The Site level indicators indicate the efficiency of the whole site.

The site level indicator was beyond the scope. On the Plant level it is possible to take into account the efficiency of the energy production technology. The CHP production is the most feasible way to produce power and heat, which no doubt will be a considerable factor in the future. The production technology becomes more important as electricity and steam are converted into primary fuel using multiplication factors (production efficiency).

12 CONCLUSIONS

Scientific contribution

Several analytical process integration tools and methods are used in research and in industry. Many of them are used to increase partial system (e.g. utility system) efficiency. An approach for treating entire systems has been missing.

According to the research, process integration is about creating efficient systems. The new definition (Chapter 9) combines different approaches to integration 1) a traditional view having a focus in the process integration methods and tools, 2) a more general view searching for synergic effects, such as better material availability, by combining production units into bigger constituents. The new interpretation for process integration facilitates the use of process integration methods in industry and points out the benefits of their use. The former definitions for process integration have not captured this feature.

The thesis presents how efficiency is created and evaluated during a process life span by presenting a new conceptual approach to process integration efficiency. The conceptual approach to integration efficiency emphasizes 1) elements supporting a numeric process integration problem analysis and 2) elements creating conditions for a numeric process integration problem analysis.

The first is the concept of *total efficiency*, which encompasses material, energy and operational efficiencies. These can be further divided into more specific criteria and indicators. The approach replaces more random practices. The second new element is the concept of *process potentials*, which clarifies the potential for improvement in integrated designs. Then, the approach provides transparency with regard to factors affecting efficiency. It highlights the role of design / evaluation boundary selection, and establishes a link to the company’s business management. Based on this, the process integration efficiency is about balancing the three efficiencies (material, energy and operational efficiency) of the system with considerations to design / evaluation scale, operational performance targets, life cycle aspects and the potential for improvement.

The developed approach is qualitative and it is applied on case-by-case basis. The approach does not contain a numeric analysis. It tends to apply the traditional engineering tools and methods, and to complement existing practices. The approach is used to formulate a basis for a numeric analysis and to choose correct analytical tools.

The conception of entirety is needed in the design and development of processes (green-field process design and development, enhancement of existing processes) and in the management of operating mills. Evaluating material and energy efficiencies of the process is conventional engineering practice. The approach widens the perspective of these studies. The analysis approach creates a framework within which the designer/ evaluator is balancing the trade-offs. In this way the optional technical alternatives become more clearly quantified. In the search for more efficient processes, the approach can be seen as a creative adaptation of the traditional methods.

The conceptual approach seeks to increase awareness about the facts affecting the efficiency of designs in a whole organization. This concerns process research and development, project engineers, project managers, middle managers and plant managers. The approach establishes a connection between the technical efficiency and the operational performance management of the plant. This is to align various objectives and to help those concerned to agree on the priorities.

Further research

The principles of the proposed concept can be applied in a variety of engineering tasks. The contents of the tasks are always case-specific, being a product of the branch of industry, life cycle phase, scale of the study, availability of design / evaluation methods and operational priorities. The concept was partly validated through several case studies (Chapter 11, Appendix 1). No single case example can be carried out to validate the whole concept. The next step in development is to apply the concept in a variety of industrial problems. The data is needed to evaluate the relevance of the proposed elements.

More research is needed on:

- the connection between process integration efficiency and business management metrics and management accounting processes. Also, the applicability of the business analyses information should be studied further.
- process integration tools and methods. Categorization according to principles presented in the thesis have to be taken further. This will allow industry practitioners to better understand the benefits of their use and to promote their use in industry.

Industrial case studies are needed to:

- provide practical examples of all three efficiencies and see whether they can be conflicting.
- validate the theory for batch processes.
- provide more evidence on how the valuation of a design / evaluation case can be different in various balance boundaries.
- demonstrate possible conflicts between physical / chemical efficiency and efficiency from the business management point of view.

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APPENDIX 1

Industrial Case Studies

CONTENTS OF APPENDIX 1

1 INTRODUCTION

The appendix consists of six case problems in the following three categories:

1) Studies reviewing theories on selected central topics:

- Case 1: Integration at the conceptual design phase (Section 2.1); studying the opportunities for integration at early process design phases especially in a chemical plant design.
- Case 2: Energy management (Section 2.2); reviewing concepts and methodological issues related to energy efficiency measurement in the pulp and paper industry.

2) Studies dealing with industrial problems:

- Case 3: Paper mill water management (Section 2.3); analyzing and further developing a new water integration management tool, a K-value theory.
- Case 4: Steel mill process retrofit (Section 2.4); analyzing mill-wide effects of a process change.
  The studies were carried out in co-operation with a collaborating company. This determined the main scope and scale of the problems.

3) Studies simulating the preliminary versions of the new concept:

- Case 5: Bio-fuel drying in a power plant (Section 2.5); evaluating a new concept to dry moist bio-fuel in a power plant. A conventional approach is supported by applying the draft elements of the proposed concept.
- Case 6: Business management material in design (Section 2.6); discussing the availability and applicability of a company's business management material.

The details of the six studies were formulated to cover the main research questions (see Chapter 3 of the thesis). The contents of the cases with regard to the main target areas of research are summarized in Table A1.

Table A1: The objectives of the case studies versus the main target areas of research.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
	Integration at the conceptual design phase	**Energy management**	**Paper mill water management**	**Steel mill process retrofit**	**Bio-fuel drying in a power plant**	**Business management material in design**
Appendix paragraph:	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**
General characteristics						
Industry	Chemical	Paper	Paper	Steel	Energy	Steel
Life cycle	Process development	Operation	Operation	Retrofit	Process development + Operation	Retrofit
Problem scale	Process (Plant) 1)	Process (Plant) 1)	Process (Plant) 1)	Plant (Unit process) 2)	Unit process (Plant) 1)	Plant (Unit process) 2)
Enhanced target-setting						
Business mgm. aspect applied	-	-	-		(x)	x
Design and evaluation criteria						
Multi-criteria decision-making	x	-	x	x	x	-
Hierarchy of criteria	x	x	x	x	(x)	-
Criteria interdependencies	x	-	x	x	(x)	-
Process operability	(x)	-	-	x	(x)	-
Process availability	(x)	-	x	x	(x)	-
Process integration methods						
Method discussed / applied	x	-	x	x	x 3)	-
Potential for improvement						
Idea discussed / applied	x	x	x	x	x	-

1) Primarily a (unit) process study, secondarily a plant scale study.

2) Primarily a plant scale study, secondarily a unit process study.

3) Falls only loosely under the category ‘process integration methods’.

2 CASE STUDIES

2.1 Case 1: Integration at the conceptual design phase

2.1.1 Objectives summary table

(see complete Table A1)

General characteristics:	
Industry	Chemical
Life cycle	Process development
Problem scale	Process (Plant) $^{1)}$
Enhanced target-setting	
Business mgm. aspect applied	-
Design and evaluation criteria	
Multi-criteria decision-making	X
Hierarchy of criteria	X
Criteria interdependencies	X
Process operability	(X)
Process availability	(X)
Process integration methods	
Method discussed / applied	X
Potential for improvement	
Idea discussed / applied	X

1) Primarily a process study, secondarily a plant scale study

2.1.2 Research objective

The objective of the study was to analyze the applicability of process integration principles in the early stages of process design, i.e. in the research, development and conceptual design phases. The definition of process integration follows the one in Chapter 4 of the thesis (more extended from the traditional heat integration). Another objective of the study was to evaluate the potential of process improvement throughout the process life span. The study deals with the process scale, but with references to plant-scale considerations. The case example was a melamine production process from the chemical industry.

Process design deals with multiple design criteria. Some of the criteria are independent and some of them are dependent on each other. The criteria also have hierarchies. The available information is in qualitative and quantitative form. These aspects make the decision-making complicated.

2.1.3 The case study and results

This section refers to Cziner et al. (2005).

The study considered the changing trends in industry, i.e. the growing demand for specialty and fine chemicals and products, and the increasing requirements of energy efficiency, health, safety and environmental aspects. Emphasizing these criteria has to be taken into account already at the process development stage. The decision-making is complex as multiple performance criteria are taken into account at the same time.

The authors found that in modern process design: 1) the aim is to consider all aspects from conception to disposal as early as possible to avoid costly changes later in design or during production, 2) several criteria, which are increasingly conflicting, are considered simultaneously, 3) information and knowledge for decision-making must be of three kinds in order to cover all the important aspects: empirical, experience-based and theoretical, 4) design, calculation and modeling in traditional process integration has required only system-level models; the new trend is towards multi-scale modeling, meaning more detailed modeling on specific aspects such as product properties and processing conditions. In multi-scale modeling, molecular levels are modeled in detail and in system level modeling the scope encompasses life cycle assessment and optimization of the supply chain.

The authors analyzed the attempts made to develop computer-aided tools for synthesis and conceptual design (or process R&D). They found that the practical applicability of the methods is limited to problems with a narrow scope, such as heat exchanger network synthesis or distillation sequence synthesis. The heuristic and hierarchical methods apply to traditional fields of chemical technology, such as petrochemical processes and bulk production. To summarize:

- The hierarchical method (conventional) tries to identify and decompose chemical processes on the basis of unit operations, where each unit copes with a specific task such as heat transfer, specific separation process, etc.
- The heuristic methods rely on the users' engineering experience. Attempts have been made to systematize the use of heuristics but without any great success, despite known concepts.
- Optimization-based methods are developed to replace manual iterative design by mathematical optimization. Optimization is based on an objective function and for a given design space called the superstructure. The weaknesses of the method are that: a) many important practical aspects, such as safety, operability and reliability, are hard to express in an objective function, b) all aspects cannot be included in one objective function, c) the definition of superstructure may leave out important design alternatives, d) since the optimization approaches are not interactive, the optimization cannot be adjusted or guided easily by the user and the result can be an impractical or even impossible solution. The mixed integer nonlinear programming (MINLP), genetic algorithm (GA) and case-based reasoning (CBR) represent varying approaches to optimization-based design. The applications of optimization-based methods have been limited to small and well-defined problems.

The field of process integration started from heat integration and was later extended to e.g. mass integration. Integration of mass and energy flows is the fundamental and traditional task of process integration in process design. The authors emphasized that heat integration is not the primary task, but comes later after the process concept and material balances have been generated.

The authors summarized that process integration is an attractive goal in the conceptual design but difficult to achieve using current methods. Especially a process synthesis method that also fulfills practical requirements such as safety and operability is still missing. Such a method should deal with various types of processes and products from batch to continuous processes. The authors indicated that specific features and more exact tools are becoming more important due to projects being more product-specific. To respond to the modern requirements, the authors developed two process development methods: *the evaluative process development method* aiming to implement the full creativity potential in design, and *the decision-based method* trying to manage the decisions in the project in a systematic way. The decision-based method includes:

- The collection of decision points in the project life cycle and their indication on the decision map.
- The study of the decision-making situations in detail by identifying a) the purpose and timing of the decisions, b) the content of the main decisions versus questions: what, why, who, what criteria are used, what information is needed, what documents are needed and what methods are used.

In general, the authors found that that the following kind of potentials exist for improving a process:

- *operational potential,* i.e. possibilities to optimize process operation
- *design potential,* i.e. possibilities to optimize process parameters (operating conditions, dimensioning, mass and energy balances); based on process analysis.
- *creativity potential,* i.e. possibilities to optimize process concept (stream connectivity, recycles, unit operation types); based on process synthesis.

2.1.4 Conclusions

The findings supporting the thesis can be summarized as follows:

At the process synthesis stage, potential for improvement is seldom calculated for a single criterion. Instead, an increase in performance in respect of several simultaneous criteria is a target. Process improvements are made through *process synthesis* by optimizing the process concept (stream connections, recycles, unit operation types, etc), through *process analysis* by optimizing process parameters (operating conditions, dimensioning, mass and energy balances etc), and through *optimizing process operation* in the operation phases. The life span phase determines which type of improvement may come into question. At the process synthesis stage, the potential for improvement is the greatest but with respect to *all design criteria*. To summarize, the potential for improvement is achieved:

- in the process synthesis stage by arranging stream connections, recycles, unit operation types, etc., as the process concept is optimized through process synthesis
- in the process analysis stage by arranging operating conditions, dimensioning, mass and energy balances, etc., as the process parameters are optimized through process analysis
- in the process operation stage by optimizing process operation.

The study states that mass and energy integration, i.e. the traditional process integration, occurs after the first process concept and material balances have been generated. Process design deals with multiple performance criteria throughout the design life cycle. The demand for efficient mass and energy utilization is only one subset of all the design requirements, and is seldom emphasized over the others at the start of design life cycle.

The trend is towards multi-scale modelling. The case formulation on each scale is different. The detailed phenomenal models utilize a different kind of information compared with the models on the system level (e.g. in Case 4). Also the design criteria and constraints become different on various levels of modelling.

2.2 Case 2: Energy management

2.2.1 Objectives summary table

(see complete Table A1)

General characteristics	
Industry	Paper
Life cycle	Operation
Problem scale	Process (Plant) [1)]
Enhanced target-setting	
Business mgm. aspect applied	-
Design and evaluation criteria	
Multi-criteria decision-making	-
Hierarchy of criteria	x
Criteria interdependencies	-
Process operability	-
Process availability	-
Process integration methods	
Method discussed / applied	-
Potential for improvement	
Idea discussed / applied	x

[1)] Primarily a process study, secondarily a plant scale study

2.2.2 Research objective

A survey was made of the concepts and methodological issues related to energy efficiency measurement in the pulp and paper industry. Energy efficiency in the operational life cycle phase was of primary concern. Hierarchies in energy measurement were also considered.

2.2.3 The case study and results

This section refers to Kilponen (2005). The results indicate the following:

- Energy efficiency indicators fall into four main groups: 1) thermodynamic (e.g. W, J, %), 2) physical-thermodynamic (e.g. J/kg, W/kg), 3) economic-thermodynamic (e.g. EUR/Wh, EUR/J), 4) economic (e.g. EUR/t, EUT/a), and 5) environmental (e.g. CO_2/kg, CO_2/J). Energy efficiency measures are used either as such or together with explanatory information, i.e. as reference to production speed, time, product quality and outdoor temperature. The same aspects can be expressed with a different indicator (primary energy use versus CO_2 emission).
- A number of problems are associated with the use of energy efficiency indicators: 1) Valuation and value judgment. The thermodynamic energy efficiency indicators contain implicit value judgments, but no method separates e.g. useful and useless (waste) energy. 2) Energy quality problem. The energy quality problem is encountered in complex systems or processes with many sources and uses of energy of different qualities. 3) Boundary problem. This implies the difficulty to define where to set boundaries for calculation and evaluation. 4) Joint production problem. This implies the difficulty to allocate energy input to multiple energy users. 5) Utilization purpose of indicators. This implies the fact that different indicators are designed to serve different purposes and are not always convertible.
- Energy efficiency improvement potential is available on various layers. At the lowest end is the market potential, which is achievable with commercial technology seen as technically and financially feasible. At the highest end is the physical potential setting the reference to the best theoretical performance.
- The activity towards energy efficiency improvement is dependent on: 1) economy-related factors, e.g. profitability and stock market reaction, 2) core business-related factors such as quality and process reliability, 3) customer-

related factors such as image and 4) managerial related factors such as human health and security. Energy information is generated and handled in a hierarchical manner inside the company (Figure A1). Thus, different types of indicators for the different levels of aggregation must be designed. Large information gaps exist compared with the ideal situation (Figure A2).

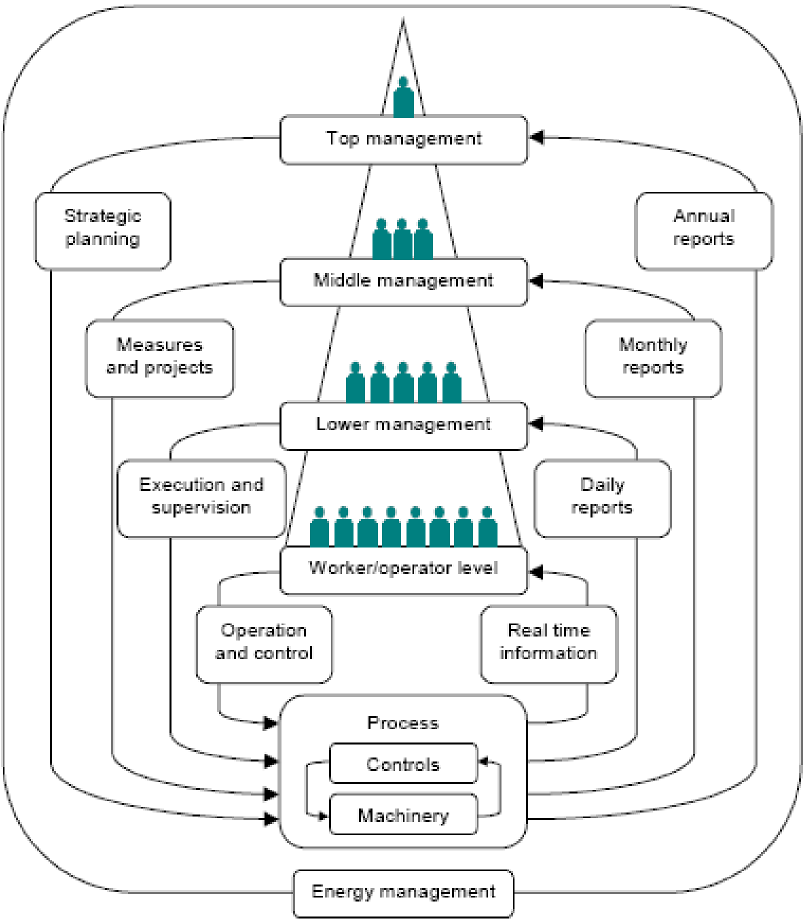


Figure A1. Energy information flows (Kilponen, 2005 (from Caffal, 1995)).

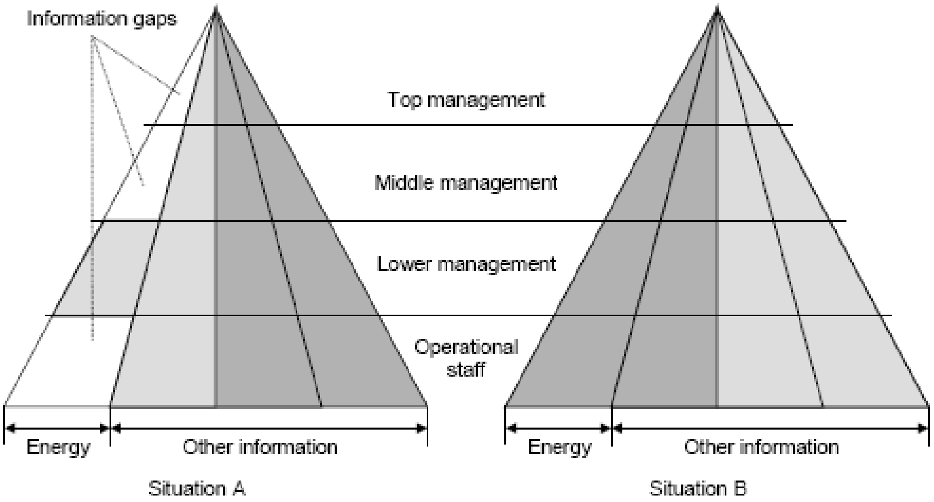


Figure A2. Effective use of information (Kilponen, 2005 (from Caffal, 1995)).

- Example of process energy efficiency indicators include: exergy efficiency, entropy generation, energy efficiency index, comparison of operational objectives, secondary energy efficiency, CO_2 efficiency, energy cost monitoring, Best Available Technology (BAT) value. Exergy analysis is a measure of the loss of quality and energy used in a process and of the degree to which losses can be avoided theoretically. Entropy generation analysis gives a measure of how far a process is from being ideal. The BAT values represent achieved levels in practice. The energy efficiency index compares measured energy consumption and calculated energy consumption. The energy efficiency index (Kuusinen et al., 2001) can be written as:

$$I_k = \frac{E_{k,measured}}{E_{k,calculated}} \tag{A1}$$

where k relates to the selected time period, $E_{k,measured}$ is the measured energy consumption, and $E_{k,calculated}$ is the calculated energy consumption.

- Energy efficiency indicators are almost without exception implicit. But as human and real processes are involved, there will be no single correct answer to state how to measure energy efficiency and what the right indicators are.

The author stated that there are several ways to measure energy efficiency. That depends on the way in which information is used in organizations and among stakeholders. Challenges in measurement are associated with value judgments, setting the boundaries, factors to be included in the analysis, and the selection of indicators.

2.2.4 Conclusions

The findings supporting the thesis can be summarized as follows:

The energy efficiency indicators are developed for different purposes of use. Energy information is generated and handled in a hierarchical manner inside a company and different information aggregation levels exist. Energy efficiency measurement in a process plant is challenging due to the complexity of industrial processes involving e.g. mass and energy re-circulation, multiple sources of energy and multiple process products. Process integration typically increases this complexity. Efficiency calculation requires clearly set boundaries, valuation and value judgments about energy quality, and correct reference values. This case study and the Case 1 confirm that different information is used on different boundaries.

A part of the energy-saving potential is achievable using market technology. A part of potential will be achieved only through technical developments over time. The physical laws set the limits for the highest achievable performance. The degree of realization depends on multiple design aspects such as project economy, layout and environmental aspects.

In general, energy efficiency improvement initiatives are motivated by the quest for better economic performance. It was noted that this must correlate positively with production-related factors such as quality and process reliability or stock market reaction or image.

In addition to integration methods, integrative indicators exist. The energy efficiency index is one example. Energy efficiency is a relationship between the actual energy consumption of a process and the calculated energy use of a process. The difference is achievable through operational optimization.

2.3 Case 3: Paper mill water management

2.3.1 Objectives summary table

(see complete Table A1)

General characteristics	
Industry	Paper
Life cycle	Operation
Problem scale	Process (Plant) [1)]
Enhanced target-setting	
Business mgm. aspect applied	-
Design and evaluation criteria	
Multi-criteria decision-making	X
Hierarchy of criteria	X
Criteria interdependencies	X
Process operability	-
Process availability	X
Process integration methods	
Method discussed / applied	X
Potential for improvement	
Idea discussed / applied	X

[1)] Primarily a process study, secondarily a plant scale study

2.3.2 Research objective

Paper machine runnability is affected by different factors such as paper structure, paper machine construction, running parameters and running history, and furnish properties. These determine the basis for wet and dry web tensile strength and tension relaxation properties and thereby the web break rate of the paper machine. One of the important factors for paper machine runnability is the wet end chemistry. Although it is well known that dissolved and colloidal substances can cause deposition and lead to web breaks in paper machines, finding a correlation between the concentration of detrimental substances and paper machine web breaks is difficult. It is, however, proven that a high level of dissolved and colloidal organic substances causes unstable conditions and deposition, and results in web breaks (Ylönen and Paulapuro, 2005).

The objective of the case was to study the correlation between paper machine runnability and wet end chemistry. The wet end chemistry was studied through a novel water management theory. The theory, called the K-value theory, has been developed for the pulp and paper industry to provide information on how effectively fresh water is used, how effectively different water circuits are separated (e.g. pulp mill and paper machine) and how effectively the counter-current system works (Kappen and Wilderer, 2002). The K-values are originally calculated from water COD (chemical oxygen demand) values. Here, the question of whether the K-value theory applies to water concentration parameters other than COD is also examined.

2.3.3 The case study and results

The K-value theory

The K-value theory indicates the state of the paper machine’s wet end chemistry. The water samples are taken from the pulp manufacturing line, paper machine white water and the effluent (Figure A3). The K-value theory was developed by analyzing the data from a number of pulp and paper mills.

$$K1 = \frac{COD_{Effluent}}{COD_{PM}}$$

$$K2 = \frac{COD_{Pulp}}{COD_{PM}}$$

$$K1/K2 = \frac{COD_{Effluent}}{COD_{Pulp}}$$

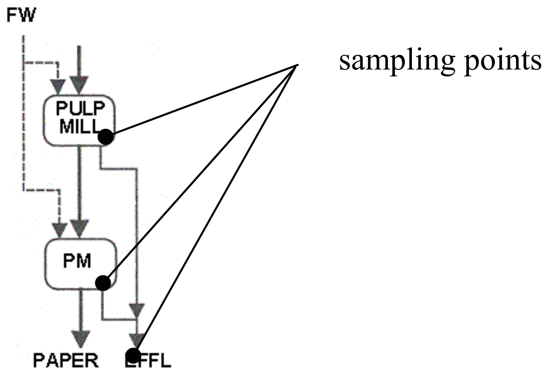


Figure A3. K-values calculation formula and the sampling points for a simple mill.

According to the theory (Figure A3):

- K1 should be >1. It indicates the amount of dilution of the effluent, i.e. fresh water use. If $k_1 < 1$, part of the fresh water goes to the effluent treatment plant unused and the COD level will be lower than in the white water.
- K1 should be >>1. The COD level of the paper machine white water ought to be substantially lower than that of the circuit water in the pulp manufacturing line. That would mean that detrimental organic substances are retained in the pulp manufacturing system.
- K1/K2 should be ≈ 1. K1/K2 indicates how the counter-current principle is realized between the pulp production and paper machine, i.e. how the fresh water is introduced to the PM and effluents are discharged from pulp production. According to the theory, K1/K2 should be studied together with K2.

The study and results

The study and results refer to Ylönen and Paulapuro (2005).

Experiments

The study was based on the analysis of four paper mills. Mill A and Mill B were physically the same paper production lines before and after a process modification. Before the modification the mill was using thermomechanical pulp (TMP) and de-inked pulp (DIP) for newsprint production. After the modification the mill was using only DIP for newsprint production. The mill produced newsprint with two paper machines. The simplified layout of the mill and the sampling points are shown in Figure A4.

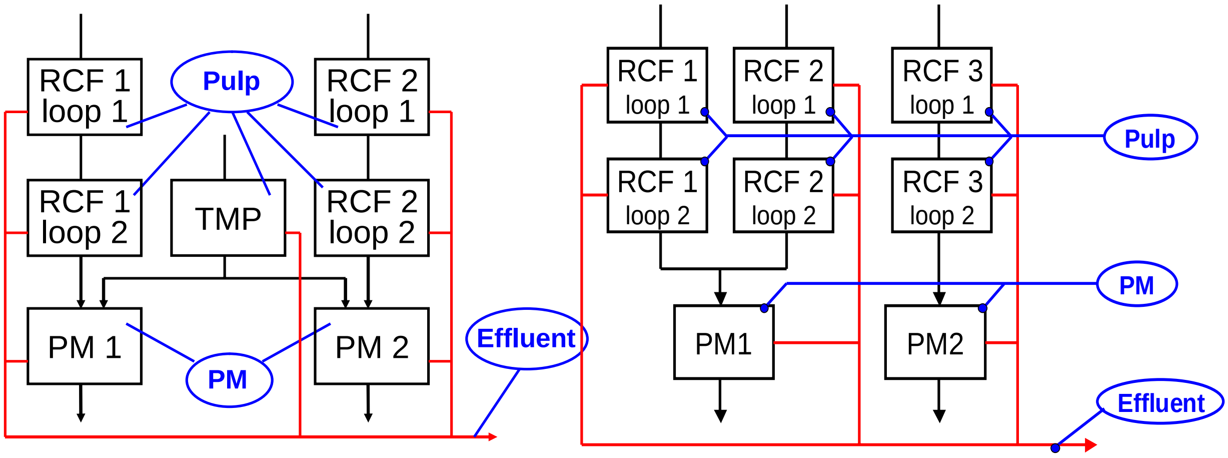


Figure A4. Simplified layout of mill A (left) and mill B.

Mill C was using (two-stage de-inked) DIP as raw material for newsprint. There was a disc filter and a screw press after the first and second circuits of the recycled fiber plant (RCF). The consistency of the pulp after thickening with the screw press was 28 %. Cleaning of the circulation water in the RCF plant was done with two microflotation units. One RCF line was feeding one paper machine in the mill. The simplified layout of the mill and the sampling points are shown in Figure A5.

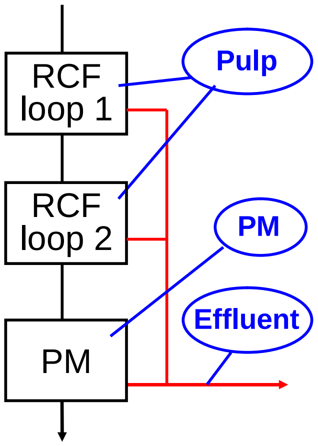


Figure A5.Simplified layout of mill C.

Mill D used bleached kraft pulp and groundwood pulp to produce LWC paper on two paper machines. The simplified layout of the mill and the sampling points are shown in Figure A6.

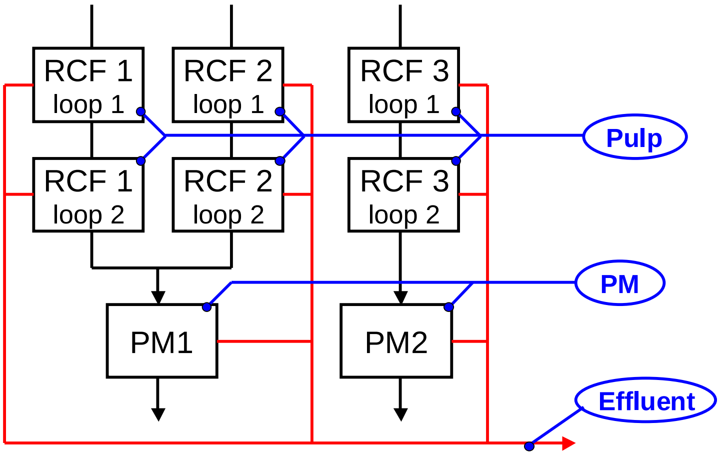


Figure A6. Simplified layout of mill D.

The measurement procedure for the water samples is illustrated in Table A2.

Table A2. The measurement procedure for the water samples.

Measurements to study wet end chemistry	Concentration parameters to calculate K-values
COD (chemical oxygen demand)	X
TOC (total organic carbon)	X
DOC (dissolved organic carbon)	X
Evaporation and ignition residues, ignition loss	X
Lipophilic extractives and lignans	X
Microstickies	X
Calcium ion concentration	X
Conductivity	
Turbidity	
Cationic demand	
Potential secondary stickies	

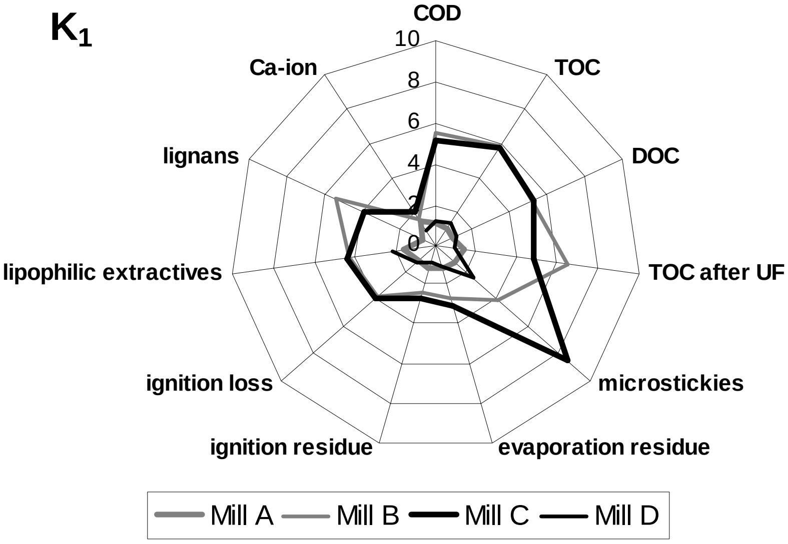
Results from experiments

Clear differences between the mills with respect to their K-values were found. The magnitude of the differences depended on the concentration parameter used (Figure A7).

K-values were affected by the carryover of organic and inorganic material to the paper machine, which can be defined by calculating K2 from the ignition loss and ignition residue. In all cases the carryover of inorganic material was higher compared with organic material. The most important finding was that the carryover of harmful substances (both organic and inorganic) was lower in the mills using only recycled fiber compared with mills using mechanical pulp as well.

In most cases, K-values were affected by the particle size of the organic material. The authors stated that this was due to the fact that the dissolved organic substances migrate and accumulate in the paper machine white water easier than the colloidal.

The study indicates that the K-value theory is applicable for obtaining information on how well organized the water cycles are with respect to some specific substances, such as lipophilic extractives and microstickies or micropitch. This can be used when studying how the most harmful substances behave in the paper machine water cycle. The K-values can be calculated for many concentration parameters, such as COD, ignition loss and lignans.



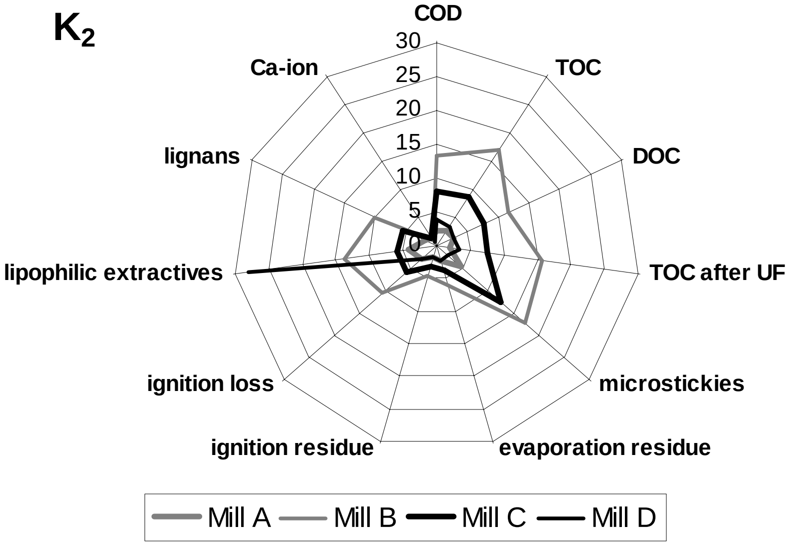


Figure A7. Comparison of K-values between the mills.

Results regarding the runnability

A runnability study was made on a mill using thermomechanical pulp (Mill A). A correlation was found between COD and average web break rates per day (production-weighed values), higher COD values indicating higher break rates. Also a correlation was found between the K2 value and web break rates: a low K2-value (COD_{pulp} $/COD_{pm}$) indicated a higher risk of web breaks (Figure A8).

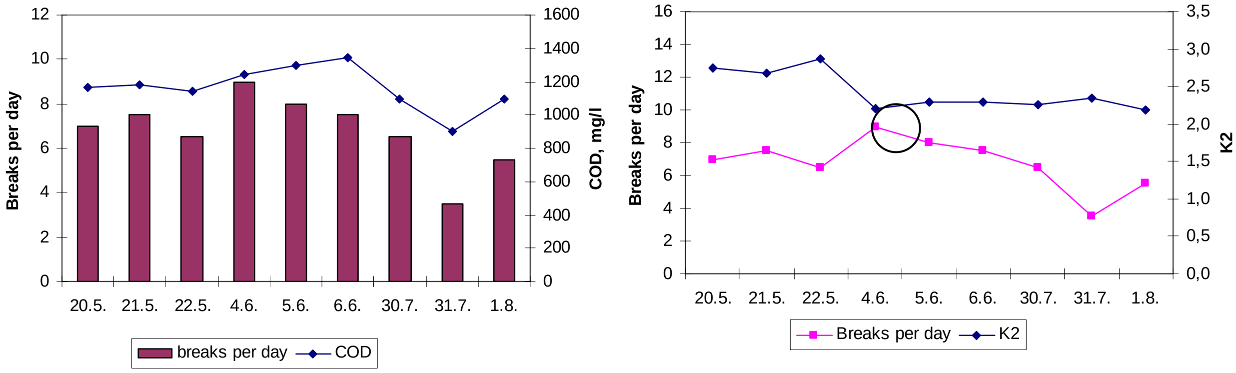


Figure A8. Left: overall COD of both paper machines vs. average web breaks per day. Right: average breaks per day vs. K2 value.

The measurements for various substances taken from specific locations provide important information about the state of the wet end chemistry and water management, and can be used to predict paper machine runnability. An online measurement practice, such as the TOC, for the organic substances is a way to monitor the chemical state of the water circuits.

2.3.4 Conclusions

The findings supporting the thesis can be summarized as follows:

The K-value theory is a practical means to evaluate the efficiency of water integration. It describes integration with respect to one resource. The case study indicates that the K-values can be calculated for many concentration parameters that have a different chemical nature and behave differently (Table A2). The parameters are measured from specific stream locations from pulp manufacturing, paper-machine circuit water and effluent flow. The K-values are measures for the degree of integration of sequential unit processes.

As the amount of dissolved and colloidal organic substances reaches high levels, the process becomes unstable. Changes in process conditions can cause deposition and web breaks to occur (Ylönen et al. 2004). A correlation between the K-values and the number of web breaks on a paper machine was found in the study. In other words, good K-values indicate high process running time. The K-value theory development is based on an analysis of industrial data from operating mills. The study indicates that industry-specific integration measures are important in promoting integration.

Paper machine runnability can be defined as *the ability to run a continuous process without breaks* (Baker, 2006). In the case study, runnability was described through the *number of breaks per day*. The commonly known contributors to paper machine runnability include factors such as paper structure, paper machine construction, running parameters and history, and furnish properties. The study indicated that a correlation exists between runnability and the K2 value as calculated from water COD. The correlations between runnability and other concentration parameters were not studied. It seems that the difficult relationships between runnability can be described through different indicator values. This is schematically depicted in Figure A9. Finding correlations is complicated in industrial processes. A multivariable process analysis is one approach to problem-solving.

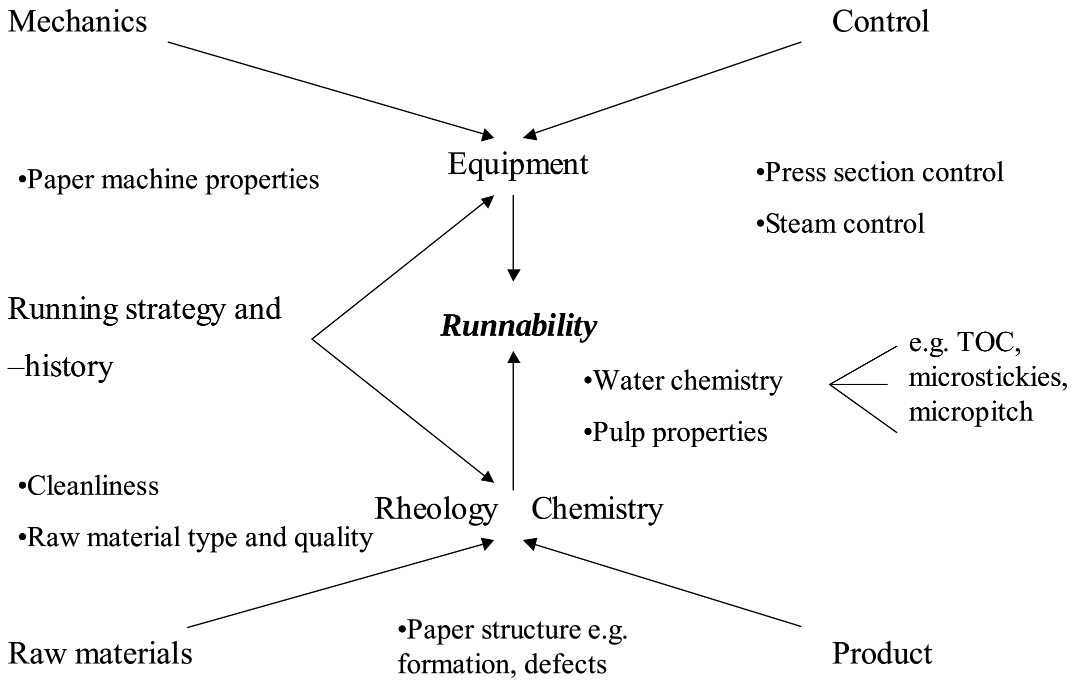


Figure A9. A schematic presentation of important factors affecting paper machine runnability with examples of indicators describing these factors.

2.4 Case 4: Steel mill process retrofit

2.4.1 Objectives summary table

(see complete Table A1)

General characteristics	
Industry	Steel
Life cycle	Retrofit
Problem scale	(Unit process) Plant[2)]
Enhanced target-setting	
Business mgm. aspect applied	
Design and evaluation criteria	
Multi-criteria decision-making	X
Hierarchy of criteria	X
Criteria interdependencies	X
Process operability	X
Process availability	X
Process integration methods	
Method discussed / applied	X
Potential for improvement	
Idea discussed / applied	X

2) Primarily a plant scale study, secondarily a unit process study

2.4.2 Research objective

The study was made at an integrated steel mill producing over 2 million tons of steel per annum. The mill consists of several unit operations including agglomeration of concentrates (sintering), coke-making, iron-making in blast furnaces, steel-making in converters, ladle metallurgical treatments, continuous casting, hot rolling and other eventual finishing processes. In addition to products, the mill produces dusts, scales, reverts etc. These are partially considered as wastes. The cost of waste had been increasing over that past years and was expected to continue increasing in the future. The waste contains iron. The company is looking for optional approaches to convert this iron into a usable form.

The objective of the case study was to analyze the process change from multiple perspectives. These were divided into economic, environmental and technical perspectives. Another objective was to analyze the process change by analyzing the potential(s) for improvement. A new flow-sheeting software, Factory, was used to calculate the data.

2.4.3 The technical context

The conventional steel-making process route generates considerable amounts of by-products, recycled material streams and waste. By-products for sale include slags form the blast furnace process (used in road construction, etc.) as well as tar, benzole and sulphur from the coking plant (used as raw materials in the chemical industry) (Rautaruukki, 2000). Recycled material streams consist mainly of dusts, scales and reverts. The materials that cannot be recycled back to the process or sold are wastes. This is due to their unsuitable chemistry, physical character (extreme fineness) or harmful impurities like sulfur, phosphorus, alkaline metals and zinc (Holappa et al., 2005).

Sintering plants are traditionally used to recycle fine material, i.e. dusts in integrated steel plants. However, returning these materials to the sintering plant has negative effects on the well-running process.

An alternative process route was studied in the case. In that route, all circulating materials are removed from the primary process and treated together with wastes in a separate process to produce hot metal. Expected benefits of such an arrangement are a better sintering plant operation and reduced waste production. Expected further benefits include higher steel production. In the latter case, the company would not need to purchase extra slabs from the market, which are required to fill a current capacity gap between the blast furnace and the rolling mill sections. The market price of the slabs varies and together with difficulties in availability represent an economic risk. This together with the waste problem is seen as an important business management issue.

2.4.4 The availability study and the results

This section refers to Kekkonen et al. (2005).

The process operability was defined as "the ability to perform an operation or series of operations in order to produce products. Process *availability* is defined as "the time that the process is performing its intended operation" (see Chapter 6 of the thesis).

The operability and availability of the sintering process were expected to improve due to more stable burning conditions in the sintering bed. These aspects were studied separately in detail. The subject was studied on a more general level in the subsequent process step, i.e. in the blast furnace.

The analysis was carried out using the plant process history data. The idea was to identify a period when less circulation was used, in order to simulate the targeted new conditions with zero circulation. This data was analyzed against normal operation data. The process personnel participated in the data evaluation.

A low dust feed was found during the period 23.12.2003 – 26.1.2004 (Table A3).
Reference periods were taken from before and after that.

Table A3. Periodical dust feed in the sintering process.

Time	*1.11-22.12.2003*	*23.12.2003-26.1.2004*	*27.1-23.3.2004*	*2002 average*	*2003 average*
	(kg/t sinter)	*(kg/t sinter)*	*(kg/t sinter)*	*(kg/t sinter)*	*(kg/t sinter)*
Amount of dust (relative)	*40*	*10*	*100*	*73*	*59*

a) Sintering plant

The equation (A2) was used at the plant to calculate the availability of the sintering process:

$$\textit{Availability, \% = 100 – (failure, \% + maintenance, \%)} \qquad \text{(A2)}$$

in which “failure, %” is defined as:

$$\text{Failure \%} = \left(\frac{\text{calculated duration of the failure}}{\text{calendar time}}\right) \cdot 100\ \% \qquad \text{(A3)}$$

and “maintenance, %” is defined as:

$$\text{Maintenance \%} = \left(\frac{\text{calculated duration of the planned stops}}{\text{calendar time}}\right) \cdot 100\ \% \qquad \text{(A4)}$$

The *availability* as a function of the dust feed is shown in Figure A10.

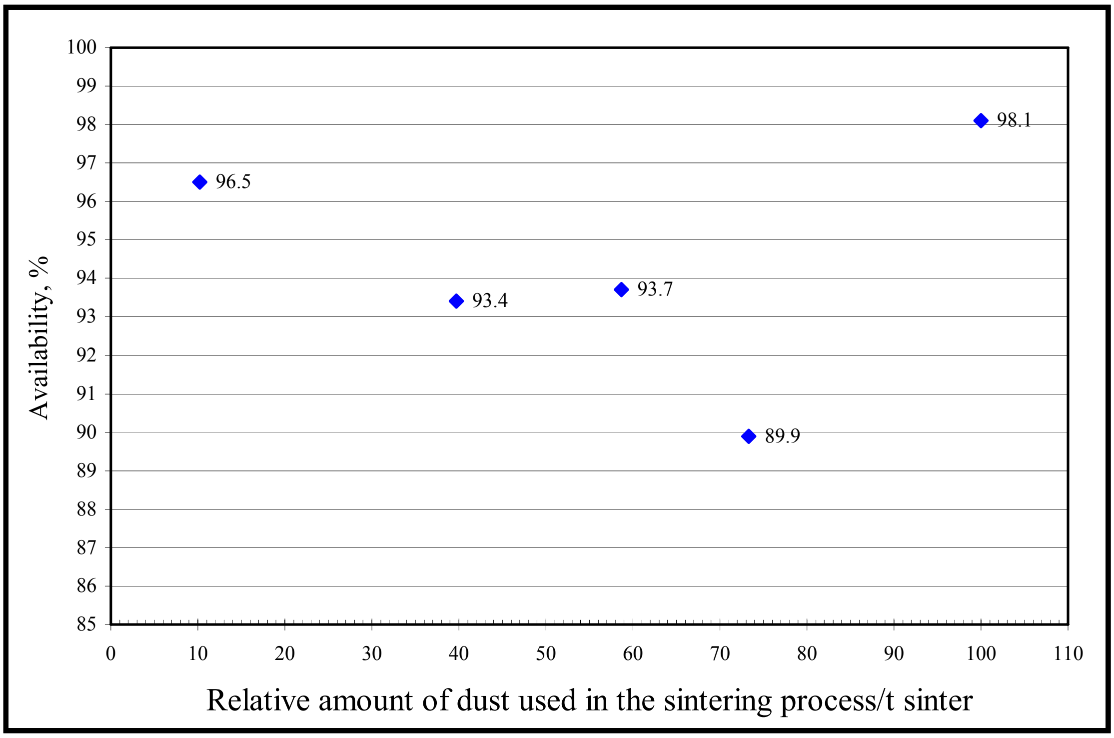


Figure A10. The availability of the sintering plant as a function of the dust feed.

The failure modes of the process were analyzed separately. The failure modes were divided into process failures, mechanical failures, electrical failures and automation failures (Figures A11-A14).

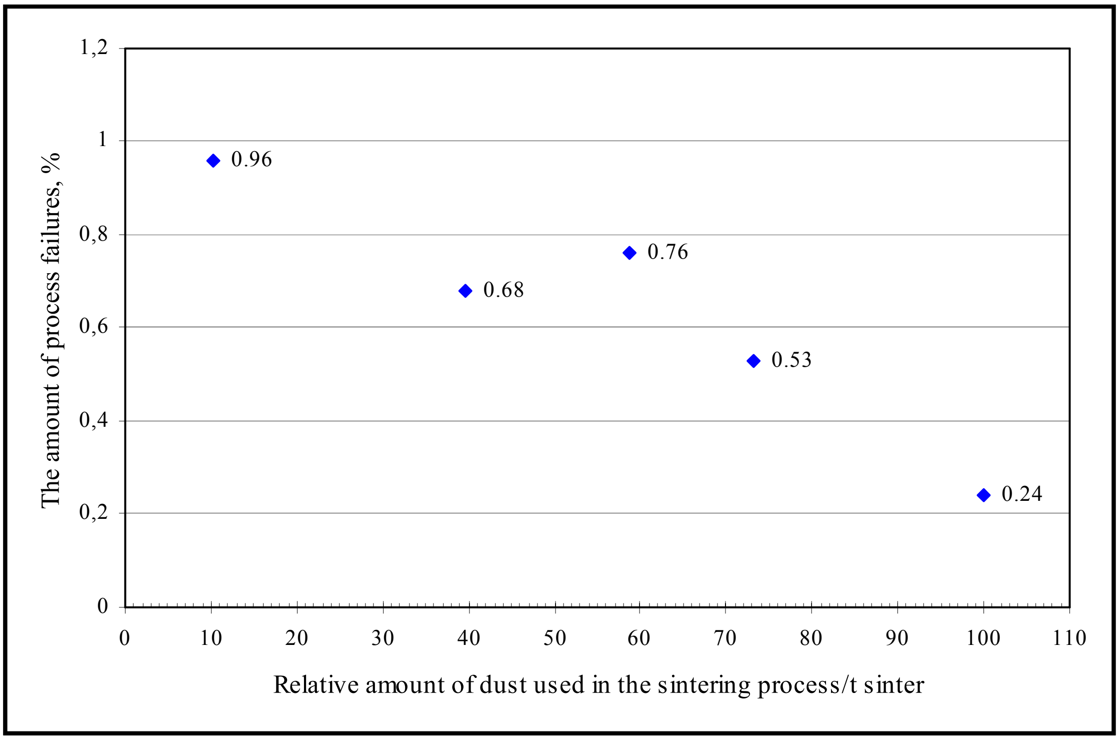


Figure A11. The process failure rates in the sintering plant as a function of the dust feed.

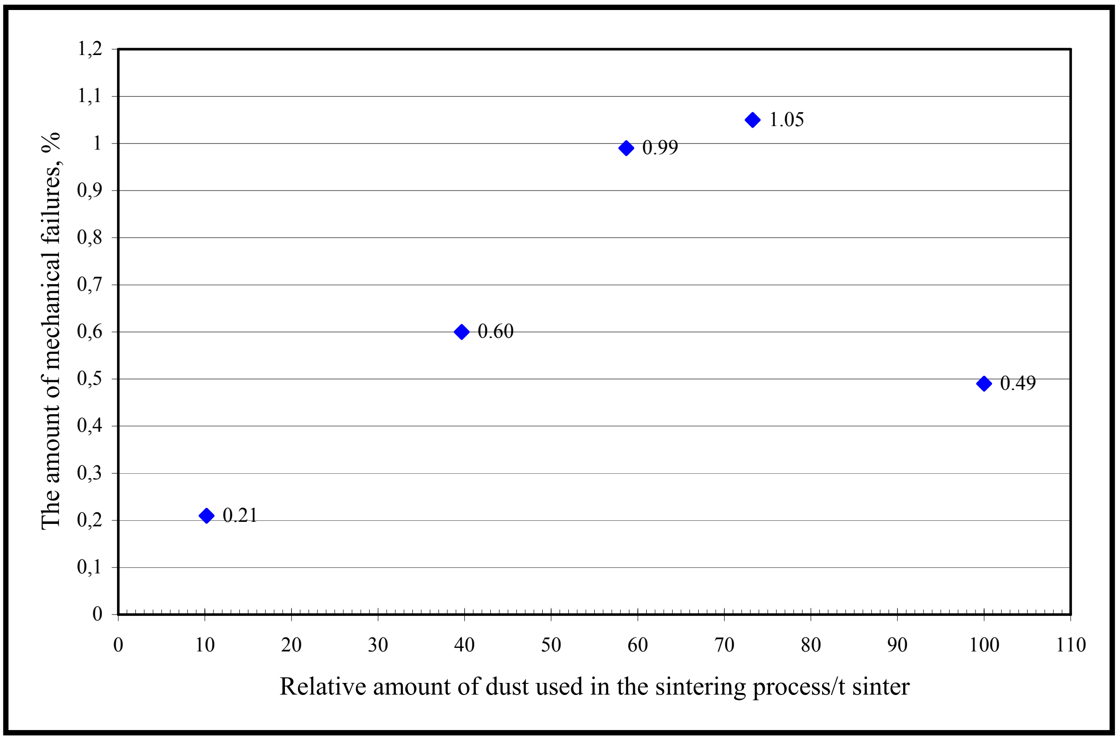


Figure A12. The mechanical failure rates in the sintering plant as a function of the dust feed.

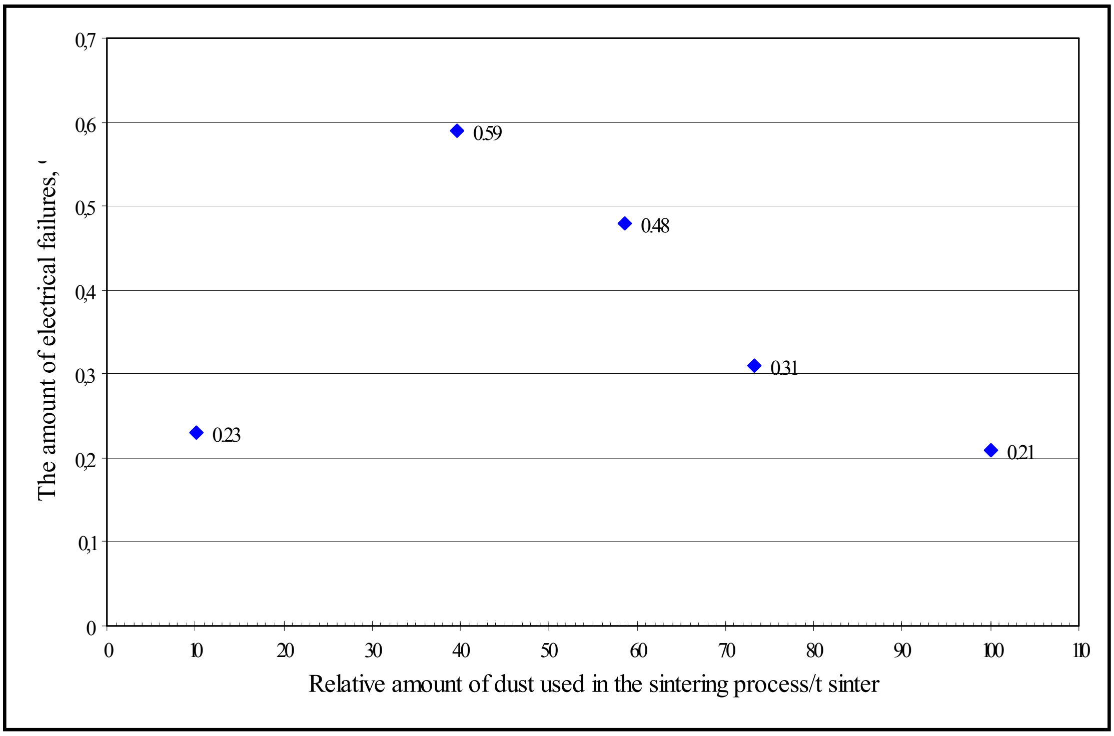


Figure A13. The electrical failure rates in the sintering plant as a function of the dust feed.

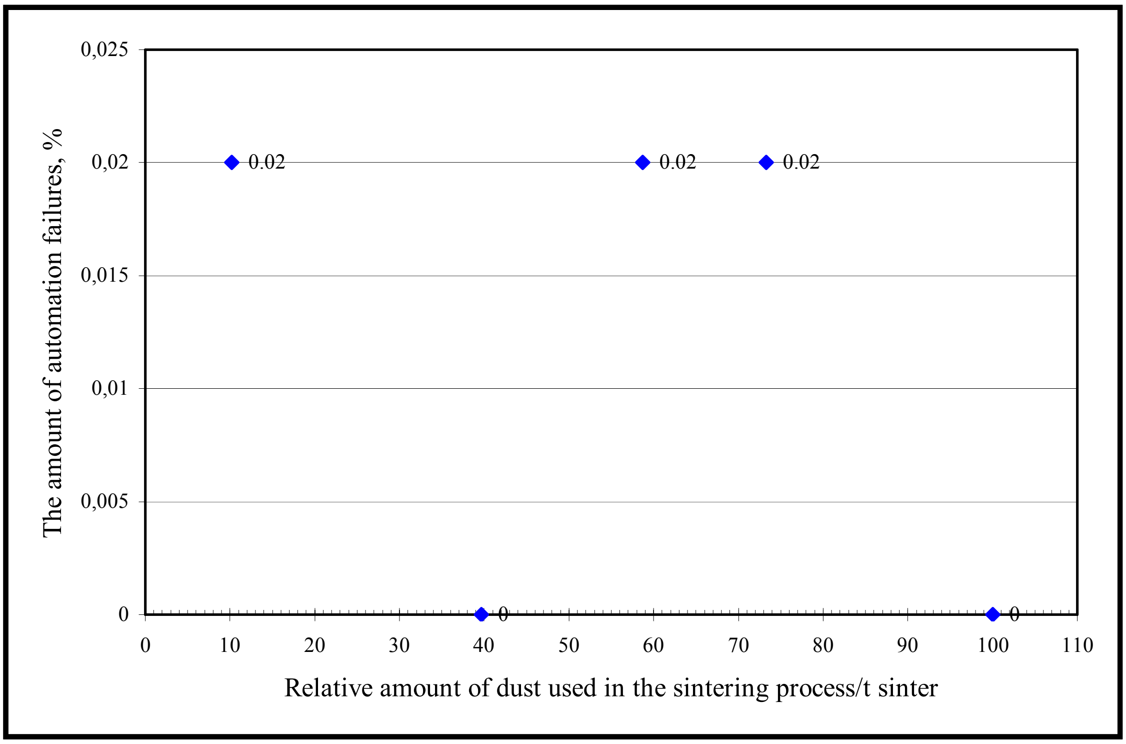


Figure A14. The automation failure rates in the sintering plant as a function of the dust feed.

Based on Figures A10-A14 no clear correlations between the dust content and the availability or failure rates were found. The operating personnel verified the results. The personnel had expected a lower amount of process and mechanical failures with the low dust content.

b) Blast furnaces

The equation (A5) was used at the plant to calculate the availability of the blast furnaces:

Availability, % =
*(1– (effective time loss for internal failure rates/number of days*24))*100* (A5)

in which "effective time loss for internal failures" is defined as:

$$\text{Effective time loss for internal failure rates} =$$
$$\text{duration of the failure} \cdot \left(\frac{\text{blast amount before the failure - blast amount during the failure}}{\text{blast amount before the failure}} \right)$$

The results are shown in the Figures A15-A16.

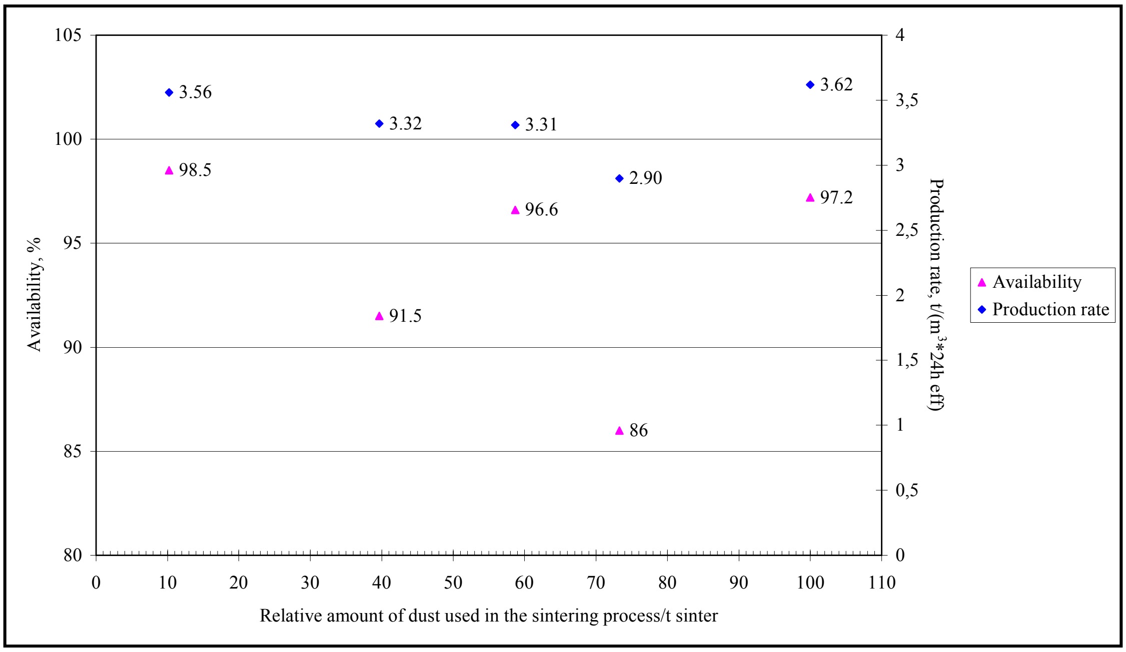


*Figure A15. The availability (left) and the production rate (right) at different time periods of blast furnace number 1. The unit: t/(m3*24h eff) is a company-specific measure to describe the amount of effectively produced hot metal per day.*

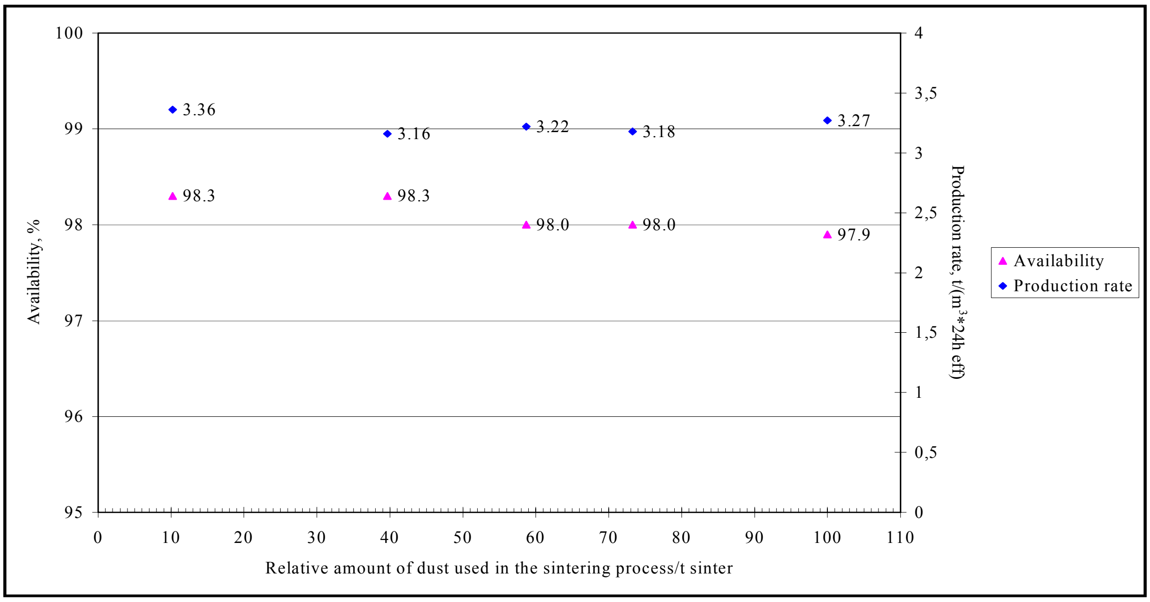


*Figure A16. The availability (left) and production rate (right) at different time periods of blast furnace number 2. The unit: t/(m3*24h eff) is a company-specific measure to describe the amount of effectively produced hot metal per day.*

Figures A15-A16 indicate slightly higher availabilities for the blast furnace processes in the “dust-free” period, but no clear correlation between availability and production. The higher blast furnace production rate was found to correlate with oil consumption, which is one means to compensate for production. It was concluded that oil consumption is a more important factor than availability (Figures A17-A18).

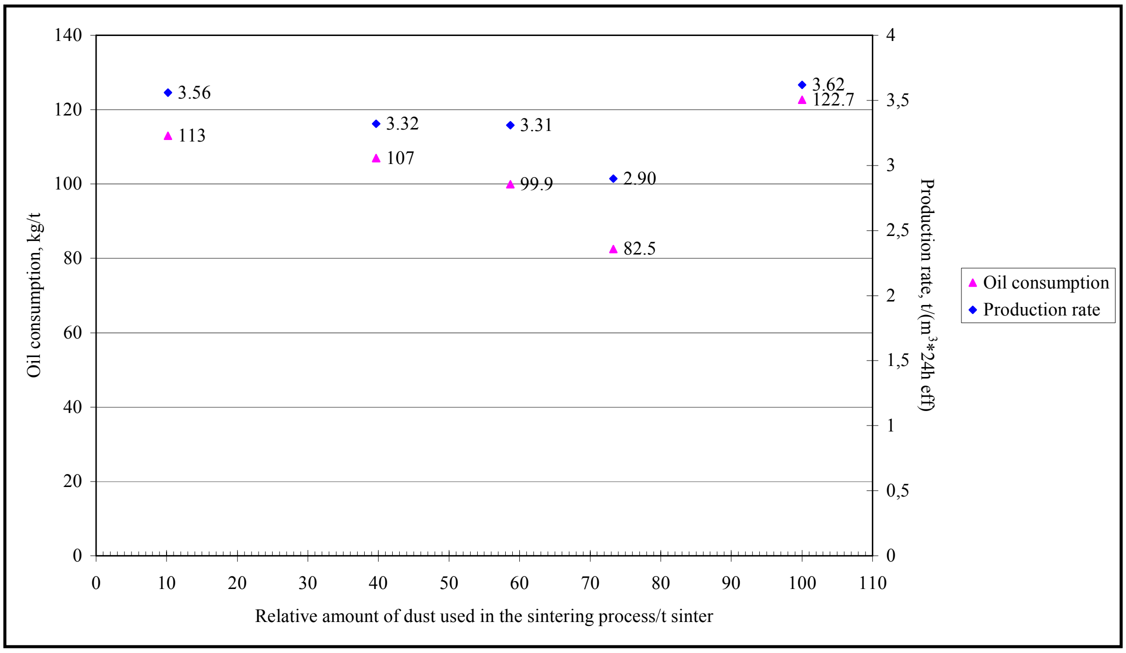


*Figure A17. The oil consumption (left) and the production rate (right) of blast furnace number 1. The unit: t/(m3*24h eff) is a company-specific measure to describe the amount of effectively produced hot metal per day.*

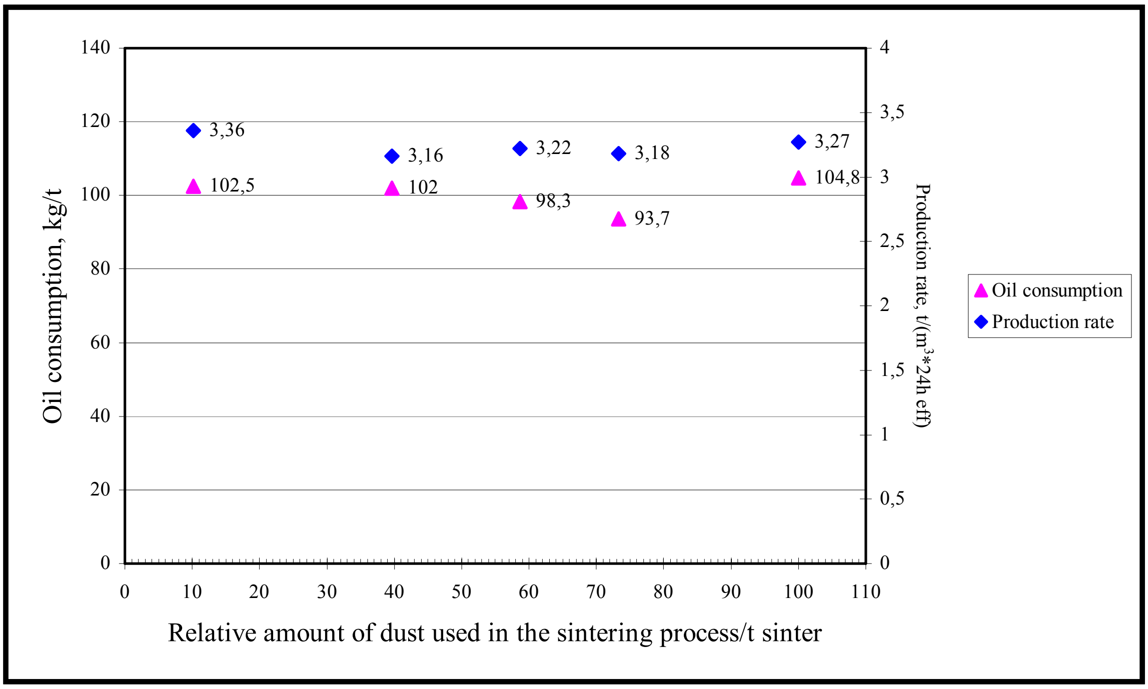


*Figure A18. The oil consumption (left) and the production rate (right) of blast furnace number 2. The unit: t/(m3*24h eff) is a company-specific measure to describe the amount of effectively produced hot metal per day.*

The study indicated no clear correlation between the amount of dust in the sintering process and the availability of the blast furnaces. The result was verified and confirmed by operating personnel.

2.4.5 The operability study and the results

This section refers to Kekkonen et al. (2005).

a) Sintering process

One of the expected changes due to process modification was better sintering plant operation and thereby higher sinter production. This was examined by analyzing the amount of undersize sinters.

The Figures A19 and A20 indicate the amount and the distribution of undersize sinters in different periods.

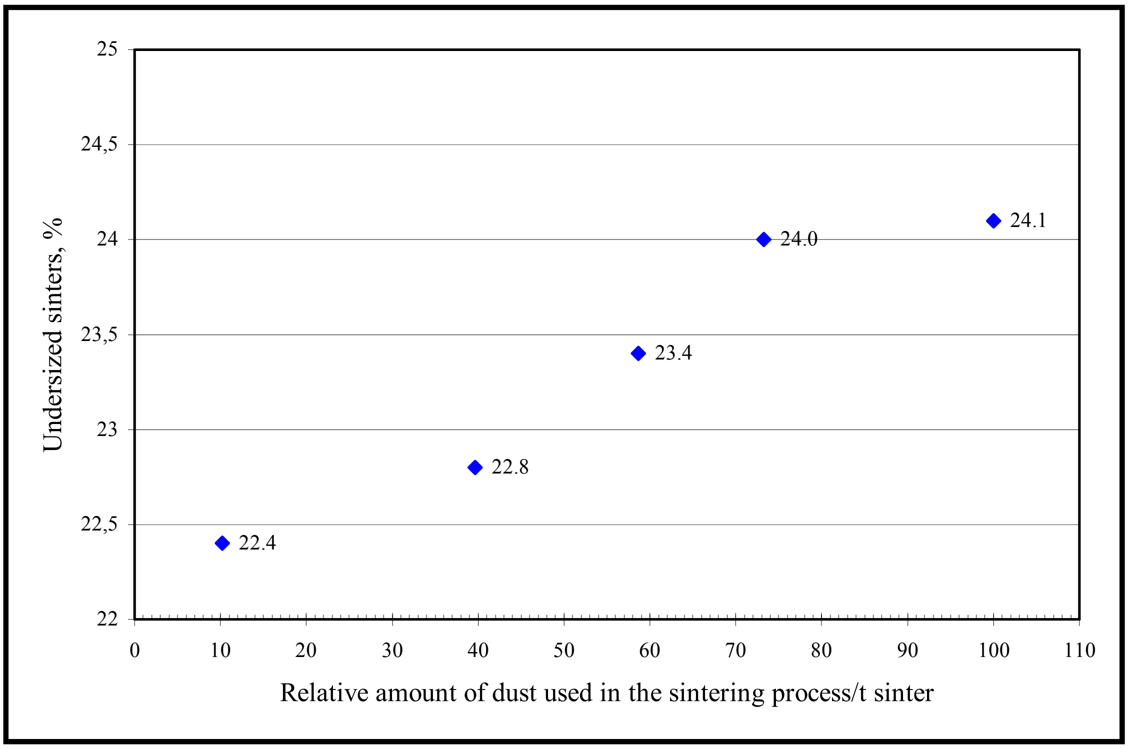


Figure A19. Amount of undersize sinters in the sintering process as a function of the dust feed.

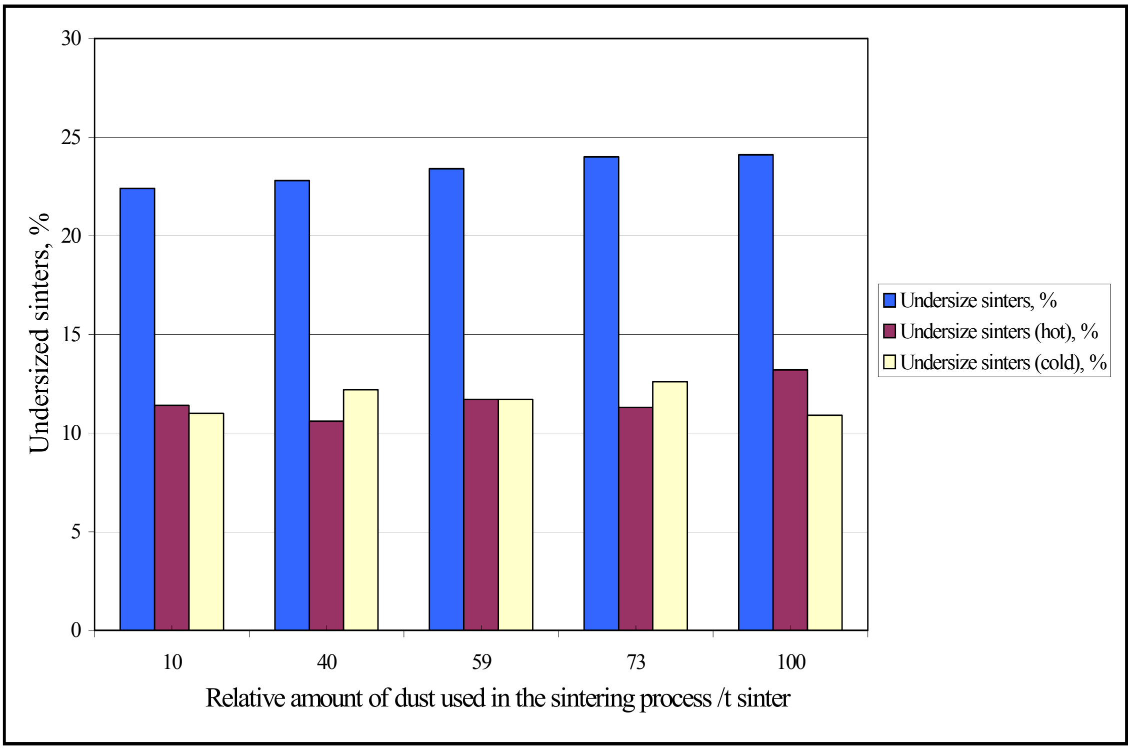


Figure A20. Distribution of undersize sinters in the hot and cold returns.

Undersize sinters (hot and cold returns) are recycled back to the sintering process. Figure A19 indicates that a decrease in the dust content reduces the amount of undersize sinters. This is due to less internal recycling in the sintering process. Figure A20 indicates that the distribution of undersize sinters does not show any trend with increasing dust amount.

Next, the question of how the dusts affect the sinter yield was examined using the following equation (A6):

$$\text{Sinter yield, \%} = \left(\frac{\text{sinter production}}{\text{sinters from screening}} \right) \cdot 100\% \qquad \text{(A6)}$$

The effect of the dust amount on the sinter yield is shown in Figure A21. The effect of the dust amount on the production rate is shown in Figure A22.

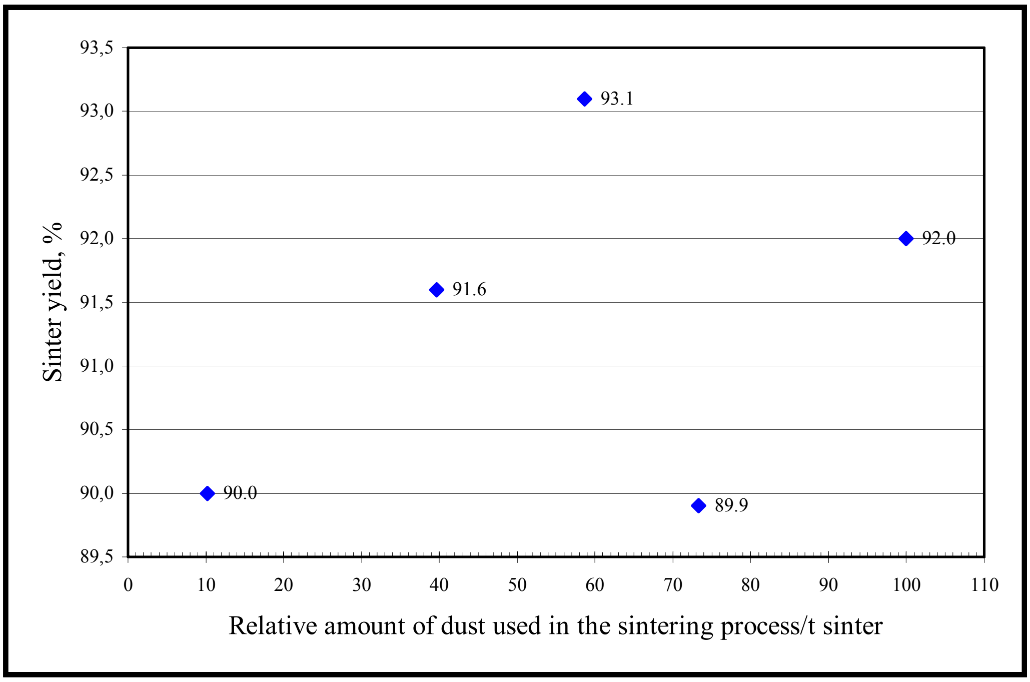


Figure A21. The correlation between the dust content and the sinter yield.

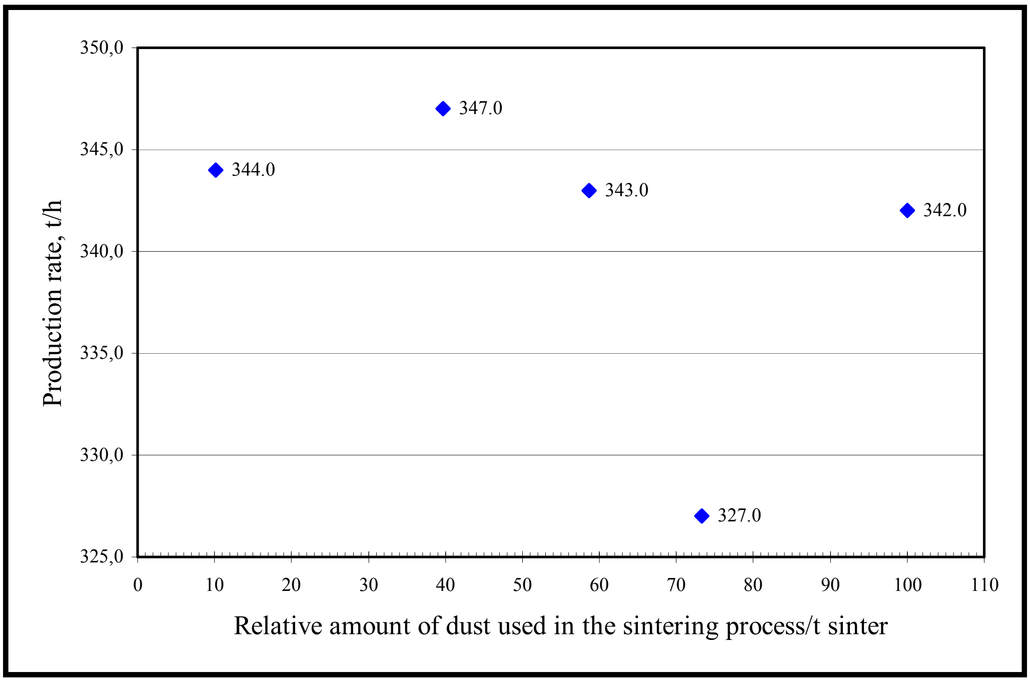


Figure A22. The correlation between the dust content and the sinter plant production rate.

No clear correlation between the dust content and the sinter yield was found (Figure A21). No clear correlation between the dust content and the production rate was found (Figure A22) and the highest production rate (347 t/h) was achieved with a relative dust content of 40 (dust/per ton of sinter). The low production rate in 2002 was not due to any technical reason.

To summarize, reducing the dust amount decreases the amount of undersize sinters. That is shown as increased sinter production. In this case example the production increased by 1.5%.

The results were verified by operating personnel. They noted that normally the variations in dust feed quality are compensated by factors like raw material quality and fuel consumption.

b) Blast furnaces

No data analyses were carried out on the blast furnace process since the only effect on the sintering plant was an increase in production. Neither had the operating personnel experienced notable correlations between the dust feed of the sintering plant and the operability of the blast furnaces. This is due to the fact that the variations are routinely compensated by other factors like raw-material quality and fuel consumption.

2.4.6 The material and energy balance calculations and the results

This section refers to Kekkonen et al. (2005).

Process flow chart and main data:

Figure A23 is a combined presentation of two flow sheets: an existing process and a modified process where dusts and other secondary materials are treated in a separate process. In the existing process some of the fine materials (dust, scale etc.) are recycled back to the process through the sintering plant. The reject streams that cannot be recycled, i.e. the wastes, are stored in the sludge basin area to await future handling. In the new process, the recycle stream and the reject stream are treated separately. The product from the separate process is then fed back to the main process through the converters (BOF).

The rotary hearth furnace (RHF) process was considered as the alternative process. In the RHF process, the process materials have to be agglomerated (pelletized) before feeding them into the furnace. Also, some extra iron ore concentrate is needed to increase the iron content of the hot metal to an appropriate level (for simplicity, omitted from Figure A23). The RHF, producing solid direct reduced iron, requires an extra melting furnace (SAF) before the product can be fed back to the production chain.

The calculations for the existing route were performed for an annual steel production of 2.8 Mt. The capacity of the SAF furnace was chosen to be 500 000 t of hot metal per year.

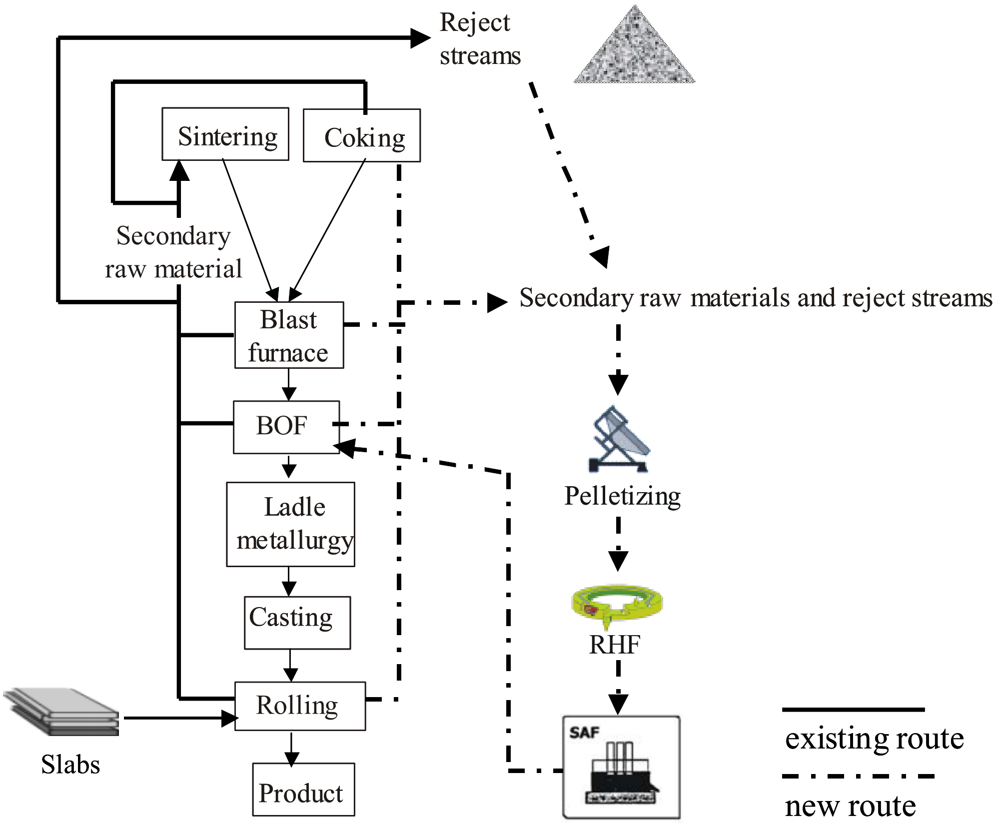


Figure A23. Flow sheet of the two alternative process concepts (Kekkonen et al., 2005).

2.4.7 The case results

This section refers to Kekkonen et al. (2005).

The objective of the case study was to analyze the new process concept from multiple perspectives. These were 1) process economy, 2) the environmental perspective and 3) the technical perspective.

1) Process economy

Process economic performance was evaluated through costs (Figure A24). Operating and capital costs were first calculated for the existing process. That was referenced to the capital and operating costs of the RHF + SAF after one year and against the operating costs of the RHF + SAF. The following assumptions were made: investment cost 150 M€, loan period 15 years and interest 10 %.

The study showed that the total cost of the new process concept is higher than that of the existing process concept. The new process concept becomes more attractive than the existing process when calculated per unit of steel production (solid line in Figure A24). The landfill cost was estimated to triple in 10 years due to stricter environmental requirements (dotted line in Figure A24).

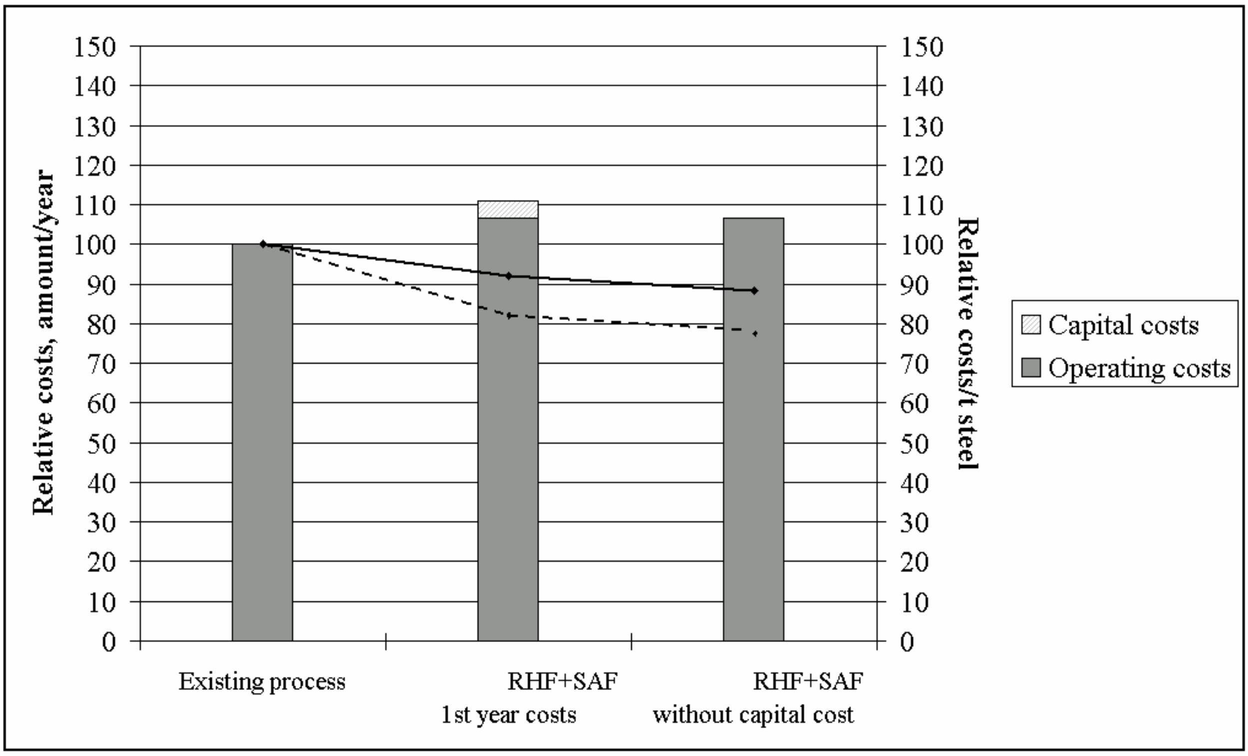


Figure A24. Relative operating and capital costs. Solid line: operating and capital cost per unit of steel production. Dotted line: landfill cost (rough estimate) per unit of steel production. Existing process = 100.

2) Environmental perspective

Environmental performance was considered through the amount of produced CO_2 (Figure A25). In that, all carbon in the raw material and fuel was burned into CO_2. The study indicates that total CO_2 emissions will increase, but the emissions per ton of steel will decrease due to increased production (line in Figure A25).

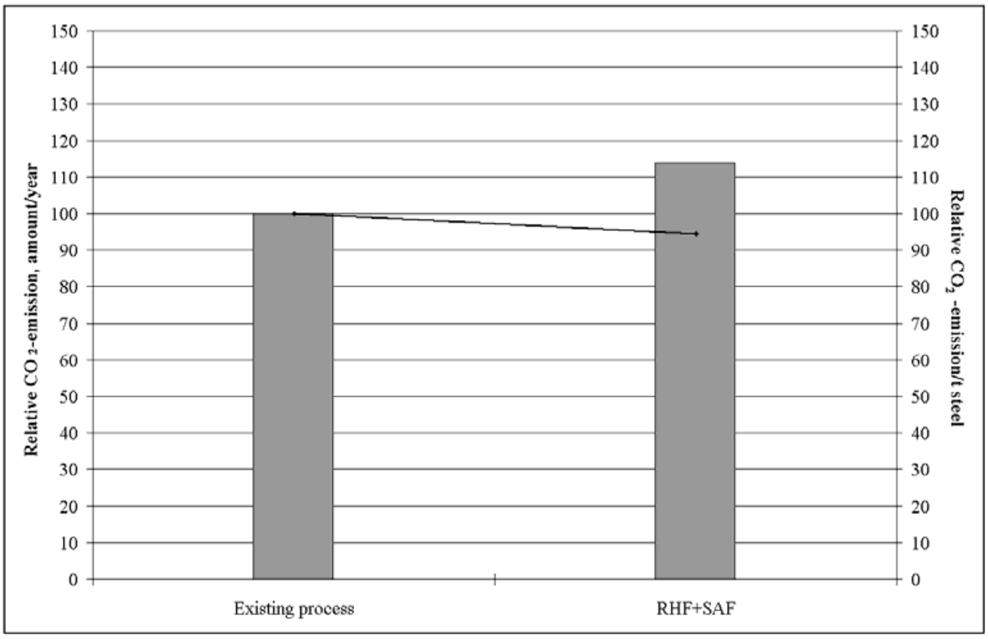


Figure A25. Relative CO_2 emissions. Columns: amount/year (left), line: amount/ton of steel (right). Existing process = 100.

3) Technical perspective

The technical performance was considered through production capacity, raw-material consumption, yield and electricity consumption. Of these, electricity consumption is shown in Figure A26. The operability and availability of the new process were examined earlier in Section 2.4.4 - 2.4.5. The obtained result was increased sinter production.

In the case example, steel production increased: by increased sinter production (minor share) and by the RHF + SAF production (major share). It was assumed that the direct reduced iron (DRI) from RHF was hot when charged to the melting furnace (SAF), resulting in lower electricity consumption compared with cold -charged DRI.

The study showed that the total electricity consumption of the plant increases substantially with the new process. Also, the consumption per ton of steel increases (line in Figure A26). This is mainly due to the energy requirements of the melting furnace in the new process.

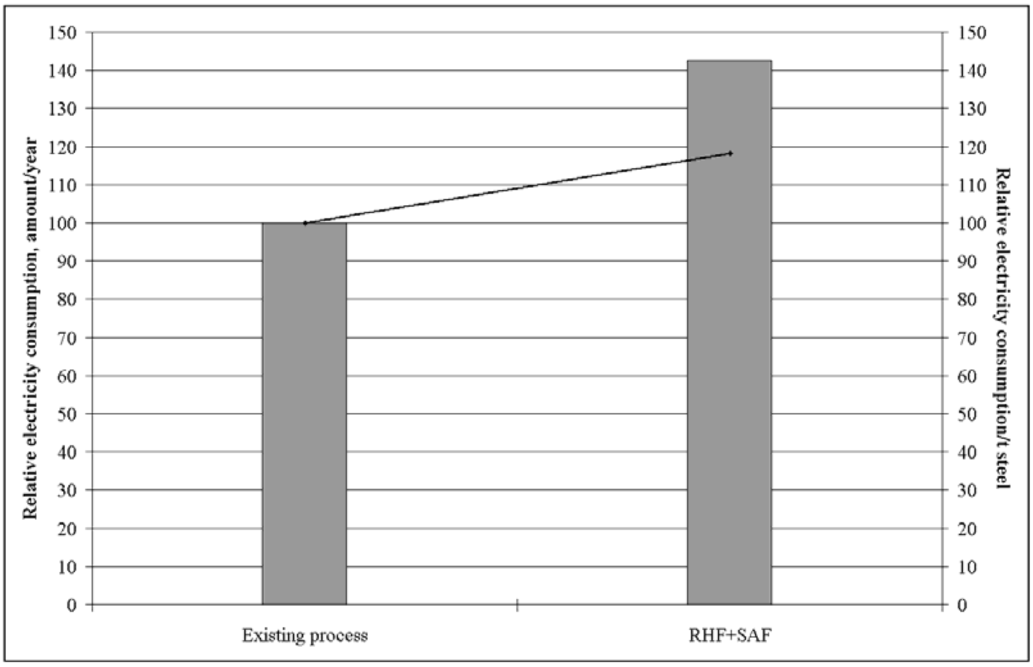


Figure A26. Relative electricity consumption. Columns: amount/year (left), line: amount/ton of steel (right). Existing process = 100.

2.4.8 Conclusions

The findings supporting the thesis can be summarized as follows:

Operability and availability analysis

The operability and availability study resulted into a revised sinter production value. In this case study the sinter production increased by 1.5 %. This was taken into account in the flow sheet calculations. The study demonstrated how the process *availability* and *operability* led to studies dealing with process output quantity and quality (here: size distribution) and the process operation time.

Following this, the study suggests that instead of studying process availability and process operability, one could study the changes in process output quantities and qualities and in the process operation time. In this case example the results were obtained by studying the process's own historic data. This covered complex interactions between e.g. mechanical reliability, level of maintenance, and materials. The operability and availability were studied in a process where the change occurred in the subsequent process steps until the effect of the change was "diluted".

Mass and energy balance calculations

Technical performance was considered through production capacity, raw-material consumption, yield, electricity consumption, operability and availability of the process. Operability and availability were examined as explained before. The balance calculations were performed using the *Factory* flow-sheet program. The technical performance analysis accounted for the major material and energy streams.

Environmental performance was considered through the amount of CO_2. The data for that was obtained from technical calculations. The CO_2 represents an output stream, which is numerical and large in quantity. It is also convertible into costs, but with more speculation compared with the technical criteria (as e.g. within emission trade). Similar criteria that could have served the same purposes include the waste amount or secondary heat releases.

The economic performance evaluation was based on calculating the operating costs and the investment cost. The operating costs consisted of material costs, energy costs and labor costs. For example, a waste cost can be one of the main contributors to operating costs, as seen in Figure A24.

The study reveals that the three perspectives of the study can be considered as different projections of the same data. For example, the economic perspective is obtained from the basic mass and energy data source, augmented by investment cost and financial constraints (here: 15 years, 10% interest rate).

The Factory flow-sheet program is a modern way to calculate stream value data for a large process concept. It is capable of calculating the data for a steady-state condition. Due to its modular structure, it is capable of calculating the stream values from unit processes and for the total sites.

The importance of balance boundaries

The electricity consumption increased in the new process concept. That was basically due to the fact that the circulating materials and wastes were treated in a new electrically operated unit process to produce hot metal. This (together with better sinter plant operation) increased the company's own steel production. This, in turn, resulted in higher electricity consumption in the mill as a whole. The treatment also increased the plant's CO_2 emissions due to the use of coal in the RHF.

The solution allowed the company to get rid of the purchased slabs. If we take into account the CO_2 emissions generated in the production of slabs and the CO_2 emissions generated using the BF-BOF route as production increases to the new level, and add it to the CO_2 emissions of the existing process, the total CO_2 emissions of the existing process will be higher than those of the new process concept (RHF+SAF) (Figure A27).

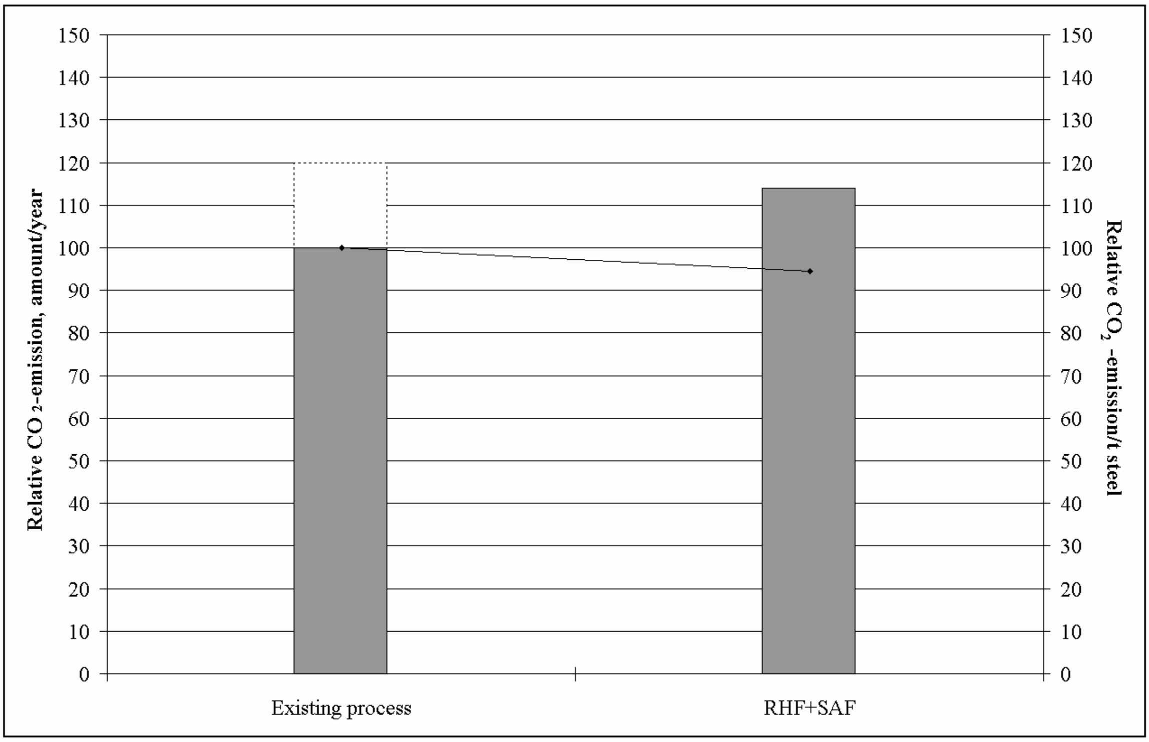


Figure A27. Relative CO_2 emissions. Columns: amount/year (left), solid line: amount/ton of steel (right). Dashed line: CO_2 emissions outside the balance boundary region. Existing process = 100.

If we take into account the electricity consumed in the production of purchased slabs (i.e. used in the existing process) and the electricity that would be needed to increase the production to the new level using BF-BOF, and add it to the electricity consumption of the existing process, the total consumption will remain lower than that of the new process concept (RHF+SAF) (Figure A28).

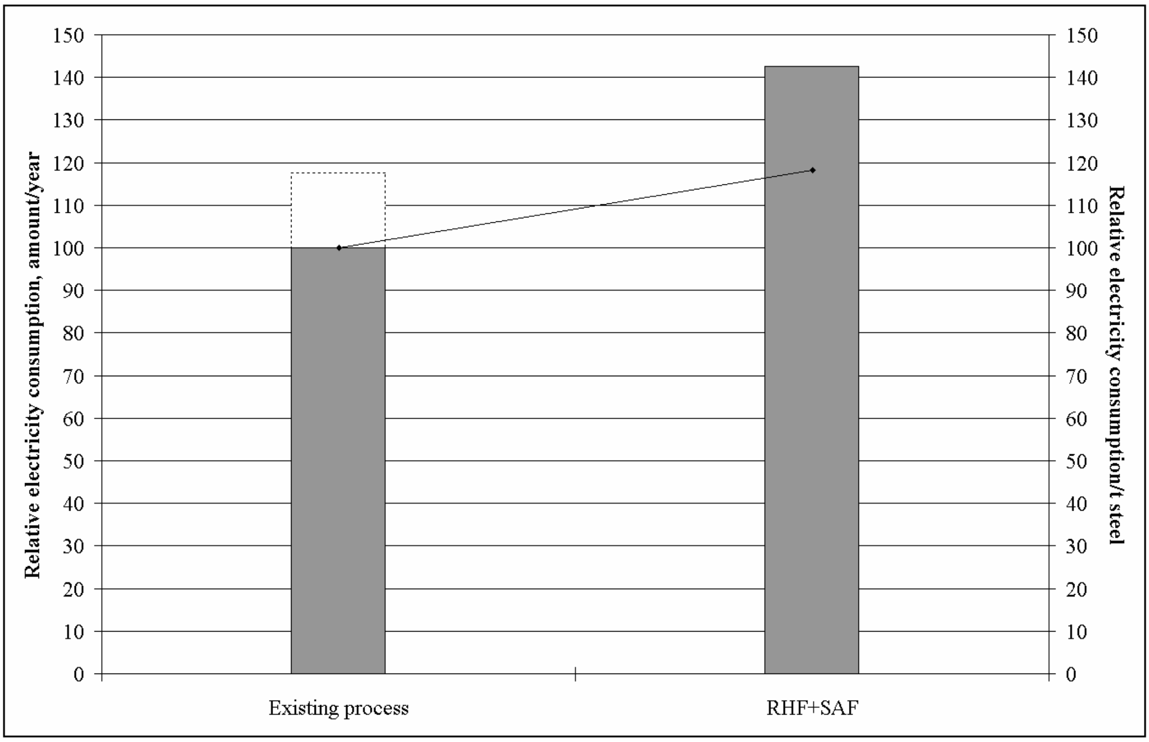


Figure A28. Electricity consumption Columns: amount/year (left), solid line: amount/ton of steel (right). Dashed line: Electricity consumption outside the balance boundary region. Existing process = 100.

The study reveals that the determination of the balance boundary has a substantial effect on the evaluation of numeric results. In the case study, CO_2 production increased on the plant scale but decreased on the global scale.

Process integration potential

To point out differences between the existing process and the new process, the potential for improvement was calculated for several criteria (Figures A29-A32).

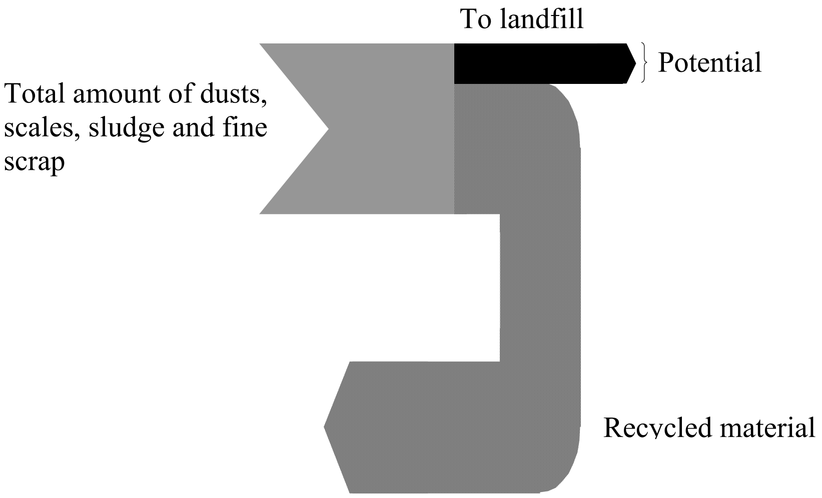


Figure A29. Potential to recover iron from waste.

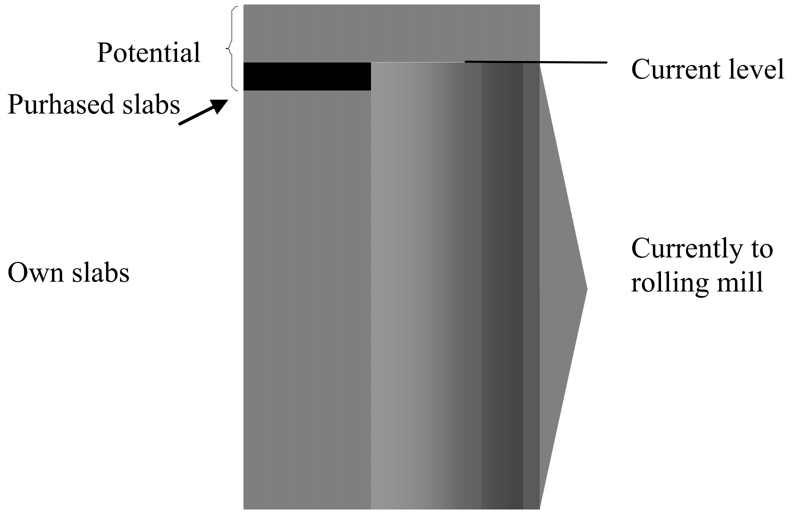


Figure A30. Potential to increase the steel production at the mill (iron from waste, better sinter plant operability).

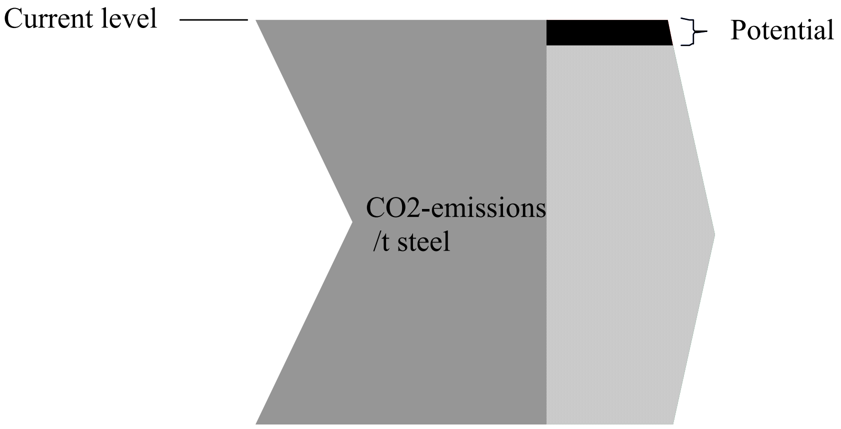


Figure A31. Potential to decrease CO_2 emissions as calculated per ton of production.

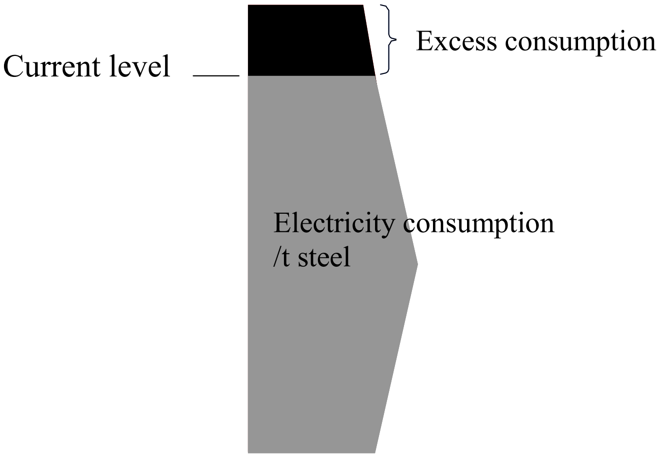


Figure A32. Increase (negative potential) in electricity consumption as calculated per ton of production.

The potentials in Figures A29, A30, A31 and A32 indicate differences between the existing case and the new process. They readily arise from the problem statement to compare an existing process and a new process (featuring zero waste production and no need to purchase slabs from the market). The differences in performance are calculated on the site level.

The operability and availability analysis resulted in a revised amount of produced sinter. Figure A30 captures this information. The detailed presentation of the potential obtained in the operability and availability study is in Figure A33. That presents the potential on a unit process scale.

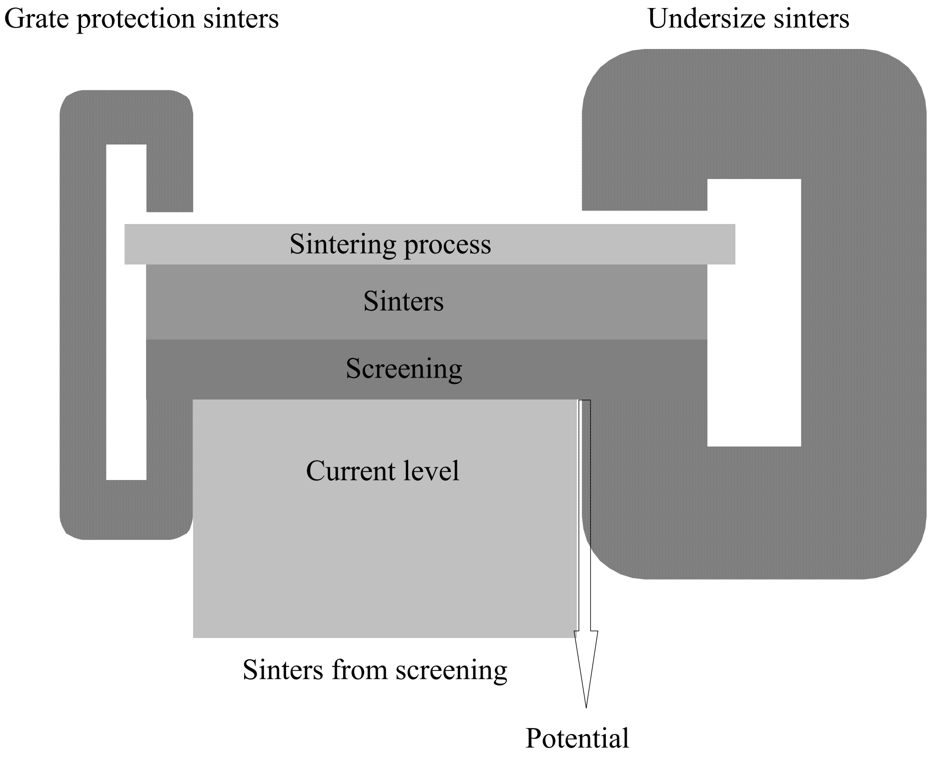


Figure A33. Potential to increase sinter production.

2.5 Case 5: Bio-fuel drying in a power plant

2.5.1 Objectives summary table

(see complete Table A1)

General characteristics	
Industry	Energy
Lifecycle	Process development + Operation
Problem scale	Unit Process (plant) [1)]
Enhanced target-setting	
Business mgm. aspect applied	(X)
Design and evaluation criteria	
Multi-criteria decision-making	X
Hierarchy of criteria	(X)
Criteria interdependencies	(X)
Process operability	(X)
Process availability	(X)
Process integration methods	
Method discussed / applied	X [3)]
Potential for improvement	
Idea discussed / applied	X

[1)] Primarily a unit process study, secondarily a plant scale study

[3)] Falls only loosely under the category ‘process integration methods’.

2.5.2 Research objective

The study was established to simulate the use of the draft elements of the evaluation concept. The draft elements of the concept are discussed at the beginning of the study, in Section 2.5.4.

The elements were fitted to support a process development initiative in a power plant. In that initiative, moist bio-fuel was dried in a multistage dryer to increase the energy efficiency of a CHP (Combined Heat and Power) plant. The CHP plant is integrated into a pulp and paper mill (later: 'the mill').

2.5.3 The technical context

This section refers to Holmberg and Ahtila (2005).

The use of multi-stage drying system was proposed to dry moist bark that was entering a CHP (Combined Heat and Power) plant. The bark was entering the power plant at varying moisture contents, between 55-65% (w.b.). A high moisture content decreases the effective heating value of the bio-fuel.

The dryer was designed to use air as the drying medium. It was possible to heat the air using secondary heat energies returned from the mill and/or steam at various pressures from the CHP plant. Bark was obtained from the mill's debarking plant.

The CHP plant used bark as the main fuel. Peat was used as a marginal fuel. The CHP plant produced electricity and steam at different pressures. It was possible to utilize the benefits of drying to decrease the marginal fuel consumption or to increase power capacity. The possible energy sources for heating of the drying air were: secondary heat flows (hot water 50-90 ^{o}C), backpressure steam (typically 3-5 bar) and extraction steam (typically 10-12 bar).

Figure A34a presents a flow diagram for a 2-stage drying system. Figure A34b illustrates the system's drying air states on an enthalpy-humidity (Mollier) chart. One drying stage consists of a heating period and a drying period. The dryer type in each drying stage is a continuous fixed bed dryer, in which air is aspirated through a fuel bed (also called continuous cross-flow dryer). Holmberg and Ahtila (2005) studied 1-, 2- and 3-stage drying systems. A single-stage dryer with once-through air heating is cheaper but less energy efficient. A multi-stage dryer is more expensive but more energy efficient.

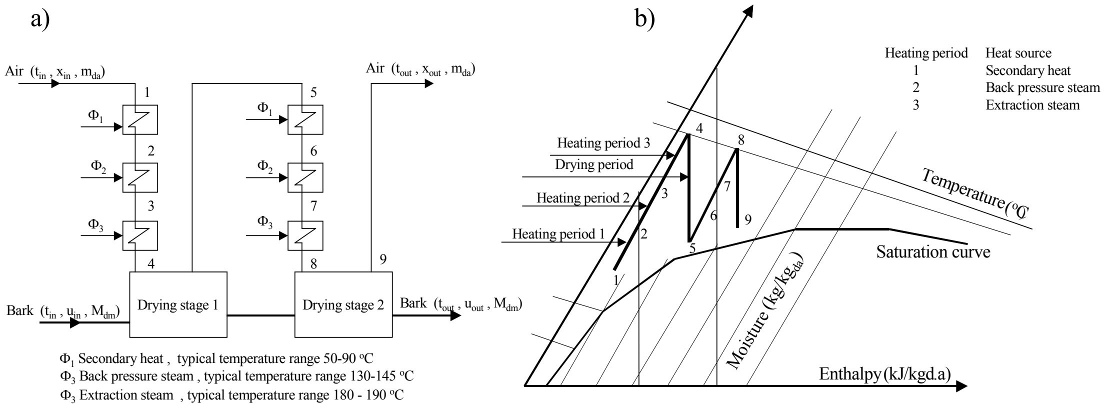


Figure A34. A two-stage drying system a) flow diagram b) states of the drying air on an enthalpy-humidity chart.

The objective of the study was to determine the optimal final fuel moisture content, the optimal number of drying stages and the optimal combination of heat sources (secondary heat, backpressure and extraction steam) by maximizing the net present value of the investment.

Drying phenomena inside the dryer were modeled. The model was based on heat and mass transfer theory and data from laboratory measurements. The phenomenal model was combined with mass and energy balance calculations. The model calculated the streams over the control region, including fuel and the heat and power inputs and outputs.

Final evaluation was based on calculating the Net Present Value, NPV over the economic lifetime of the dryer:

$$NPV = \sum_{\tau=0}^{\tau=k} \frac{(NI\tau_{op} - C_{maintenance})}{(1+i)^{\tau}} - C_{investment} \tag{A7}$$

where NI is the net income cash flows, k is the total number of years over which cash flows occur (10 years), τ_{op} is the annual operating hours of the dryer, $C_{investment}$ is investment cost, $C_{maintenance}$ is maintenance cost. The net income is the sum of marginal fuel savings and increased power production, and was dependent on the fuel and electricity prices. The investment cost was expressed as a function of capacity factor:

$$C_{investment} = f(\dot{m}_{da}) \tag{A8}$$

where $\dot{m}_{da}$ is the mass flow of drying air. The maintenance costs were estimated at 3% of the investment cost. The interest rate (5%), utility prices and economic life of dryer (10 years) were fixed.

The resulting NPV was calculated for one design case. Its sensitivity was tested in terms of the length of economic life, marginal fuel price, electricity price and secondary heat price. In each sensitivity analysis, the result was given as a function of: final bark moisture content, drying temperatures and number of drying stages. According to the study, it is most economical to use secondary heat sources for drying to reduce marginal fuel costs.

2.5.4 The case study and results

The purpose of the study was to support the study by Holmberg and Ahtila (2005). This was done by evaluating: 1) what are the optional design balance boundaries for calculation, 2) what additional information would the scenario analysis bring, 3) what additional information is gained by analyzing the process availability, flexibility and controllability and 4) what additional information is gained from the study of process potentials.

The optional design balance boundaries

The drying system will become an integral part of the power plant and a mill. This means that a couple of alternative approaches exist to define the design balance boundary regions (Figure A35):

- Equipment scale. The question is to determine the optimal drying process, meaning the final fuel moisture content, airflow, etc. The mathematical models can be made exact on this level, but modeling would probably take some important aspects for granted. These include the availability of heat sources used in drying, the boiler efficiency and the detailed economic consequences.
- Process scale. The question is to optimize the heat and power production process. The main task is to determine material and energy flows in and out of the CHP process. The flows include fuel consumption (including the marginal fuel), energy production (process heat, district heat, electricity) and waste generation (CO_2, NO_x, ash). Mathematical programming and optimization could still be used without loosing the required accuracy. Design on this level raises questions such as the effects of drying on boiler operation.
- Site scale. The aim is to integrate the CHP production and the mill in an optimal way. Design on this scale involves e.g. optimizing bark flow, secondary heat energy flows and steam flow between the mill and the power plant. The use of secondary heat energies in the drying of biomass increases the energy efficiency of the site as a whole. Design on this scale requires a substantial amount of data, and may lead to difficulties in problem-solving.

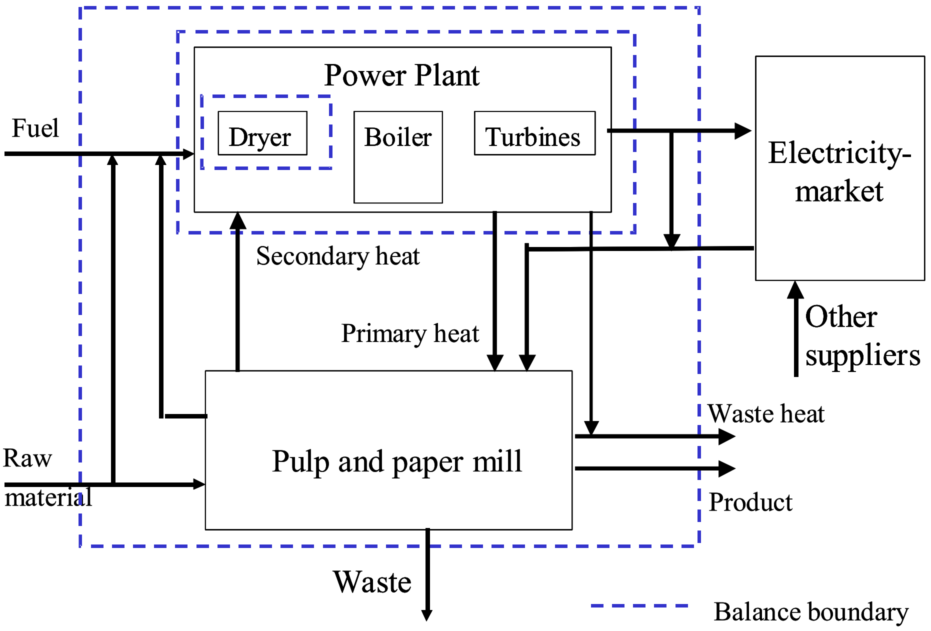


Figure A35. Alternative balance boundaries in the case study.

The dryer is an integral part of the CHP process: Drying has an influence on boiler dimensions, and the feasibility of the system is determined by the chosen heat energies. Design on the equipment scale allows exact problem-solving but simplifies the problem too much. Design on the site scale would most probably increase the design effort too much. Therefore it was reasonable to study the dryer, boiler and the turbines as a whole, i.e. discuss the problem on the process level. The other design scales were not analyzed further.

Scenario analysis information

A *hypothetical* scenario analysis was written for the CHP plant's future:

- *Fixed dry mass flow 55-65 % w.b. for bark is expected. The mill has no other plans (like gasification) for bark. Big variations in bark mass flows are not expected.*
- *Multiple of secondary heat sources 50-90 ^{0}C (like mill warm waters) for fixed flow and quality are available. The mill has no other plans for the warm water. Big variations in the mass flows are not expected.*
- *Electricity and marginal fuel prices are expected to increase in the future. It seems desirable to decrease marginal fuel consumption or increase electricity production. At the moment the only process heat load is the mill, which has no plans for capacity increases in the short term. Additional steam sinks are required to increase electricity production:*
    - *In the long term, the CHP production may become favored by laws and regulations. One future option is an auxiliary condensate turbine.*
    - *One optional trend is that companies integrate with each other. This may bring new steam users to the site.*
    - *The trends in technology, especially in paper drying, may change the mill utility requirement in the future.*
- *CO_2 regulations are tightening and the cost of producing it will most probably increase. There is continuing interest in lowering CO_2 emissions. The role of the current marginal fuel (peat) is hard to estimate in terms of CO_2, costs and availabilities.*

The analysis shows that: 1) secondary heat energies and bark are available for drying at least in the short term, 2) there is continuing interest in increasing the energy efficiency of the plant and 3) the most important factors against which the design alternatives should be analyzed are the electricity production and the CO_2 emissions.

The analysis specifies the design targets and constraints from the business management point of view and on the time scale. The result is a sharpened design scope. When multiple companies operate at the same site, the analysis helps to scope the common targets.

Process availability, flexibility and controllability

a) Process availability, flexibility and controllability in Holmberg and Ahtila (2005)

For the dryer and for the boiler, the study:

- assumed fixed operating hours in a year.
- assumed constant input/output parameters. The dryer and the boiler are operating with the found ('variable') values.
- did not consider controllability aspects.

The study assumed that the dryer is bypassed if it becomes inoperable. The equipment and flow data are listed in Table A4.

Table A4. A table to illustrate how flexibility, controllability and availability were considered in Holmberg and Ahtila (2005) in case bio-fuel drying. The comments refer to texts on the next page.

Total production maximization:	Quantity	Quality				Operating time			
	(Mass flow)	temp. (^{0}C)	press. (bar)	moist.cont. (kg/ kg$_{dm}$)	density (kg$_{dm}$/i-m$_3$)				
Design criterion:							Flexibility	Controllability	Availability
Dryer						Fixed (8400 h/a)	Assumed adequate flexibility/ comment 1	Assumed good controllability/ comment 1	Fixed/ comment 4
Process inputs									
- bark *)	4 kg$_{dm}$/s	-	-	1,5	85				
- drying air	Variable	Variable	-	0.004	-				
- secondary heat	Variable	75	-	-	-				
- backpressure steam	Variable	133	3	-	-				
- extraction steam	Variable	150	10	-	-				
Process outputs									
- bark	4 kg$_{dm}$/s	Variable	-	Variable	85				
- drying air	Variable	Variable	-	Variable	Variable				
- condensates	Not considered	Not considered							
- extraction gases	Not considered	Not considered							
Boiler + turbine **)						Fixed (8400 h/a)	Assumed adequate flexibility/ comments 1 and 2	Assumed good controllability/ comments 1 and 3	Fixed/ comment 4
Process inputs									
- bark*)	4 kg$_{dm}$/s	Variable	-	Variable	85				
- marginal fuel (peat) *)	Variable	-	-	-	-				
- combustion air	Not considered	Not considered							
Process outputs									
- electricity	Variable	Not applicable					comment 2)		
- backpressure steam	Variable	133	3	-	-		comment 2)		
- extraction steam	Variable	150	10	-	-		comment 2)		
- flue gases	Not considered	Not considered							
- heat losses	Not considered	Not considered							

* lower heating values for moist fuels: bark 16,3 MJ/kg$_{dm}$, peat 18 MJ/kg$_{dm}$, ** boiler efficiency 0.87, see comment 3

b) An enhanced way to consider process availability, flexibility and controllability

The criteria availability and operability are defined in Chapter 6 of the thesis. Operability is divided into flexibility and controllability:

- *Flexibility* means ‘the feature to account for variability in normal operating conditions’. Considering flexibility means that the ranges of flow quantities and qualities and other important parameters are specified as well as the variability in them.
- Process *controllability* means ’the ability to operate at various set-point values over a feasible operating range’. Considering controllability means that the effects of new operating circumstances on the operation are studied and taken into account in design.
- Process *availability* means ‘the time that the process is performing its intended operation’. Considering availability means that the time during which the unit operates in the new circumstances is studied and taken into account in design.

Following the findings in Chapter 6 of the thesis, the above criteria can be studied through *product quality, production quantity and operating time.*

This reasoning results in the treatment of the following questions (numbers refer to comments in Table A4):

1. The moisture content of the bark varied a lot (Figure A36). Moisture variation requires extra flexibility on the part of the boiler. Variation also has an effect on boiler controllability. Operation of the system becomes more predictable along with an equalized moisture content.
2. The turbine pressure levels were fixed at 3 bar and 10 bar. The only process heat load was the mill. In order to increase the electricity production, an additional heat load is needed. Alternatives for this are: a) to utilize steam in drying b) to invest in auxiliary condensate system or condensate turbine and a condenser.
3. For example, for a 150 MW boiler: 1% increase in boiler efficiency may result in savings of about 200 000 e (150 MW steam output, 8400 h/a, marginal fuel price 14e /MWh, initial boiler efficiency 0.87 = thermal energy input to power plant process per boiler fuel input). But increased boiler efficiency does not account for all savings. Potential savings sources include decreased power consumption of flue gas fans and combustion air fans.
4. Boiler availability may change due to biomass drying. This is seen as e.g. changes in cleaning periods. This has to be tested in pilot-plant trials.

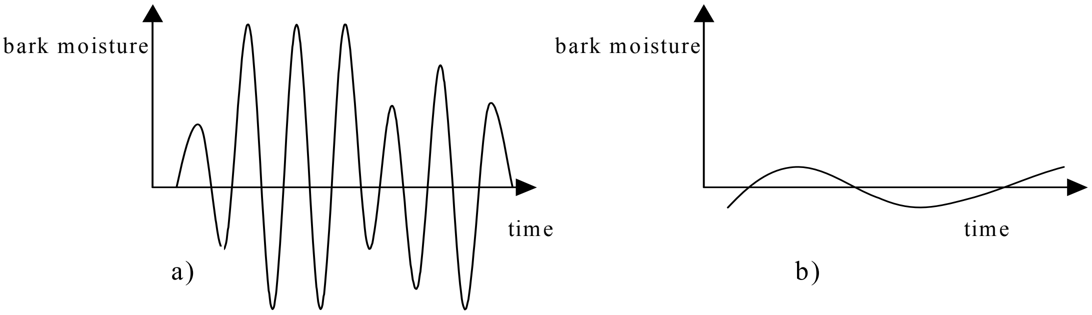


Figure A36. Schematic of the expected moisture content variation of boiler feed a) without drying b) after drying (represents an optimal case).

Detailed study of the flexibility, controllability and availability identifies the consequences of drying. In this case, the consequences concerned the CHP process.

Treating these questions allows more specific target-setting for the pilot-plant trials and a more thorough feasibility study.

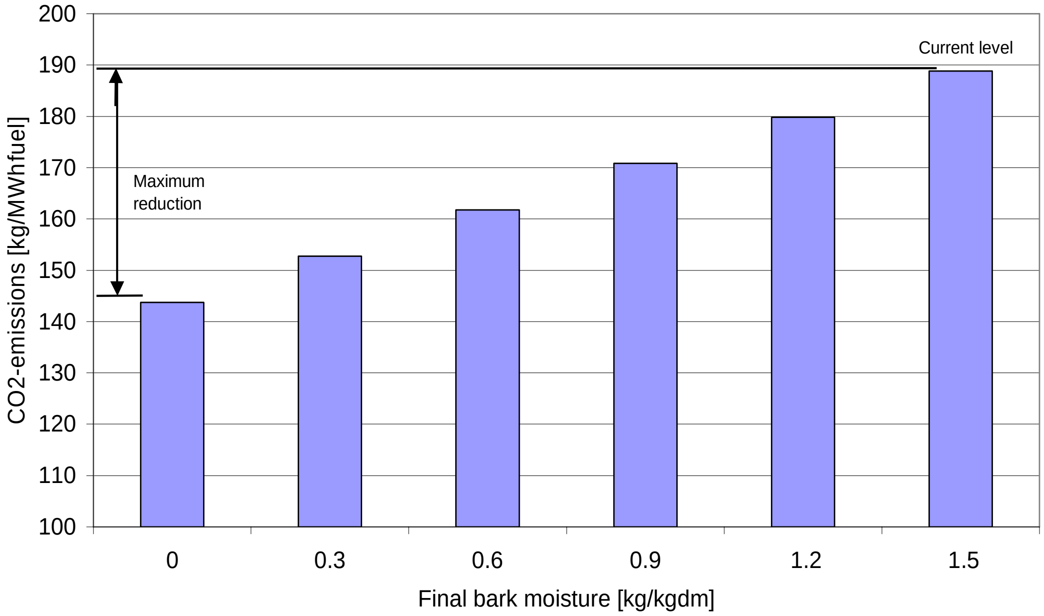
Process integration potentials

Process potentials indicate the potential for improvement available through process integration. The potential can be calculated against the most important business management aspects. In this case, the potentials were calculated against the CO_2 emissions and the power-to-heat ratio.

a) The theoretical potential

The maximum theoretical improvement was calculated for the CO_2 emissions and for the power-to-heat ratio (Figure A37) as a function of the bark moisture content. The maximum CO_2 reduction and maximum increase in power-to-heat ratio were achieved with completely dry bark. The calculation assumes that the bark is “sun dried”, e.g. no extra equipment or energy is used in drying. The values are calculated using a spreadsheet model.

a)



b)

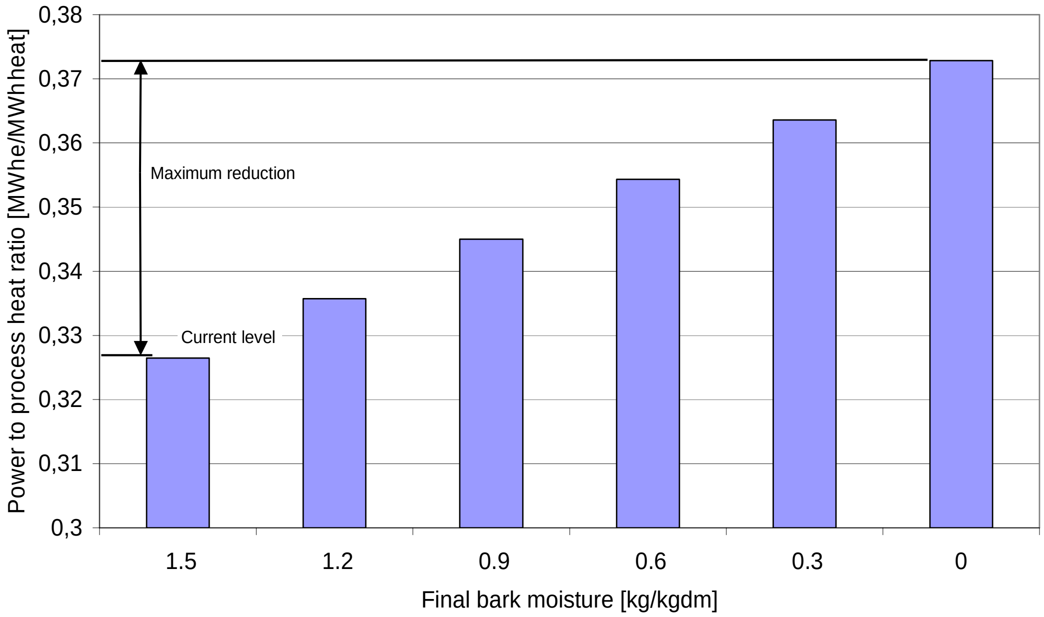


Figure A37. The theoretical reduction potential in terms a) CO_2 emissions and b) power-to-heat ratio as a function of bark moisture content. It was taken that the marginal fuel is peat.

The theoretical potential identifies the maximum achievable performance with respect to the selected criterion.

b) The technical potential

The technical potential indicates the potential for improvement as feasible technical solutions are applied (Figure A38). Five drying concepts were studied: a dryer operating with 1) secondary heat 2) backpressure steam 3) extraction steam 4) secondary heat and backpressure steam and 5) secondary heat, backpressure steam and extraction steam.

The following assumptions were made:

- single-stage dryer
- the available heat sources for heating of drying air are secondary heat (drying temperature 70 ^{o}C), backpressure steam (drying temperature 120 ^{o}C) and extraction steam (drying temperature 150 ^{o}C)
- the dryer can use either one or several heat sources at the same time
- the drying air after the dryer is fully saturated, i.e. the maximum moisture absorbing capacity of air is achieved
- process values, e.g. process efficiency, current power-to-heat ratio, and steam pressures are fixed
- the final bio-fuel moisture content is 0.3kg/kg$_{dm}$).

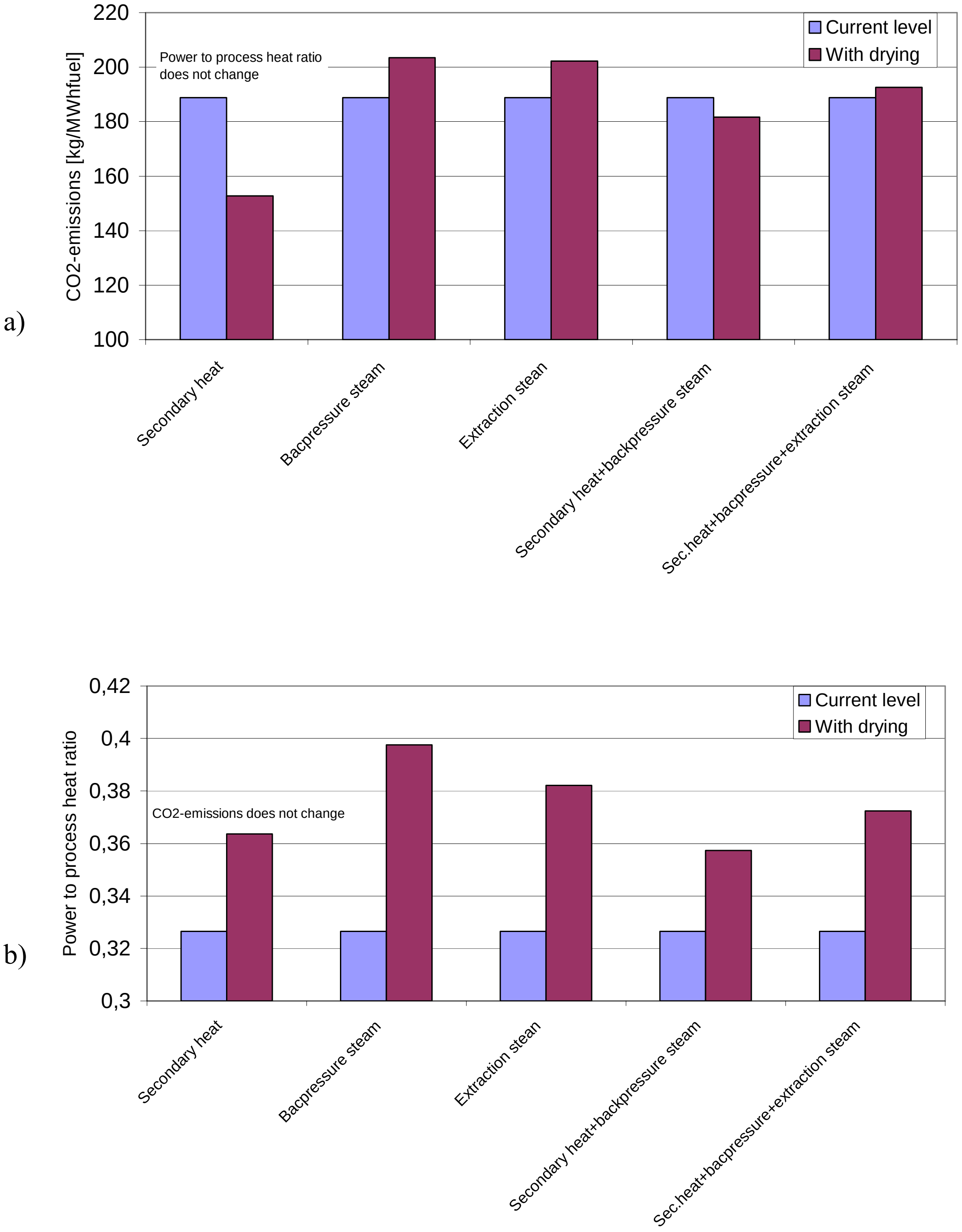


Figure A38. Technical improvement potentials in terms a) CO_2 emissions and b) power-to-heat ratio as a function of bark moisture content.

Technical potentials demonstrate how close to the targets each of the technical alternative will get.

2.5.5 Conclusions

The findings supporting the thesis can be summarized as follows:

The original case study demonstrates the use of detailed phenomenal modeling in process design. The drying phenomenon inside the dryer was modeled. The model was based on a heat and mass transfer theory and on data from laboratory measurements. A concise analysis was needed to understand time-dependent factors such as drying speed, which is the basis for dryer dimensioning. The phenomenal model was combined with mass and energy balance calculations. The calculated streams over the balance region included fuel and the heat and power inputs and outputs.

The complementing study pointed out that alternative approaches exist to define the design and evaluation balance boundary regions. Design on the equipment scale allows exact problem-solving but probably simplifies the question too much. Design on the site scale increases the design effort too much. The relevant scale in this case was the one with a capability to apply mathematical methods but with considerations to process and plant level aspects. The scenario analysis sharpened the design goals and constraints, including the expectation for the secondary heat availability.

Process potentials were calculated to quantify the maximum improvement available through integration. The potential for integration was calculated against the most important criteria, which were identified in the scenario analysis. Two types of potentials were calculated: theoretical potential indicating the maximum theoretical improvement, and technical potential indicating how close to the theoretical targets each of the technical alternatives will get. Process potentials are a straightforward means to simplify and visualize the problem, and position each of the optional process concepts against the targets.

The study of the flexibility, controllability and availability dealt with the consequences of drying for the total system (dryer and CHP process). Treating these questions sharpens the design scope and allows enhanced target-setting for the pilot-plant trials.

2.6 Case 6: Business management material in design

2.6.1 Objectives summary table

(see complete Table A1)

General characteristics	
Industry	Steel mill
Life cycle	Retrofit
Problem scale	Plant (Unit process) [2)]
Enhanced target-setting	
Business mgm. aspect applied	X
Design and evaluation criteria	
Multi-criteria decision-making	-
Hierarchy of criteria	-
Criteria interdependencies	-
Process operability	-
Process availability	-
Process integration methods	
Method discussed / applied	-
Potential for improvement	
Idea discussed / applied	-

[2)] Primarily a plant scale study, secondarily a unit process scale study

2.6.2 Research objective

The purpose of the case study was to evaluate the availability and applicability of the business management material proposed for use in Chapter 8 of the thesis. The material for the study was obtained from a mill producing over 2 million tons of steel per annum. The company was preparing a large process modification.

2.6.3 The case study and results

The material available for the study is as follows (Table A5):

Table A5. Material available in the case study.

Chapter 8 elements	Material available in the case company:
Company's analysis information	'Business Analysis'. Contains a macro-environment, industry environment and resource analysis. Only the macro-environment analysis was studied.
Company's performance controls	A Balanced Scorecard system.

a) The Business Analysis

The Business Analysis included a macro-environment analysis, industry environment and resource analysis. The macro-environment analysis consisted of observations of global trends, such as: "market is globalizing", "market is expanding", "climate change is going on", "peoples' environmental consciousness is increasing" etc. The company had refined most of the observations into conclusions, and a few of them, further into an action plan. An action plan was typically a recommendation to make a more detailed study about the particular subject.

The obtained data was found to be on too general a level to be used in process development, and needed refining. The work was done in co-operation with company strategists.

Firstly, the list of observations was completed into conclusions. Then some of the conclusions were converted into a technical indicator and its target value, e.g. a target product quality or a target emission level. Some of the conclusions were converted into a trend analysis. Those included, for example, a scenario for a raw material price. The remaining ones were difficult to convert into numeric form. Still, they raised issues that were seen as important from the technology development point of view (see Table A6).

Table A6. Example of scenario analysis material data refining.

Observation	**Conclusion**	**(Recommendation)**	**Indicator and its target value**
Markets are globalizing	New competitive elements from new areas	Process performance must be upgraded to correspond to new challenges	List of foreseeable requirements.

The study indicates that a way to treat the Business Analysis material is to convert it into conclusions and further into technical indicators and their target values, into a trend analysis or into a list of foreseeable requirements.

b) Balanced Scorecard System

In the Balanced Scorecard System (BSC), firms use the criteria to control their standing relative to the scorecard’s four perspective, which are financial, customers, internal business processes, and learning and growth. Three independent Balanced Scorecard Systems existed in the company: process-BSC, production-BSC and company-BSC:

- **Process-BSC** covered the main production line at the site. It included only technical indicators such as time-efficiency, yield, production amount, raw materials consumption and quality. The indicators were allocated to unit processes.

- **Production-BSC** covered the main production line at the site and two other processing lines at another site. It included the same technical indicators as the process-BSC, but the balance boundary for the controlling was larger. In addition, it included overall production cost data (e.g. production cost per ton of product, value of intermediate storages) and customer reclamation data.

- **Company-BSC** covered the main production line at the site and all the other processing lines at another sites. It included only a few of the technical indicators. Instead, it concentrated on economic indicators (e.g. ROI) and customer satisfaction indicators (e.g. delivery accuracy, follow-up on products sold).

To summarize, the process-BSC dealt with unit process performance in relation to technical aspects such as raw materials, production quantity and quality, and time-efficiency. The company-BSC dealt with financial performance and customer satisfaction, and less technology. Learning and growth (the fourth dimension of the Balanced Scorecard) was emphasized on none of the levels.

2.6.4 Conclusions

From the perspective of this thesis, the following can be summarized:

The case company had three hierarchical Balanced Scorecard performance controlling levels. The performance controlling on the low hierarchical level emphasized technical functioning of unit operations, whereas the highest hierarchical level emphasized technology, economy and customer relations. Process design and evaluation dealt with similar criteria and indicators but from an engineering perspective. This was seen e.g. in Case 2 dealing with energy efficiency, Case 3 dealing with paper machine operating efficiency, Case 4 dealing with material and energy efficiency and Case 5 dealing with emissions and fuel efficiency.

The case study indicates that both of the analyses can be considered as a new type of information for engineers, currently lacking from practices. The material is useful as it is refined into a more appropriate form: into new indicators and their target values, into a trend analysis and into a list of foreseeable requirements. The material adds to our understanding of the causes and effects of identified changes in the operating environment.

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