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# Energy and Production Planning for Process Industry Supply Chains

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*“Everyone of us begins life with an open mind, a driving curiosity, a sense of wonder.”*

Carl Sagan (1980)



## **Abstract**

This thesis addresses industrial energy issues from a production economic perspective. During the past decade, the energy issue has become more important, partly due to rising energy prices in general, but also from a political pressure on environmental awareness concerning the problems with climate change. As a large user of energy the industry sector is most likely responsible for a lot of these problems. Things need to change and are most likely to do so considering current and assumed future governmental regulations. Thus, the energy intensive process industries studied and focused on in this thesis exemplify the importance of introducing a strategic perspective on energy, an appropriate approach for planning, as well as the possibilities of including energy issues in a production and supply chain planning model.

The thesis aims to provide models, methods and decision support tools for energy related production and supply chain planning issues of relevance for process industries as well as for other energy intensive industries. The overall objectives are to analyze the strategic importance of energy management, production and supply chain planning, and the opportunities provided when energy is included in a production and supply chain planning model. Three different studies are carried out, analyzed, and presented as in this thesis.

The first study is a case study at a specialty chemicals company and resulted in the first paper. Since the energy issue is not only a cost issue driven by supply and demand, but also a political issue due to its environmental aspects, it is likely to believe that political influence and especially continuity will have escalating effect on the energy intensive process industry sector. Thus, the strategic dimension of energy is highly relevant in this thesis. The importance of organizational integration, having a main responsible person, locating core business, and political continuity are addressed as prerequisites for including energy into the corporate strategy. Regarding long term profitability, the importance of correctly utilizing the energy system by appropriate energy planning and with respect to energy efficiency and effectiveness in both flexibility and investment issues are addressed. Further on, the quest of finding alternative revenue while striving for a proper energy usage is addressed.

The second study is a multiple case study with four different case companies involved; pulp, specialty chemicals, specialty oils, as well as a pulp and paper company. The need for improved production and supply chain planning is also addressed where for instance the lack of planning support for process industries is still an area of improvement. The production and supply chain planning in process industries is found to be rather poor compared to regular manufacturing companies. The planning methods found are often tailor made and adapted to the individual characteristics that are typical for many process industries. It has further on been difficult to distinguish similarities and differences among process industries regarding these planning issues and thus hard to generalize.

The third study focuses on mathematical modelling and programming developing a combined supply chain and energy optimization model for a pulp company. Taking the first papers together there are reasons to believe that a planning and optimization model that take energy aspects in consideration, as a previously missing link, will contribute to improve

the operations in process industries. A clear impact of involving energy issues into the supply chain planning is shown. The results show that a different production schedule is optimal when the energy issues are applied, and depend on, for instance, variations in energy prices such as the one for electricity. This is shown by using a model for a supply chain where the energy flow, and especially the utilization of by-products, also is involved.

## Sammanfattning

Denna avhandling tar avstamp i produktionsekonomi och riktar ett särskilt fokus på industriella energifrågor. I takt med stigande energipriser och en alltjämt ökad politisk medvetenhet kring klimatförändringarna och dess problematik väcks frågan om energi i ett större sammanhang. En hållbar utveckling eftersträvas och ställer stora krav på förändringar, inte minst avseende energianvändningen och dess klimatpåverkan. Då industriell aktivitet står för en betydande del av energianvändningen bärs således en stor del av ansvaret av dessa aktörer. För att bibehålla god konkurrenskraft och samtidigt leva upp till olika myndighetskrav krävs därför ett nytt strategiskt förhållningssätt för många företag. Detta blir särskilt intressant för de energiintensiva processindustrier som studerats där inte bara ett strategiskt perspektiv för energifrågor utan även planeringsfrågor kommer upp till ytan. Därtill påvisas vilka möjligheter som finns med att inkludera energi i planeringsmodeller för produktionen och dess försörjningskedja.

Avhandlingen har som målsättning att lyfta fram modeller, metoder och beslutsstöd för främst den energiintensiva processindustrin. Därtill även att skapa medvetenhet om energi och dess betydelse, samt ge guidning i energi- och planeringsfrågor för olika beslutsfattare. Tanken är således att analysera den strategiska vikten av energiledning, produktions- och försörjningskedjeplanering, samt de möjligheter som uppstår då energiaspekter inkluderas i dessa planeringssammanhang. För detta ställs tre forskningsfrågor som analyseras i tre olika studier vilka sammanfattas i varsin artikel.

Den första artikeln utgår från en fallstudie av ett specialkemiföretag. Med hänsyn till energifrågan och dess klimatpåverkan är det rimligt att anta ett ökande politiskt tryck på energiintensiva företag där politiskt inflytande och framförallt politisk kontinuitet i frågan ses som allt viktigare. Vikten av organisatorisk integration, att ha en huvudansvarig, lokalisera kärnverksamhet och politisk kontinuitet belyses som förutsättningar för att involvera energi i affärsstrategiska sammanhang. För att ytterligare uppnå långsiktig lönsamhet belyses vikten av att korrekt utnyttja sitt energisystem. Detta genom lämplig planering och att arbeta med energieffektiviseringar i anslutning till både flexibilitets- och investeringsfrågor. Dessutom belyses potentialen för alternativ avsättning och vikten av lämplig energianvändning avseende dess kvalitet eller så kallad exergi.

Den andra artikeln utgår från en multipel fallstudie med fyra olika företag involverade; pappersmassa, specialkemi, specialoljor, samt ett pappers- och massaföretag. Vikten av bättre planering för produktion och dess försörjningskedja belyses där exempelvis bristen på systemstöd för planering i processindustri fortfarande är ett stort problem. I jämförelse med vanlig tillverkningsindustri är produktions- och försörjningskedjeplaneringen i processindustrier generellt något eftersatt. De planeringsmodeller och verktyg som ändock finns och används är oftast skräddarsydda, vilket styrker bilden av att processindustrier är väldigt olika sinsemellan med individuell karakteristik. Det har i den andra artikeln dock varit svårt att urskilja generella likheter och skillnader mellan hur de olika processindustrierna planerar sin produktion och försörjningskedja, och således också svårt att dra generella slutsatser i det avseendet.

I den tredje artikeln ligger fokus på matematisk modellering och linjärprogrammering för produktionen och försörjningskedjan i ett massaföretag. Genom att kombinera de två föregående artiklarna finns det goda skäl att inkludera energiaspekter i planering och optimering av produktionen och dess försörjningskedja. På så sätt knyts områdena samman och den länk som tidigare saknats i sammanhanget byggs upp. I den tredje artikeln påvisas flertalet fördelar med att involvera energiaspekter i produktions- och försörjningskedjeplaneringen. Resultatet avslöjar en annorlunda produktionsplan när energiaspekterna involveras och beror av till exempel variationer i energipriser såsom elpriser. Detta visas via en modell där energiflödet samt speciellt även utnyttjandet av biprodukter inkluderas vid sidan av flödet för huvudprodukterna.

## **Foreword**

I have gone through many phases while working on this thesis and experienced many different moods of emotions. This period of time has involved everything from frustrations to excitements depending on the situation at the moment. I have learned and found out more things than I expected to, yet realize that I just opened the door to the world of knowledge.

During the research I have communicated with many people who have helped me in one way or another. First I want to direct a special thank to my supervisors Martin Rudberg and Helene Lidestam who have supported me through working with this thesis and also as co-authors in the first and third papers presented. I would also like to thank Joakim Wikner for going through the thesis and helping to increase the quality. In addition, I would like to thank my colleagues at the Division of Production Economics at Linköping University for keeping a good spirit at work, especially Johan Johansson and Martin Kylinger who not only provided support in plenty discussions but also co-authored the second paper. Further on, I would like to thank Patrik Thollander and Magnus Karlsson and my other colleagues at the Division of Energy System at Linköping University for many discussions regarding the complexities of energy. I would also like to thank all the personnel among the companies involved for taking your time and willingness to provide the information and insights that has helped building this thesis.

Finally, I would like to thank my closest friends, family and beloved fiancée for supporting me when needed the most. Thank you for keeping fate in me and helping me to become who I am today.



## Thesis outline

This publication entitled *Energy and Production Planning for Process Industry Supply Chains* is a licentiate thesis in Production Economics at Linköping University. The thesis consists of two parts; first an introductory and summary part, and second a collection of three papers. The first part introduces the topic, overall purpose and research questions, discusses the literature, and summarizes the papers. Moreover it analyses the research in relation to the literature, presented papers and formulated research questions in order to locate the essence of the research done and its contribution. Some further research ideas are also proposed. The second part comprises the papers listed below, where the origin and the current state of publication is noted.

### Paper 1

Rudberg, M., Waldemarsson, M. and Lidestam, H. (2012) "Strategic Perspectives on Energy Management: A Case Study in the Process Industry", *Applied Energy*, revised for the second review.

An earlier version of this paper was presented at EurOMA 2010:

Waldemarsson, M., Rudberg, M. and Lidestam, H. (2010) "Energy management in process industries: current practices and future challenges", *Proceedings of the EurOMA 2010 Conference*, held 6<sup>th</sup> - 9<sup>th</sup> June 2010 in Porto, Portugal.

### Paper 2

Johansson, J., Kylinger, M. and Waldemarsson, M. (2012) "Production planning in process industries", *Working Paper: LIU-IEI-WP-12/0002*, Department of Management and Engineering, Linköping University, Linköping, Sweden.

An earlier version of this paper was presented at NOFOMA 2011:

Johansson, J., Kylinger, M. and Waldemarsson, M. (2011) "Production planning in process industries", *Presented at the NOFOMA 2011 Conference*, held 9<sup>th</sup> - 10<sup>th</sup> June 2011 in Harstad, Norway.

### Paper 3

Waldemarsson, M., Lidestam, H. and Rudberg, M. (2012a) "Including energy in supply chain planning at a pulp company", *Applied Energy*, in review.

An earlier version of this paper was presented at ICAE 2012:

Waldemarsson, M., Lidestam, H. and Rudberg, M. (2012b) "Including energy in supply chain planning at a pulp company", *Proceedings of the Fourth International Conference on Applied Energy (ICAE2012)*, held 5<sup>th</sup> - 8<sup>th</sup> July 2012 in Suzhou, China.

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Papers

- Paper 1. Strategic Perspectives on Energy Management: A Case Study in the Process Industry
- Paper 2. Production planning in process industries
- Paper 3. Including energy in supply chain planning at a pulp company



# 1 Introduction

The very foundations of a company are to deliver value to its owners in terms of growth and profit. Some of the key ingredients for most industries are capital, workforce, resources and energy, carefully used in a wisely chosen mix in order to be successful. Process industries tend to be both capital and energy intensive besides involving a lot of resources. However, today the corporate energy system is very often seen as a support function and not included in the production and supply chain planning. The view on energy from only the cost side is not always beneficial, especially when an energy surplus can be extracted to create additional revenue. It is therefore of interest to analyze how energy issues are viewed upon in process industries and how they can be included in production and supply chain planning.

## 1.1 Background

By definition, output of work from a system can be measured in the amount of energy. Today, the yearly use of energy worldwide stands for some 140 PWh (EIA, 2010). To understand the magnitude of this energy usage it is, in a way, comparable to a world where every human being would have ten horses, each working 8 hours per day all year around, and pay much less than a US dollar per horse and day. As a comparison, the energy each and one of use is enough to lift 2 metric tons per hour to the top of Empire State Building. In reality, the consumption of this workforce is however not evenly distributed; in fact more than 2 billion people lack of sufficient energy supply (Cai et al., 2009). The main sources of energy used today are furthermore expected to be depleted in a not too distant future (Hammond, 2007; Aleklett et al., 2010). Another escalating problematic issue regarding our energy system is the anthropogenic climate change due to emissions of greenhouse gases mostly originating from the use of fossil fuels (e.g. Plass, 1956; Mann et al., 1998; Friedlingstein et al., 2010) as well as the costs issue of the supposed consequences (Stern, 2008). Solving these problems is to be a tremendous task requiring not only new and more efficient technologies but also new managerial methods, no matter if we run out of the current energy sources or not. After all, we didn't leave the Stone Age because we ran out of stones, as the old expression say.

Nevertheless, from an industrial perspective, production economics and cost-issues are still among the main drivers for changing the way of doing things, where the energy costs of course are essential. Since the industry sector stands for a major part of the use of energy in our energy system (Thollander et al., 2007), one could argue that there should be plenty of motivation for improvements due to the cost side of energy, at least from a strategic and tactical perspective. That seems however not to always be the case today, although there most likely are benefits to achieve by planning differently. Energy is furthermore already a highly ranked issue regarding, for instance, planning systems (Özdamar and Birbil, 1999), designing energy efficient production systems (Wolters et al., 1995), cost optimization (Harris et al., 2011), energy intensive industries (Thollander and Ottosson, 2010) as well as within process industries (Bakhrankova, 2010; Bloemhof-Ruwaard et al., 1996) and their

possibilities to extract an energy surplus and to make it available to the surrounding community (Klugman, et al., 2007; Grunow and Günther, 2008). How to work with energy management and planning related questions in energy intensive process industries is thus an essential question.

Beside the complications around the energy intensity in process industries there are other issues regarding the level of resources and capital intensity. Thus, production planning in process industries tends to be capacity orientated (Taylor et al., 1981a) and addressed as a key module in many process industries (Taylor et al., 1981b), yet somehow neglected in a general sense due to lack of literature and software for capacity oriented scheduling methods (Taylor et al., 1981a). More recently, Ashayeri et al. (2006) concluded that this seemed to be true and argues that the existing planning software did not fit process industries very well. There are however some, more or less tailor made, examples or suggestions for system support given in the literature such as those presented by Bakhrankova (2010) and Grunow and Günther (2008) among others. On the other hand, Kallrath (2002b, p. 219) argues that *“there has been a tremendous progress in planning and scheduling in the process industry during the last 20 years”* although he further confirm the lack of suitable commercial software for process industries. The pursuit for improved production planning with respect to process industry conditions thus remains vital.

For the process industries, that normally use a relatively large amount of energy (Özdamar and Birbil, 1999), the energy issues are, as previously mentioned, very essential from at least a planning perspective. Even though some process industries are not that dependent on external supply of energy, since energy often becomes a by-product when the incoming raw materials are transformed into the main products, effective and profitable use of energy is still an important and strategic issue. Bloemhof-Ruwaard et al., (1996) underline, for example, the importance of combining recycling, cleaner pulp production and energy recovery in the pulp and paper industry. That some process industries are forced to reduce, or even stop, their production in times of high electricity prices (Affärsvärlden, 2010), further highlights the strategic dimension of effective energy planning. The issue of including energy in the supply chain planning seem thus to be promising.

## **1.2 Scope and Purpose**

The core of this thesis can be narrowed down to include energy management issues in production and supply chain planning among energy intensive process industries. Thus, the scope of the studies done in this research relies on three main topic areas: energy management, supply chain planning, and merging energy and supply chain planning. As such,

*the purpose of this thesis is to investigate the most important energy management issues as well as to map the current state of art regarding production and supply chain planning in process industries, in order to integrate them into a common model for strategic and tactical planning, and thereby show the possible impact on profitability.*

Besides to contribute in terms of models, methods and decision support systems, the thesis also aims to provide guidance and bring further awareness of energy and planning issues that can be useful for decision-making among process industries as well as for other energy intensive industries.

### **1.3 Research Questions**

To fulfil the purpose previously stated, the overall objectives are to analyze the strategic importance of energy management, production and supply chain planning, and the opportunities provided when energy is included in a production and supply chain planning model. These objectives are moreover formulated in three research questions which are presented below and analyzed through three different studies.

Regarding the energy management part, there are beside the energy system perspective also environmental obligations and risks as well as government regulations to consider. More specifically the first part of the research therefore aims at analyzing the possible outcome of the following research question:

*RQ 1. How do process industries strategically work with energy management issues to ensure long term profitability?*

Since most of the literature found on production planning in process industries is rather old and since there are indications on progress in the area, the second part of the research furthermore aims at analyzing the outcome of the following research question:

*RQ 2. How do process industries typically perform production and supply chain planning?*

Finally, while taking the results from the previously two research questions into consideration, the last part of the research in this thesis aims at answering the third research question:

*RQ 3. How can process industries improve their planning by including energy related issues in their production and supply chain planning?*

Whereas the first two research questions aim at mapping and analyzing energy (RQ 1) and production planning (RQ 2), the third focuses on their integration (RQ 3). The common set that binds all three questions together can thus be summarized in energy management, supply chain planning, and merged energy and supply chain planning for process industries.

The remaining part of the thesis begins with a methodology chapter describing the research process and the research design. This is followed by a frame of reference discussing the literature related to this research. Three individual papers have been written, one for each respective research question. These three papers are presented and summarized in chapter 4 together with the results of the thesis and some concluding remarks. Finally some further research ideas are discussed. The three research papers are attached at the end.



## 2 Methodology

In this chapter the research methodology is presented in terms of a research design and the research process from both a holistic perspective as well as more in detail for each paper. Validity and reliability regarding the results are furthermore discussed.

### 2.1 Research Design

The research design is based on the three research questions presented in section 1.3. Each question lays the foundation for each paper as previously mentioned. The general design aimed at putting the first two questions together in order to answer the third one, as illustrated in Figure 1. In this way the first two studies each build up an area around its topic that moreover is merged in the third study.

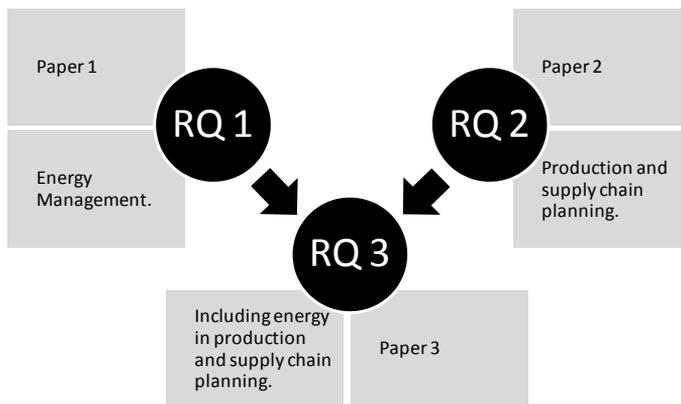


Figure 1. Research Design.

The first paper is based on a case study at Perstorp which is a specialty chemicals company. The second paper is based on a multiple case study at Södra Cell, which is a pulp company, Korsnäs, which is a pulp and paper company, Nynas, which belongs to the specialty oils segment, and Perstorp. The third paper has a mathematical modelling approach to a supply chain problem at Södra Cell.

The design chosen for conducting the case studies for the first and second paper has been based on Yin (2009). The use of case studies is very common in the field of operations management and addressed as one of its most powerful research methods (Voss et al., 2002). Yin (2009) also suggests a process when working with case studies: *Plan* (1), *Design* (2), *Prepare* (3), *Collect* (4), *Analyze* (5), and *Share* (6). These steps are in general followed throughout the first two papers, although there have been some iterations with going back and forth between steps to refine the studies. When typical questions like *how* and *why* is asked the choice of case studies is suitable (Yin, 2009). Since this is the case for the research questions it thus motivates the chosen design for the first two papers. Case studies are also a quick way to get started and a good way to make up a picture of the scope, limitations and system boundaries of the research project. According to Yin (2009) a case study can be

defined as an empirical investigation that analyses a present phenomenon in its real context, especially when the boundaries of the problem are diffuse. The case study investigation is moreover able to handle complex technical situations where often more variables than data are of interest. It also depends on multiple sources of information, which further on is useful to triangulate data in order to validate results. In his two fold definition Yin (2009) shows how case studies cover a logical design, techniques for data collection, and specific approaches for analyzing data. Eisenhardt (1989) argues in addition that it is easy to be overwhelmed by all the data unless focus is on the core of the research. These are aspects that have been considered in *planning* for the first two papers.

When *designing* the case studies the unit of analysis has been defined along with formulation of case study questions and scanning of the literature in order to achieve a theoretical framework. The design is identified to be holistic for both the single and the multiple case studies performed. According to Yin (2009) the design should provide a logical connection between gathered data and the conclusions drawn from the analysis of them, and the initial case study questions. These aspects have been in the authors mind while designing each study. The authors have also aimed at constructing validity by using multiple sources, chains of evidence and verifications by key informants. Internal validity has been achieved by pattern matching and explanation building. External validity is achieved by using theory in the single case study, and by repeating the logical structure in the multiple case study. By using a case study protocol and development of a case study database the reliability of the case studies has been secured (Yin, 2009).

*Preparations* before *data collection* have been done in order to ensure the quality of the research. In the *data gathering* process the case study protocol has laid the fundamental agenda. The *analyze* step is mainly done throughout the composing part of each paper whereas the last part, *share*, is done for both company personnel and researchers at scientific conferences as well as future publications in scientific journals. These aspects are moreover discussed for each paper in the research process section below.

Whereas the first two papers are qualitative in their methodological design, the third paper can in general be seen from a quantitative modelling approach (e.g. Bertrand and Fransoo, 2002). As such, a set of variables varies over a specific domain, with quantitative and casual relationships defined in-between. Mitroff et al. (1974) present a framework for quantitative research and argue that system science is not a science itself but a holistic point of view on sciences and enlighten that certain aspects of science can only be studied from a holistic system point of view. In their framework, there are four different dimensions that can be included and six different processes. The dimensions are the reality with the problem situation (I), the conceptual model (II), the scientific model (III) and the solution (IV), whereas the processes in-between are 1) Conceptualization [I-II], 2) Modelling [II-III], 3) Model Solving [III-IV], 4) Implementation [I-IV], 5) Feedback [II-IV], and 6) Validation [I-III] (Mitroff et al., 1974). The third paper, involving conceptualization, modelling, and model

solving, can be seen to be empirical and normative (Bertrand and Fransoo, 2002) in its approach although the implementation phase is yet left ahead.

## **2.2 Research Process**

Literature studies have taken place more or less continuously during the entire research process in order to reflect the essence of each research question in a larger context. The process for each paper is presented more in detail below.

### **2.2.1 Paper 1**

The first research question aims at achieving an overview of the energy issue in the process industries from a managerial point of view. This is carried out through the first paper based on a case study that follows an explorative nature in line with Yin (2009). The case company is a specialty chemical process industry where data has been gathered through semi structured interviews among personnel working with operational, tactical and strategic issues regarding energy management. As such, multiple sources of data have been used in order to be able to achieve valid results from triangulation. The data gathering process follows in general the guideline of the composed case study protocol and data was later verified by the personnel. The case study database as well as the case study protocol was further of good help to ensure the reliability of the study (Yin, 2009). The study leading to this paper has also provided the author of this thesis with plenty of insight in the field of industrial energy issues.

### **2.2.2 Paper 2**

The second research question aims at achieving an overview of the production and supply chain planning procedure among process industries. This is carried out by the second paper based on a multiple case study that followed a descriptive procedure (Yin, 2009). The case companies are within the segment of pulp, pulp and paper, specialty chemicals and specialty oils. Data was gathered through several semi structured interviews among personnel holding key positions for production planning and supply chain planning at the companies. Besides the use of multiple sources and triangulation, validity was also achieved by crosschecking the data with the personnel, and reliability was ensured through a case study protocol and a case study database. The documentation is further constructed to support a chain of evidence for each assumption and conclusion (Yin, 2009). This paper has given the author of this thesis a broader understanding of how production and supply chain planning is performed at the case companies. This has been very useful moreover in the conceptualization part of Paper 3.

### **2.2.3 Paper 3**

The third research question aims at synchronizing the relevant energy issues with the supply chain planning. This is carried out through the third paper that, in a way, puts the first two papers together in a common context. In line with Mitroff et al. (1974) a real problem situation has been conceptualized and modelled into a scientific mathematical model. Thus, a mixed integer linear programming (MILP) model has been built for involving energy in the

supply chain planning at a pulp company. The model is partly based on a previous model for the same company and adjusted for the energy issue purpose. The supply chain data origins from the previous model and additional data for energy is gathered from process engineers and managers at the company sites. This paper has given the author insights in how to include energy parameters and variables in a supply chain model and how to connect them with the moreover common production and product parameters and variables. As such, a good foundation for further research has been achieved.

### **2.3 Author's Statement**

The research is performed within the Process Industry Centre (PIC) supported by the Swedish Foundation for Strategic Research (SSF). PIC is divided into PIC-Lu at Lund University and PIC-Li at Linköping University, each collaborating with several process industries. The author of this thesis is a PhD student within PIC-Li and has performed studies at most of the member companies. The content in this thesis is however mainly based on studies at four of them; Södra Cell, Perstorp, Korsnäs, and Nynas.

The first study was made together with the primary and secondary supervisors, whereas the author of this thesis had a major responsibility in conducting the case study and presenting its earlier version of the paper on the EurOMA conference in Porto 2010 (Waldemarsson et al., 2010). The primary supervisor took thereafter the overall responsibility of finalizing the conference paper for further publication (Rudberg et al., 2012), hereafter referred to as Paper 1.

The second study was made together with two PhD student colleagues within PIC-Li, where each author took equal responsibility in performing the study, although the paper (Johansson et al., 2011) was presented on the NOFOMA conference in Harstad 2011 by the author of this thesis. The paper has thereafter gone through some minor changes and is at current state a Working Paper (Johansson et al., 2012), hereafter referred to as Paper 2.

For the third paper the author of this thesis has had a major role in both the conceptualization and the mathematical modelling part as well as in writing the paper. The third study had a starting point in a model previously developed by the secondary supervisor (Gunnarsson et al., 2007; Gunnarsson and Rönnqvist, 2008). Thus, the secondary supervisor has been involved in the modelling and writing, whereas the primary supervisor contributed to overview discussions and writing. The third paper (Waldemarsson et al., 2012b) was presented at the ICAE conference in Suzhou 2012 and was moreover selected for submission to conference special issue in Applied Energy. Some minor changes has thus been made, and the paper (Waldemarsson et al., 2012a) is hereafter referred to as Paper 3.

### 3 Frame of Reference

The layout of the frame of reference is as presented in Figure 2 below. As a base, the field of process industries consists of two parts and will be discussed in section 3.1. This is an essential part of the thesis due to its focus on process industries regarding energy and planning issues. The importance of energy issues is discussed more in general, in section 3.2, mainly from a managerial point of view along with addressing some of its fundamental constraints and how those affect the industry. Some literature guiding production and supply chain planning and optimization is generally discussed in section 3.3. At the top, the problem of integrating energy with production and supply chain planning and optimization is reviewed and discussed in section 3.4.

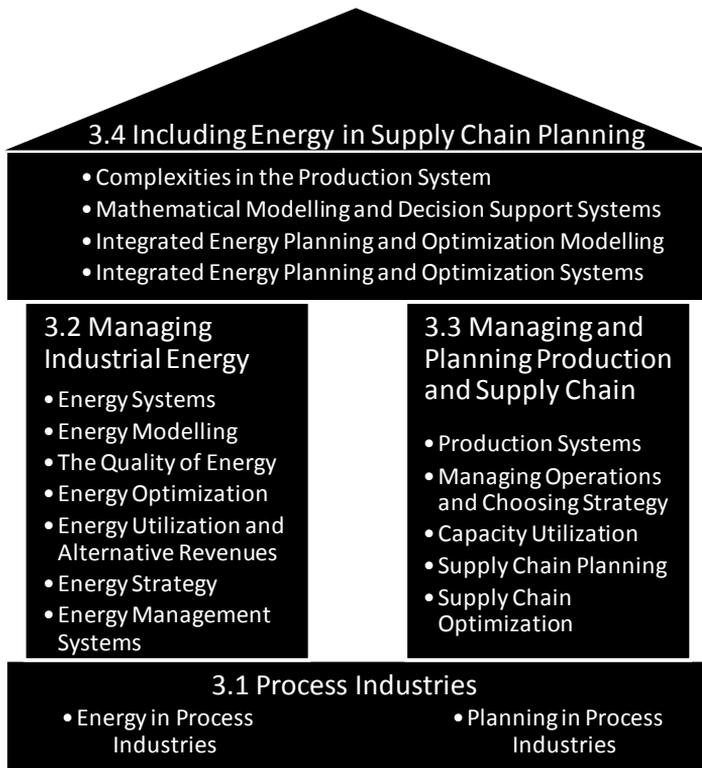


Figure 2. Frame of reference design.

#### 3.1 Process Industries

The concept of process industry is not well-defined in the literature according to Grunow and Günther (2008), yet process manufacturing can be defined as (APICS, 2008, p. 104): *Production which adds value by mixing, separating, forming, and/or chemical reactions.* Process industries are in general classified as basic converters, often positioned early in the value chain (Finch and Cox, 1987; King, 2009). Most of the products made in process industries become discrete first during packaging and can be characterized into powders,

liquids and gases. These are typically produced in processes such as pipeline, chemical, refining, food processing or metal processes following a batch or continuous mode (APICS, 2008). The industry is in general capital intensive with relatively high costs for transportation along the supply chain (Taylor et al., 1981a), partly due to that products have a low value to weight ratio (Fransoo and Rutten, 1994). Production is in general flow orientated (Taylor et al., 1981a) with layout characteristics that in general fit quite well into the lower right corner in the product-process matrix presented by Hayes and Wheelwright (1979a; 1979b). Important decisions often involve issues within the choice of flexibility; concerning problematic issues on how to deal with product diversity and equipment dedication as well as how to maintain responsiveness to rush orders when enforcing scheduling sequences (Taylor et al., 1981a). Flexibility is achieved in two ways, *volume* flexibility by increasing/decreasing throughput or *mix* flexibility by dividing capacity between different products (Fransoo, 1992), where *volume* flexibility in general is difficult to achieve (Fransoo and Rutten, 1994). This goes hand in hand with the fact that process industries most often are lagging in terms of capacity due to the objective of maintaining a high utilization of resources (Olhager et al., 2001), and also is in line with APICS (2008, p. 104) definition of process flow production: “*a production approach with minimal interruptions in the actual processing in any one production run or between production runs of similar products*”.

There are many variations between different process industries and the field of process industries might be too large to more precisely define, in line with Grunow’s and Günther’s (2008) statement. The above mentioned definition and description of what is typical for process industries is however considered good enough to understand the complications around process industries discussed in this thesis.

### **3.1.1 Energy in Process Industries**

Process industries are not only capital intensive but also very often energy intensive with energy costs around 10-20% of the total costs (Thollander and Ottosson, 2010). Stratton (1979) addresses the difference in added value in relation to the amount of energy usage for different types of products where typical process industry products such as cement, energy (refinery), iron and steel top the list of energy usage per added value. Many studies on energy intensive industries such as for example the pulp and paper industry (Bloemhof-Ruwaard et al., 1996) and the chemical industry (Grau et al., 1996) can be found in the literature.

Besides cost, value and usage issues there are also other closely connected aspects to consider. For instance, because of the energy intensity in process industries, Taylor et al. (1981a) address the importance of long range energy plans and to ensure waste products within the limits of environmental laws. Kalenoja et al. (2011) moreover argue that supply chain decisions can have significant impact on the use of energy even in energy intensive heavy-industry where generally the production phase is dominant. There are thus plenty of planning and decision issues regarding energy. In further contrast to the very common cost

perspective on energy, many process industries can also extract an energy surplus from by-products with high energy content. This can be used to create additional revenue in terms of selling electricity, steam or heat to for instance the surrounding community within a regional cooperation (Klugman et al., 2007). Taylor et al. (1981a) however note that these by-products are produced in proportion to given conditions such as chemical and natural characteristics where an uneven demand can lead to large inventories of one product or limited production of the other. They also emphasize the issue of optimizing product blends in process industries, where linear programming is useful and common. This will altogether broaden the dimension of planning and decision issues even further.

### **3.1.2 Planning in Process Industries**

Planning issues in process industries are often capacity oriented and centred on a Make-To-Stock (MTS) strategy where undifferentiated products are considered (Fransoo and Rutten, 1994). There are however often difficulties to distinguish between different process industries regarding material or capacity dominance, time phased or rate based, or even the choice of MTS or Make-to-Order (MTO) and Assemble-to-Order (ATO) (Dennis and Meredith, 2000). Capacity can be limited by different bottlenecks and when choosing between capacity and material focus, process industries tend to first schedule capacity and then materials in order to achieve the capacity utilization according to plan (Taylor et al., 1981a). Moreover, Taylor et al. (1981a) point out that production plans for process industries must account for that raw materials have natural variations in quality, as previously mentioned, and that there are vast variations in the bill of materials among the different ingredients. Interchangeable products up to a specific stage in the manufacturing process, and limited availability as well as varying prices of seasonal raw materials (Mallya et al., 2001), further complicates the planning procedure for process industries.

Taylor et al. (1981a) also point out two strategies for reducing inventory: setting a rate equal to demand or running for full capacity and, as preferred regarding energy costs, periodically shut down. They furthermore enlighten some risks concerning location, plant capacity and transportation issues that are of extraordinary importance for process industries, especially from a supply chain perspective. Thus, since process industries are very different from other industries (Taylor et al., 1981a), the special capacity domination, energy intensity, and for instance raw material complexities will in other words have a larger impact on planning in process industries than in other manufacturing industries.

In a framework developed by Taylor et al. (1981b) for process industries, production and inventory planning is closely connected to Master Production Scheduling (MPS), Intermediate level Forecasting, and Resource Requirements Planning (RRP) where workforce, raw material, energy and information are essential. They address production planning (see section 3.3.4 for description) as a key module in many process industries, involving many key operating and resource utilization decisions. Due to its key aspects, Taylor et al. (1981b) also list some questions of importance when designing a production

planning module, reflecting: how to allocate production among multiple plants, what strategy to use in order to meet seasonal demand, if the sales mix of finished products can be optimized as well as if requirements for major raw materials should be planned directly from the production plan. Ashayeri et al. (2006) more recently argue that there, for typical process industries, are generally benefits with tailor-made cyclic planning and that this is of special importance regarding recycling flows. Even though the occurrence of recycling flows is very common in the energy intensive process industry, the importance of a correct value stream mapping and elimination of waste, as it also occur from a Lean-philosophy point of view (e.g. King, 2009; Shah and Ward, 2003), is still most essential and will be discussed moreover in this thesis.

### **3.2 Managing Industrial Energy**

Thirty-five years ago O'Callaghan and Probert (1977, p. 128) presented a definition of Energy Management:

*“Energy management applies to resources as well as to the supply, conversion and utilisation of energy. Essentially it involves monitoring, measuring, recording, analysing, critically examining, controlling and redirecting energy and material flows through systems so that least power is expended to achieve worthwhile aims. A mixture of accurate record-keeping, inspired forecasting and persuasive communication is needed.”*

O'Callaghan and Probert (1977) also explain the concepts of energy management through a flow chart of typical activities where the *objective to be satisfied* is on top. They address the importance of for instance *alternative energy sources, taxation incentives, national and international policies* and *material resources availability and alternatives*, which also are important in this thesis. However, even though their definition is broad and that they mention the “*least power*” perspective they still lack of a more in-depth discussion of energy quality, efficiency and effectiveness and its economic side (see for instance section 3.2.3). Later on Capehart et al. (2003, p. 1) define energy management as “*the judicious and effective use of energy to maximize profits (minimize costs) and enhance competitive positions*”. Bunse et al. (2011) focus more on the energy utilization and improvement activities for energy efficiency in their definition of energy management in production and address the importance involving cost, flexibility, delivery time, and quality. The goal of energy management can moreover be argued to ensure a “*high efficiency of the energy system in the light of the sustainable development of companies*” (Lampret et al., 2007, p. 783). Thus, in order to secure long term profitability, Energy Management should be included in all operational, tactical, and strategic decision-making processes that involve or affect operations or businesses regarding energy use, efficiency and/or effectiveness. As such, management will not only focus on cost, flexibility, delivery time and/or quality but also on a sustainable development of the total production system and its corresponding energy system.

### **3.2.1 Energy Systems**

The capacity of a physical system to perform work is measured in the amount of accessible energy in the system. Energy exists in several forms such as thermal energy (heat), kinetic or mechanical energy, electromagnetic energy (energy radiation, e.g. light), potential energy, electrical energy (electricity), and nuclear energy. According to the laws of thermodynamics, energy can neither be created nor destroyed; therefore the total energy of a system remains constant, since energy use may result in transformation into one or more of the other forms and, as such, from a high quality form (low entropy) to lower quality form (high entropy). (e.g. Grubbström and Hultman, 1989; Hammond, 2007; Science Clarified, 2010)

From a global system perspective, energy originating from the lithosphere, such as fossil fuels, can be viewed as a capital resource whereas renewable energy sources can be seen as energy income (e.g. Hammond, 2007; also illustrated by Trenberth et al. 2009). Thus, our world is filled with complex systems affecting each other in different ways and the energy system is one of them (Stratton, 1979). Due to the complexity of different systems the concept of system boundaries is vital when studying an energy system (e.g. Kalenoja et al., 2011). For industrial cases these studies can be done in terms of for example energy auditing or energy system analysis. Some studies focus on a single machine while others include both the plant and the surrounding community (e.g. Klugman et al. 2007). Including environmental issues such as emissions of CO<sub>2</sub> and renewable energy has also become more useful (e.g. Marshman et al., 2010). Maintaining a holistic view on the energy system is however most vital in order to fully understand the consequences of each change, update or different procedure applied.

### **3.2.2 Energy Modelling**

Most energy system models are developed based on an energy balance approach describing a network of energy flows from various primary energy sources, through conversion and consumption in utilization processes or other end use demands. The history of energy modelling can be traced back to the 1960's when focus was mainly on one single energy form such as oil, gas or electricity and its supply and demand. After the energy crisis in 1973 a more rapid evolution of energy modelling took place. The concepts of energy system models developed due to the need of describing, for instance, the interfuel substitution related to changing energy prices or environmental considerations in the different sectors where energy is used. (Rath-Nagel and Voss, 1981)

According to Rath-Nagel and Voss (1981) there are in general three methodologies dominant in energy modelling: engineering process analysis, mathematical programming, and econometrics. Input-output methods, system dynamics approaches and game theories have also been of use. Most of the models from the 1970's are devoted to the area of energy-economy interaction in order to connect the energy sector with the rest of the economy in a larger scale (Rath-Nagel and Voss, 1981). Kopelman and Weaver (1978) give one example and discuss energy modelling as a tool for long range planning of energy supply and demand

in energy related industries from a general national or global point of view. Other examples such as the nonlinear programming models for energy policy analysis in the energy planning of a country given by Güven (1994), and the multi criteria decision aid approach on regional renewable energy problems given by Georgopoulou et al. (1997), and the input–output energy-economy planning model supporting decision making on national level discussed by Borges and Antunes (2003), can despite their wide scope give some ideas when modelling energy related industrial activities. When modelling energy systems there is thus plenty of information to reflect upon. The energy demand and supply by fuel, the fuel price and availability and its effect on cost of materials, capital and labour, future markets and eventual fuel or material substitutions are as such important to consider (Stratton, 1979).

### **3.2.3 The Quality of Energy**

In addition to the cost, demand and supply issues of energy there are also other factors of major concern while modelling and determining the characteristics and system boundaries of for instance an energy intensive production system. For example, it is of great importance to comply with scientific and physical laws such as the laws of thermodynamics. As previously stated, the first law of thermodynamics about energy conservation defines that the total input of energy is equal to the total output whereas the second law states that entering exergy level is larger than the exergy level on the output side (e.g. van Gool, 1987; Grubbström and Hultman, 1989; Wolters et al., 1995). Measuring energy is thus a difficult process if you want to be fair and square to its quality or exergy content that depends on factors such as temperature and pressure (Grubbström and Hultman, 1989). Hammond (2007) provides an overview of industrial energy analysis with respect to thermodynamics and sustainability and addresses the importance of exergy analysis in order to locate the exergetic improvement potential within an energy system. This potential can also be discussed together with the energy efficiency gap which according to Hammond (2007) can be as much as 80% of today's energy use with respect to the thermodynamic potential, yet still 50% with respect to the technological potential available today. Even though there is a lot of energy to save, solutions still needs to consider the costs of energy and show profitable return of investments. Therefore the managerial aspects of energy are also important.

Several other studies also enlighten the importance of valuing energy from its exergy content and mention terms like exergy cost (e.g. Rosen and Dincer, 2003; Lampret et al., 2007; Grubbström, 2007) as a transparent way of analysis. Lampret et al., (2007) further point out potential benefits with this more transparent way for calculating the costs for energy usage and measuring energy efficiency while performing cost optimization. Stratton (1979) also addresses the relationship between increase in entropy, energy usage, capital, and process rate related energy usage as an important area, especially for modelling the industrial sector.

### **3.2.4 Energy Optimization**

After developing a model with respect to the system perspective and the laws of thermodynamics the next step will naturally be to optimize the energy system. There are plenty of studies focusing on optimizing the energy flows and minimizing the costs. For instance, McMahan and Roach (1982) present a Site Energy Optimization model developed for the refineries of Exxon in the early 1980s. Ordorica-Garcia et al. (2008) more recently presented a model for energy optimization with the objective to minimize costs for energy supply and subject to CO<sub>2</sub>-emission constraints in the unconventional oil industry (tar sand). Even though some 10-30% of CO<sub>2</sub> reductions is possible for the latter one (closer to 10% while striving for the best cost reduction), their models should also be discussed from different system perspectives with wider boundaries. Marshman et al. (2010) moreover look at the optimization of the energy flows in a pulp and paper mill cogeneration facility. Bollapragada et al. (2011) furthermore show a cost minimization model implemented at General Electric with the purpose of supporting renewable energy investment decisions. An approach focusing at only the energy flows and/or its cost issues is despite its importance however only a part of the company and thus too narrow for the scope in this thesis. Gunnarsson et al. (2004) address, for instance, the increasing importance of bioenergy in a supply chain modelling situation, which is taking one step closer to the holistic perspective this thesis is striving for. This will be moreover discussed in section 3.4.

### **3.2.5 Energy Utilization and Alternative Revenues**

In order to utilize existing energy resources in an optimal way Arivalagan et al. (1995) address some decision problems that need to be considered. First, an ideal mix of generated steam as well as both purchased and cogenerated or condensed power need to be determined, and second, the supply pattern of purchased power needs to be analyzed through its effect on the long term energy planning.

When Stratton (1979) points out the link between user utility and economic cost through addressing the product value in relation to the value of utilized energy he also argues in favour of the importance of engineering data and feasible technological alternatives. This can in combination with appropriate thermodynamic design save both capital and energy, if profitable, as previously mentioned. For example, Wolters et al. (1995) show that, from an energy point of view, it is worthy to retrofit a plant or rebuild it with more respect to the laws of thermodynamics in the production unit operations and that it is possible to achieve an optimal production system by combining non-optimal production unit operations with each other's and elements of, in their case, the heat recovery system. The possibility of postponing energy use or supply by using the energy system in a more appropriate way with respect to total energy cost or environmental impact can also be promising (e.g. Tari and Söderström, 2002; Karlsson, 2011). Working with energy efficiency, in order to optimize the energy utilization, will thus free up a certain amount of energy that could be used later on for other purposes and possibly create additional revenues.

Furthermore, Carlsson et al. (2009) address the energy issue as an increasingly important competitive issue for most pulp and paper industries. Due to rising prices and governmental policies the use of bio-energy, especially that has its origin from by-products in such industrial sector, is expected to become even more important regarding, for instance, competitiveness on the heating market (Carlsson et al., 2009). The possibility to extract energy surplus from by-products can also generate additional revenue, either in terms of energy intensive products such as biofuels or as energy carriers such as electricity and heat.

### **3.2.6 Energy Strategy**

The strategic dimension of energy has shown to be of great importance (e.g. Lovins, 1976), especially in times of runaway energy prices as witnessed the recent years. As such, rising electricity prices is crucial for the energy intensive industry and considered to be one of the greatest threats to their long-term survival (Thollander et al., 2009). Another strategic issue discussed by Kopelman and Weaver (1978) is the concept of economic rent. They argue that owners of energy resources many times are unwilling to sell their resources at only the cost plus return of investment, especially regarding depleting sources and in times of rising prices while believing that the price tomorrow can excel today's value. Similar patterns could be discussed today and how it influences, or will affect, the energy intensive industry.

An energy strategy can be very simple, Marshman et al. (2010) argue in favour for selling electricity when the price is high, however more problematic to follow in practice due to difficulties in forecasting (Mitropoulos and Samouilidis, 1983). Marshman et al. (2010) consequently address the need for an energy optimization strategy including forecasting of electricity prices and the cogeneration complexity. Arivalagan et al. (1995) further on refer to the economically optimal energy-mix as an important decision problem for process industries. There are therefore several issues to consider in the strategic choices concerning energy.

Focus on resource utilization with the strategy of capacity lag and levelled production (Olhager et al., 2001) is preferable for a typical process industry. However, varying demand and price patterns of energy such as electricity would, in a way, require the opposite strategy, especially when electricity falls out as a revenue generating by-product. This illustrates one of the many complexities regarding energy utilization with respect to the overall corporate strategy and its long term planning issues.

### **3.2.7 Energy Management Systems**

In order to manage energy issues, as previously described, the use of Energy Management Systems (EMS) can be helpful and provide guidance and tools for a company while working with such issues. For instance, Cai et al. (2009) aim at identifying optimal strategies in the planning of energy management systems (EMS) and show the interactive relationships within an EMS as well as give an example of such system applied in a region of three cities. One can also argue, in line with Stratton (1979), that a corporate energy system is a part of a larger energy system. Stratton (1979) moreover presents a model that can be useable at any

level as an interactive tool. These levels where the model is usable could be industries, sectors, nations, groups of nations or even the world where the environment of one level is constituted in the higher level. Thus, considering issues outside your own energy system can be useful to broaden the impact of your own EMS and the usage of it.

### **3.3 Managing and Planning Production and Supply Chains**

A supply chain is according to APICS (2008, p. 134) the “*global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution, and cash*”. Supply Chain Management (SCM) can further on be described in many different ways. Stock and Boyer (2009) have reviewed the different definitions in literature and include reverse flows of material, value adding, maximizing profitability through efficiencies, and achieving customer satisfaction in their own definition. An overview of SCM can be found in Stadtler and Kilger (2008) that in addition give definitions and describe the structure of the supply chain. They address the foundation of SCM to involve for example logistics, operations research, purchasing and supply, but also enlighten the importance of advanced planning, process orientation and use of information and communication support in order to achieve the ultimate goal of SCM, namely competitiveness.

#### **3.3.1 Production Systems**

Whereas the energy system considers energy to be refined, transported and used in different ways along the supply chain, the production system has the task of converting raw materials into finished goods and products through different processes. Hayes and Wheelwright (1979b) divide these process structures into four categories: *Jumbled flow (job shop)*, *Disconnected line flow (batch)*, *Connected line flow (assembly line)* and *Continuous flow*. Hill and Hill (2009) further list five types of process types: *Project*, *Jobbing*, *Batch*, *Line* and *Continuous processing* whereas King (2009) categorizes the manufacturing processes into two groups; assembly manufacturing and process manufacturing. Both *continuous* and *batch production systems* can be distinguished in the process industry (Kallrath, 2002b). Regarding supply chain issues in general there is thus always a quest to adapt to its right type that matches the product produced. For process industries which mostly manufacture functional products there is consequently a direct match with an efficient supply chain focused on throughput, capacity utilization and cost minimizations (Fisher, 1997). The strategic choice of focus and matching production system will moreover be discussed in the next section.

#### **3.3.2 Managing Operations and Choosing Strategy**

In order to match the products produced with the processes used the product-process-matrix (Hayes and Wheelwright, 1979a; 1979b) is frequently mentioned along with the concepts of product profiling (Hill and Hill, 2009). In typical process industries with continuous flows, this matching of the market is done with standard product types with a narrow product range and large customer order sizes. There is preferably also a low rate of

new product introductions and the price is a typical order winner. It is generally of advantage to have a dedicated process technology, allow lower process flexibility, and produce large lot sizes with few setups. A relatively high cost per setup is consequently allowed, but low cost operations in average will hence fulfil the overall key operations task of most process industries (Hill, 2000). These concepts are very central in the field of Operations Management (OM) that can be defined as *“the design, operation, and improvement of the systems that create and deliver the firm’s primary products and services”* (Chase et al., 2007, p. 9). On the input side we have labour, capital, nature resources, constructions, machines, material and energy. And on the output side we have goods and services. In between there are transformations in the form of operations. APICS (2008) also include planning, scheduling and control of these transformations as important elements of Operations Management.

An increased competitive advantage can be gained in many ways and depend very much on the skills in managing the operations. When aiming to gain additional such advantages over competitors a company can determine a set of plans and policies and formulate a strategy. Doing so there are more issues than just low costs and high efficiencies as manufacturing key objectives to consider (Skinner, 1969). A successful manufacturing strategy strives for productivity, but should not be too narrow in its focus. Skinner (1969) also refers to strategy in the concept of competitive advantages. When for instance highly developed energy efficiency in relation to other companies is achieved it could thus be seen as competitive advantage. In the literature there are furthermore plenty of other descriptions and discussions around manufacturing strategy. Fine and Hax (1985) mention strategy as a method to secure long term sustainable advantage over competitors. Berry et al. (1995) discuss in addition strategy as the choice of investments and its influence on the capability to reach a chosen market. Mohanty and Deshmukh (1998) further mention green manufacturing as a new paradigm in the manufacturing strategy context. The direction is clear towards sustainability and Dangayach and Deshmukh (2001) also mention the importance of eco-efficiency and the fact that there have been only a few studies towards environmental issues in the field.

Even with a perfect strategy and good management guidelines, the task of reaching profitability, with a positive cash flow achieved through good enough margins on the activities, still remains vital. As such, value adding is done in change of time, place and/or shape of a product. Rudberg and Olhager (2003) argue that such value adding can be done in a value network, consisting of one or more organizations. Beside the different views and focuses on the value network from an Operations Management or Supply Chain Management perspective, Rudberg and Olhager (2003) also reflect on the globalization and its affect on the value network. To buy a product from the other side of the world is today very common, however less convenient when it comes to energy, especially in the form of heat due to the difficulties of its transportation. The value adding processes are also discussed by King (2009) who for instance reflect on how to achieve a perfect continuous

flow with minimized waste (see also Schonberger, 1986), particularly in process industries. Matching a global supply chain on the ordinary product side with an often more regional or local supply chain on the energy side consequently becomes extraordinary interesting, especially for energy intensive products.

### **3.3.3 Capacity Utilization**

From a manufacturing strategy point of view, capacity can be seen as a structural decision category that needs to be adjusted to the long term changes in demand (Buffa, 1984; Fine and Hax, 1985; Olhager et al., 2001). Thus, capacity utilization can from this angle be seen as a result of previous strategic decisions made within the strategic horizon and how well the forecasted need of capacity matches the current demand. A framework for capacity strategies in terms of lead, track or lag in combination with sales and operations planning strategies such as chase, mix or level is presented by Olhager et al. (2001). Process industries traditionally use a lag capacity strategy due to its capital intensive environment and a level planning strategy due to the most often lacking volume flexibility. A more agile planning and scheduling approach can however free up capacity for mix flexibility purposes, where for instance set up times are important. Due to the most often lagging capacity in process industries the bottle neck is therefore of extraordinary importance regarding management and planning of such equipment and facilities. These aspects are more frequently discussed in the Theory of Constraints (TOC) (see e.g. Jacobs et al., 2011). Too high capacity utilization can however result in runaway average flow times, as illustrated in the *“Throughput Delay Curve”* by Anupindi et al. (2012, p. 201).

As previously discussed there are several approaches to handle capacity utilization and its impact on the different types of flexibility. But there is also a connection between capacity and investments that often is needed in order to obtain additional flexibility, as well as to decrease supply risks, regarding for instance energy. Even though the investment is needed the task of convincing the decision-makers remains, and the importance of assumptions when evaluating different investment alternatives has been noted in the literature (e.g. Borgonovo and Peccati, 2006). But to be more accurate and to make a firm more obedient towards such investments, there is consequently an emergent need for reliable data and accurate cost and benefit analysis (e.g. Tang and Tomlin, 2008), indicating a need for suitable models.

An increased need of capacity and additional flexibility, as previously discussed, can thus be handled through investments, improved planning, or a combination of them both. Whereas flexibility is typically restrained by hard-wired production process characteristics, Van Wezel et al. (2006) also focus on the planning process and those organizational procedures that have a clear impact on flexibility. They address the issue of balancing efficient production with flexible performance and argue that planning events are not handled properly in this matter. Thus, better planning and communication with both the supply and demand side of energy may lead to a decreased need for flexibility in that matter. To exemplify, additional

oil used to increase the output of the energy supply side in peak periods may therefore no longer be necessary. Improved planning is consequently both a key for higher system efficiency in terms of capacity utilization within a tactical horizon, as well as a rather cost efficient alternative to investments for increased capacity.

### **3.3.4 Supply Chain Planning**

Planning is about setting goals and to determine how to utilize resources in order to accomplish these goals. Taylor et al. (1981b, p. 23) define the production planning objective to “*develop intermediate range operating plans in response to demand forecasts so as to optimize the utilization of resources*”. With respect to the previously given definition of a supply chain, supply chain planning can thus be described as “*the determination of a set of policies and procedures that govern the operation of a supply chain*” (APICS, 2008, p. 135). Beside policies for production, inventory and replenishment, the planning procedure also includes the determination of marketing channels, promotions, respective quantities and timing aspects. In this sense, planning as such set up the parameters for the supply chain and its operations (APICS, 2008). Kallrath (2002b) states that planning can either focus on strategic long term acquisition, consolidation, and capacity analysis or on short and mid-term sales and operations planning. Kallrath (2005) further argues that there often is a diffuse border line between operative and strategic planning and addresses that there are strong overlaps between strategic planning and the planning of production, distribution, or even supply chain management. Planning activities within Supply Chain Management can, according to Grunow and Günther (2008), also be decomposed into three hierarchical levels; strategic network design, supply network planning, and operational planning and scheduling.

As previously shown there are a lot of aspects to involve and consider when defining the concept of supply chain planning. This thesis also involves production planning and combines the holistic supply chain perspective with a more detailed production focus. This is mostly relevant in Paper 2 as well as in Paper 3 and its model for the analyzed pulp company. Supply chain planning for the pulp and paper industry is also discussed by Carlsson et al. (2009) who enlighten the planning problems that most often occur along the supply chain. They present a matrix where these problems are divided into a strategic, tactical and operational level as well as separated for procurement, production, distribution and sales. Energy supply is as such addressed as a crucial and strategic factor (Carlsson et al., 2009).

Of further importance in the supply chain planning context is also the use of optimization as an important tool. Optimization often plays a central role in Advance Planning Systems (APS) which usefulness has been exemplified for some typical process industries in the literature (e.g. Jonsson et al. 2007; Rudberg and Thulin, 2009; Rudberg and Cederborg, 2011). Both Jonsson et al. (2007) and Rudberg and Thulin (2009) show improvements regarding costs and revenues impacting the profitability due to the use of APS, whereas no such changes could be found in Rudberg and Cederborg (2011). The usefulness of APS is moreover

discussed in section 3.4.4, and supply chain optimization issues per se are more discussed in the next section.

### **3.3.5 Supply Chain Optimization**

Supply chain optimization is preferably done by using a model with respect to the structure of the production system and its surrounding supply chain that connects input with output and its corresponding operations. Hax and Candea (1984) discuss several optimization models for production planning in both a single stage production systems as a regular “knapsack-problem” and advantages with aggregated as well as disaggregated levels of planning. Kallrath (2002b) addresses in addition the issue of blending problems in process industries and refer to the so called *pooling problem* or *fuel mixture problem* in the refinery or petrochemical industry. This problem is closely related to the issue of by-products in proportion to chemical and natural characteristics, as previously mentioned in section 3.1.1. As such, the laws of physics are, once again, important constraints that determine limitations that need to be followed, in particular the laws on entropy limiting the exergy on the energy side.

The use of optimization in process industries is getting more and more important for both their planning and design of their supply chains (Shah, 2005). Rudberg and Olhager (2003) address for example the importance of optimization in a multi-site environment for a single organization, which is the case for the pulp company focused on in the third paper in this thesis. In order to be fully productive one also needs to question how to allocate products and volumes among the plants as well as production and distribution within the network (Rudberg and Olhager, 2003). Another issue addressed by Rudberg and Olhager (2003) is the issue of harmonization when multiple organizations are involved, which is the case for regional co-operations. Planning for such multi-enterprise supply chains need, according to Shah (2005), however more work in the field. These issues have been discussed in the previous planning context and will moreover be discussed in section 3.4 below.

## **3.4 Including Energy in Supply Chain Planning**

There is a close connection between sustainability and energy efficiency and effectiveness, as previously indicated. The concepts of sustainability are further believed to continue to change management and influence companies in different ways (e.g. O’Brien, 2002; Hopkins, 2009; Markevich, 2009). Material intensity, energy intensity, water consumption, toxic emissions and pollutant emissions are, for example, commonly used as basic indicators of sustainability (Schwarz et al., 2002; Kalenoja et al., 2011). Kalenoja et al. (2011) also state operations strategy, scheduling, integration and demand response as issues affecting the energy efficiency of a supply chain. Additional energy efficiency indicators in a supply chain can be found in not only the total use of energy but also in the carbon footprint, consumption of electricity, water and heat, as well as load utilization rate. Kalenoja et al. (2011) moreover underlines the need to examine the whole supply by arguing that the most important energy efficiency decisions are made in production planning and product design.

This consequently highlights the importance of involving energy issues in supply chain contexts.

Another example is given by Wolters et al. (1995) that enlighten different aspects around industrial energy conservation from a managerial point of view. They argue that decision makers tend to hide the problem by simply adding some energy conserving technique instead of focusing on the energy consuming part in their production system and discuss different solutions from a larger perspective. Thus, when planning and managing a supply chain it is important to involve all your operations, all products made and everything necessary for their processes, including by-products. The importance of involving the entire plant in strategic decisions about industrial energy systems is also enlighten in the literature (e.g. Bengtsson et al., 2002; Tari and Söderström, 2002; Karlsson, 2011). Lampret et al. (2007) further point out industrial energy flow management with respect to exergy as an increasingly important issue. Even though the energy costs accounted for only 1.75 % of the total business expenditures in their study on a pharmaceutical company, it is still enough to highlight the issue. These numbers stand yet rather small in both volume and percentage in comparison to the corresponding numbers within the energy intensive process industries.

To consider everything within a company will result in large and complex models, despite its necessity. Already in the end of the 1970<sup>th</sup> Stratton (1979) pointed out a lack of adequate models for the industrial sector, especially for models that incorporate the relationship between change, capital investments, and energy usage trough reflecting upon the diversities of the production functions. The importance of cross-functionality and involving several decision makers and departments throughout the organization is also notified by Bakhrankova (2010) who in addition enlighten the need for Decision Support Systems with a decent and user-friendly interface. Bakhrankova (2010) further on discuss some relevant Decision Support Systems and planning methodologies with some continuous production applications. The availability of general system support for typical process industries, often with divergent material flows, however still seems to be narrow since existing systems among these companies mostly are created for individual purposes. Grunow and Günther (2008) present for instance a proprietary developed decision support tool, based on linear programming optimization, for the supply network planning in a chemical industry involving the use of alternate production resources and production of by-products such as electricity. The model has been implemented and proven to be of major value for both strategic and operational decisions, justifying the very need for similar models in similar or even more energy intensive industries.

The supply chain for the case company used for the third paper in this thesis has previously been studied numerous times. Carlsson and Rönnqvist (2005) give for example a general overview and discuss the decision support tools used for supply chain planning, Gunnarsson et al. (2006) look at the distribution planning problem and involve routing issues and terminal locations in a mixed integer programming model. Gunnarsson et al. (2007) consider

the whole supply chain and present a model for a one year planning period. This model is further developed by Gunnarsson and Rönnqvist (2008) who also consider multiple time periods and use heuristics. The same authors, Lidestam and Rönnqvist (2011), later on study the supply chain and develop a mixed integer linear programming model and use a Lagrangian heuristic method based on Lagrangian decomposition to solve the problem. However, none of these have taken the energy issues into special consideration.

### **3.4.1 Complexities in the Production System**

The inventory problem regarding energy has many complications. Since energy, compared to its origin in different fuels, is difficult to store (Grubbström and Hultman, 1989) the need for flexibility in the energy supply is unavoidable. For example, electricity needs to be used at the exact moment as it is produced, and heat is volatile and difficult to store depending on its carrier (Grubbström and Hultman, 1989). Inventory and safety stock is in general used to handle uncertainties in quantity, which partly can be done on the input side of the energy supply chain, depending on the inputs specifics. When the demand or output side however is difficult to forecast a more flexible input side is needed. This strive for flexibility therefore increases costs in terms of holding, setup, ordering, and shortage (Khouja, 1999). Grubbström and Hultman (1989) present in their exploratory study some economic models for storage of exergy and heat, describing how economic and inventory policies depends on variations in both the energy demand but also on specific thermodynamics. For future research they for instance address the opportunities with optimal choice of inventory and the potential of programming in order to empirically determine physical conditions. Tari and Söderström (2002) as well as Karlsson (2011) further refer to the problem of energy storage in terms of system optimization and discuss the influence on energy costs, such as time-of-use-prices of electricity, of material inventory through a case study from the pulp and paper industry where they include material storage into the Method for analysis of INDUSTRIAL energy systems (MIND). This method can also be used as decision support for additional industrial energy systems (e.g. Karlsson, 2011).

In linear production systems the input-output analysis methods (Grubbström and Tang, 2000) is useful in order to provide sufficient mapping and planning data for a production system. The inventory system also need a set of safety factors to be calculated, which traditionally is based on normal distributed and simplified data, but it can also be done based on higher order moments to more properly reflect the reality (Tang and Grubbström, 2006). This is rather easy when it comes to material and ordinary goods that are discrete, concrete and easy to store. But when it comes to energy, which has more complex properties, the input-output analysis becomes more problematic. This due to a lot of factors such as the properties of a heat-exchange system, losses in general and the need for immediate use of the output of non-storable energy carriers, which leads back to the inventory problem previously discussed. These issues are thus very central for the energy intensive process industries.

As previously indicated, aiming for more reuse of energy and striving for optimal energy efficiency and effectiveness makes the production system more and more complex. In the model developed by Grunow and Günther (2008) the amount of by-products produced is, for instance, constrained by the capacity of the energy transformation equipment. This indicates the importance of being able to buffer or sell the surplus when internal energy demand is limited. Several interesting issues consequently occur when energy intensive products can be found both on the input side as well as on the output side in a supply chain. This can be connected with some parallel issues concerning, for instance, reverse logistics or closed loop supply chains (CLSC) as it also can be called (e.g. Thierry et al., 1995; Fleischmann et al., 1997; Atasu et al., 2008), where materials as well as energy can be recycled and used over and over again in order to recover the embedded value. This is according to Shah (2005) the “supply chain of the future”.

### **3.4.2 Mathematical Modelling and Decision Support Systems**

Due to more complexities within production systems in general, the need for modelling and system support increases. As such, mathematical modelling for industrial planning and optimization problems has become more and more important, but also useful due to the possibilities provided along the technological development of computer power. There are plenty of examples given in the literature. Arivalagan et al. (1995), for example, refer to the optimal energy-mix that can be tackled by a mixed integer linear programming model. Kallrath (2002a) combines both operative and strategic planning aspects in one mixed integer linear programming model that shows cost savings through reduction of urgent transportations. Kallrath (2005) furthermore gives an overview of planning and design problems for the process industry that are solved through the use of mixed integer optimization. Kallrath (2005) also states that it is common to use mixed integer linear optimization to solve supply chain planning problems. Paiva and Morabito (2009) recently presented a mixed integer optimization model for aggregated production planning in a sugar and ethanol milling company. The latter also aim at providing decision making support involving choice of production processes, quantities, inventory levels, suppliers and transports suppliers.

The usefulness of mathematical modelling, as previously exemplified, it can in addition be used in providing Decision Support Systems of different kinds. For instance, Mallya et al. (2001) integrate production planning and inventory control decisions and present a Decision Support System for a continuous manufacturing environment with widely varying and independent demand patterns, originally designed for a large process industry. Gunnarsson et al. (2004) also present a decision support tool for strategic analysis and tactical planning regarding supply of forest fuels. Bredström et al. (2004) have developed mixed integer models in a pulp company for determining daily supply chain decisions over a planning horizon of three months. Thollander et al. (2009) more recently investigated the use of decision support practices for complex production related investments and show that the impact of fluctuating electricity prices affect the choice of investment. Another investment

support tool is discussed by Bollapragada et al. (2011) that present a practical case of a decision support and analysis tool for General Electric to use in forecasting the demand of renewable energy for the decade to come. As it seems, there are plenty of useful examples of Decision Support Systems, however most of the examples found do not merge the energy system with the production and supply chain system, as strived for in this thesis.

### **3.4.3 Integrated Energy Planning and Optimization Modelling**

The field of supply chain simulation and analysis is according to Shah (2005) an emerging area that is expected to grow rapidly, and for this the modelling phase is a key issue. When however narrowing down the literature found on modelling, planning and optimization to also include energy there are fewer examples to choose between. Nonetheless, Wolters et al. (1995) present a modelling method for a general industrial production system and divide it into three different subsystems; transforming raw materials into desired commodities by using energy (transformation), making energy available in the right quantity and quality (utility), and recovering residual heat (heat recovery). They argue that this decomposition is applicable for most production systems and that an additional subsystem; controlling starting and finishing times of different batches (control) in case batch processes are present. They also identify boilers and combined heat and power (CHP)-units as the most important elements in the utility subsystem due to the domination of electrical and thermal energy flows in energy-intensive production systems. If the objective moreover is to minimize the use of energy in a production system, the transformation (sub)system should be incorporated in the first optimization decision, according to Wolters et al. (1995).

Other examples such as the one given by Schmalzried (1998) show how to achieve cost savings through optimization of production planning. They show that 10% of the energy costs in a cement industry can be saved using their approach. Tari and Söderström (2002) also address some advantages of using a mixed integer linear programming model for planning problems with capacity restrictions. Gunnarsson et al. (2004) furthermore address the issue of integrating interrelated planning situations within the concept of SCM and Kalenoja et al. (2011) more recently present a framework of system boundaries for measuring the energy efficiency in a supply chain from a logistic perspective. As such, there are some examples of models found in the literature that consider energy issues in a production and/or supply chain planning context, however, yet only a few.

### **3.4.4 Integrated Energy Planning and Optimization Systems**

The lack of sufficient planning and decision support systems for the process industry has previously been addressed. After adding the requirement of a system that also includes energy aspects there are not many examples left in the literature. For energy issues per se, MIND has been developed for the optimization of industrial energy systems (e.g. Bengtsson et al., 2002; Tari and Söderström, 2002; Karlsson, 2011). In process industries, it seems to be common to combine different tools and tailor-make your own planning system, as moreover discussed in Paper 2. Mallya et al. (2001) give an example of this and use Excel and Access in

combination with AMPL, yet without any special concern to energy. Previous mentioned examples from the literature (e.g. Jonsson et al. 2007; Rudberg and Thulin, 2009; Rudberg and Cederborg, 2011) also show that Advance Planning Systems (APS), as a more standardized system support, however can be useful.

With more respect to energy Bakhrankova (2010) presents a model-based Decision Support System, entitled Energy Optimizer (ENEO), built on two modules, one for energy cost minimizations and one for joined energy cost minimization and output maximization. As such, ENEO simultaneously is deciding on intermediate and final products, their production quantities and resource utilization while synchronizing production and distribution planning. It is built upon three main solution steps using VBA macros in Microsoft Excel, database access connecting Excel with AMPL, and a read and write configuration via the Open Database Connectivity standard under Windows. Some of these solutions steps have also been of use while working with the model presented in the third paper of this thesis. According to Bakhrankova (2010), their system can provide help in daily production planning through several operational functions, reaching substantial energy cost savings and improving both reactivity and capacity utilization. Closely connected to this issue Grunow and Günther (2008) pointed out that APS did not provide enough support to model the particularities of the chemical processes. Energy origin from by-products in particular did not fit well into the APS, indicating the improvement potential within the area of planning support with respect to energy for process industries.

## 4 Summary and Contribution

Today, energy is mostly viewed upon from the cost side, with a few exceptions, even though there might be revenue possibilities downstream in the energy flow. The real value of the embedded energy in the product might therefore differ depending on how capable the company is in using the energy in the most efficient and effective ways. It also depends on the origin of the energy and its compatibility in the energy system. These are very important issues to consider in decision making processes regarding for instance investments and strategic planning. Consequently, integration between energy and production planning seems necessary.

The remainder part of this chapter will answer the research questions and reflect back to the purpose. Doing so, the papers will be summarized with respect to content and contribution. To also connect the content of each chapter and section in the previous frame of reference (Chapter 3) to its relevance for each paper, Table 1 below provides some general guidelines.

**Table 1. Content relevance for each paper.**

Chapter / Section:	Relevance, more (***) or less (*):		
	Paper 1	Paper 2	Paper 3
3.1 Process Industries	***	***	**
3.1.1 Energy in Process Industries	***		**
3.1.2 Planning in Process Industries		***	**
3.2 Managing Industrial Energy	***		***
3.2.1 Energy Systems	***		***
3.2.2 Energy Modelling	*		**
3.2.3 The Quality of Energy	**		**
3.2.4 Energy Optimization	*		**
3.2.5 Energy Utilization and Alternative Revenues	***		***
3.2.6 Energy Strategy	***	*	*
3.2.7 Energy Management Systems	*		*
3.3 Managing and Planning Production and Supply Chains		***	**
3.3.1 Production Systems	*	***	*
3.3.2 Managing Operations and Choosing Strategy	***	**	*
3.3.3 Capacity Utilization	***	***	*
3.3.4 Supply Chain Planning		***	***
3.3.5 Supply Chain Optimization	*	**	***
3.4 Including Energy in Supply Chain Planning	**	*	***
3.4.1 Complexities in the Production System	*	*	**
3.4.2 Mathematical Modelling and Decision Support Systems		*	***
3.4.3 Integrated Energy Planning and Optimization Modelling	*	*	**
3.4.4 Integrated Energy Planning and Optimization Systems	*	*	***

## 4.1 Answering Research Question 1

*How do process industries strategically work with energy management issues to ensure long term profitability?*

This question is mainly answered through the content in Paper 1. A summary of Paper 1 is therefore presented below followed by section 4.1.2 with a more collective summary and discussion of overall contribution based on this question.

### 4.1.1 Summary of Paper 1

The contribution of this paper is that it addresses important energy issues regarding energy intensive process industries. Of special importance is the strategic dimension of energy, the energy system utilization, and the issue of generating alternative revenues from sources that very often have been viewed upon as just waste. Moreover, this paper is the result of the first study that seeks to answer the first research question. *The purpose of the study is thus to investigate the necessary prerequisites for putting energy management on the strategic agenda in energy-intensive process industries.* The purpose is then divided into three more specific case study questions:

- CQ 1. What issues are important to consider for establishing a strategic perspective on a company's energy system?*
- CQ 2. What issues are important to consider for getting strategic attention on the utilisation of a company's energy system?*
- CQ 3. What issues are important to consider for getting strategic attention on investigating the possibilities for finding alternative revenues from a company's energy system?*

Each of the three case study questions is connected to its corresponding perspective of how energy management is treated strategically with respect to the: 1) holistic perspective, 2) energy system utilization perspective, and 3) alternative revenue perspective. This is investigated in the case company that is a specialty chemicals company with energy costs accounting for some 15% of the total costs. A literature review has also had impact on the analysis and the outcome of the paper. Most findings however confirm current literature and interesting results are found for each case study question:

- 1) For the overall holistic perspective the authors address the issues of poor organizational integration, neglected view on energy costs, restrained investments for energy solutions, and the benefits of governmental programs. The prerequisites for moving energy into the strategic dimension are thus governmental programmes, political continuity, the view on energy as core to the business and having an energy manager with the main responsibility for energy issues.
- 2) For the utilization perspective the issue of poor energy planning, triggers for working with efficiency and effectiveness, and flexibility regarding the choice of energy fuels are addressed. These issues for best utilizing the energy system enlighten some challengers such as how to deal with centralized planning, realizing potential in the decision-making

while investing in better energy solutions, focus on energy system efficiency and effectiveness, as well as the influence on energy quality and its alternative costs through process innovations.

- 3) The third perspective on alternative revenue addresses the issues of revenue possibilities and limitations, and proper exergy usage. The location of the site, re-designing the process in order to make energy available for alternative use, and governmental support for competitiveness (e.g. green certificates providing competitiveness) are pointed out as important prerequisites for alternative revenue.

#### **4.1.2 Contributions to Industrial Energy Issues**

The findings of Paper 1 thus answer research question 1 by not only showing an example on how process industries do work, but also how they can work, with energy management issues to ensure profitability in a long term strategic way.

As a further conclusion, the neglected view on energy costs and not perceiving energy as core for the business, should be taken seriously for the company's long term survival (in line with e.g. Thollander et al., 2009). Even though an Energy Management System is applied and followed within the company, the potential of the energy system in relation to available opportunities outside the corporate boundaries (e.g. Stratton, 1979) might be limited due to such narrow view. In addition, we can find that the lack of responsible energy managers together with a poor energy planning risk to undermine proper energy investments in the decision making processes within the companies.

In order to moreover utilize the energy system and release additional energy surplus for alternative revenue generating purposes, the proper exergy usage is furthermore discussed in Paper 1. In order to achieve such improvements, investments issues in redesigning the process are however discussed. The issue of restrained investments for worthy energy solutions argued in Paper 1 depends therefore on feasible technological alternatives (e.g. Stratton, 1979; Wolters et al., 1995).

The utilization perspective is also about finding alternative revenues from, in this case, the energy surplus that is provided. For this, the limitations or possibilities of district heating due to, among other factors, the factory location or competitiveness (e.g. Klugman et al., 2007; Carlsson et al., 2009; Georgopoulou et al., 1997) are confirmed to be important.

The issue of climate change and its resulting political pressure have also been discussed in Paper 1. This is put in relation to some benefits of governmental programs and political continuity as well as the triggers this can provide for working with energy efficiency and effectiveness, both internally and from a larger system perspective. Altogether, there are a lot of factors to involve in the decision-making processes when investing in better energy solutions. The runaway pricing issue on energy (Kopelman and Weaver, 1978) can moreover provide insight or arguments for investing in renewable technologies. Energy sourcing is therefore highlighted as a strategic issue.

## 4.2 Answering Research Question 2

*How do process industries typically perform production and supply chain planning?*

This question is mainly answered through the content in Paper 2. A summary of Paper 2 is therefore presented below followed by section 4.2.2 with a more collective summary and discussion of overall contribution based on this question.

### 4.2.1 Summary of Paper 2

The contribution of this paper is that it gives insights in production planning processes for process industries. It analyses some specific conditions for a number of process industries and discusses why the different production planning processes are designed as they are. Moreover, this paper is the result of the second study that seeks to answer the second research question. *The purpose is to map the production planning process in process industries and analyze how it is related to their specific planning conditions and available literature.* Furthermore the research aims at detecting similarities and differences in production planning at the tactical level. This study followed a holistic multi-case design with focus on planning processes involving several entities within the companies. The four case companies are; a pulp and paper company, a specialty oils company, a specialty chemicals company and a pulp company. The companies operate in niche markets with large enough volumes for distinct products, and maintain their competitiveness by doing so.

The findings of the study are mostly concentrated to some similarities and differences within long term planning and medium term planning among the case-companies. Concerning long term planning similarities, the companies show a high focus on resource utilization, and a planning which is centralized to the Supply Chain division due to its coordinating activities within the company. Planning on this level also seems to be a spread sheet task by using Excel. Some of the differences at long term planning are the involvement of procurement, the way disaggregation or products groups are used, as well as to what extent the use of mathematics and dedicated planning software are used. Some planning differences regarding material dominance compared to capacity dominance are addressed. The similarities found in the medium term planning are that they all aim at achieving flexibility through quick changes in production besides never (or really late) freezing the plan. The issue of how to achieve flexibility with centralized planning is also pointed out. The usage of the results from long term planning in the medium term planning is different among the companies as well as the use of cyclic planning. The results also indicate that planning with respect to by-products is complicated and result in a larger need for more proper and further tailor made planning tools. To sum up, the structure of long term planning is very similar whereas the medium term planning exhibits more differences, calling for higher degree of customization of planning support/system, and the case companies are surprisingly flexible in short time spans (for a similar study in a more general context see e.g. Olhager and Rudberg, 2002).

#### **4.2.2 Contributions to Management and Planning of Production and Supply Chains**

The findings in Paper 2 answer research question 2 by mapping the current state of art in production planning in process industries. Compared to the situation for most manufacturing companies, the production and supply chain planning in process industries is however found to be rather poor. One explanation can be that process industries are different from most manufacturing industries and consist of individual characteristics that are tricky and difficult to create generalizable planning methods for. The planning support found is consequently often tailor made for each process industry. The authors also found it difficult to distinguish general similarities and differences among the process industries regarding these planning issues and thus hard to generalize.

One of the similarities found among the case companies in Paper 2 is the high focus on resource utilization which also is discussed within the issue of matching products with the necessary production processes needed to achieve an efficient supply chain (Fischer, 1997). Another set of similarities in both the long term and the medium term planning is the ability to achieve flexibility. Whereas the long term planning is centralized to the supply chain division the medium term planning uses quick changes in production and almost never freezes the plan. Since both mix- and volume flexibility is not very supported by the production processes, and inventory is viewed as costly, mix flexibility is, instead, strived for in the planning procedure within some of the case companies, in line with van Wezel et al. (2006). Another important issue for agility is the need to analyze the supply chain, by using reliable data and providing accurate cost and benefit analyses, as addressed by Tang and Tomlin (2008). Beside capacity concerns, this is also essential regarding investments for example new and flexible energy solutions, as discussed in Paper 1. As such, adjustments of capacity in relation to demand (Olhager et al., 2001), might be needed and analyzed moreover, calling for a model suitable for such purposes.

Further on in Paper 2, planning is pointed out as poor and as a spread sheet task with very limited use of optimization based planning software or system support. This confirms the lacking, mismatching and poor usage of adequate system support stated in the literature (e.g. Taylor et al., 1981a; Ashayeri et al., 2006). The complications to plan with respect to by-products, its proportions, and potential energy surplus as discussed in Paper 2 and previously in Paper 1, is in addition to be more deeply analyzed in Paper 3. As such, the model presented in Paper 3 aims to moreover contributes to the underdeveloped support for production and supply chain planning in process industries, especially with respect to energy.

### 4.3 Answering Research Question 3

*How can process industries improve their planning by including energy related issues in their production and supply chain planning?*

This question is mainly answered through the content in Paper 3. A summary of Paper 3 is therefore presented below followed by section 4.3.2 with a more collective summary and discussion of overall contribution based on this question.

#### 4.3.1 Summary of Paper 3

The contribution of this paper is that it gives an example of a supply chain model where energy flows are considered and combined with the product flow for revenue generating purposes. As such, the paper shows that it does matter to include energy in the production and supply chain planning process for a multi-site pulp company.

This paper is the result of the third study and the modelling phase that seeks to answer the third research question. *The purpose of this paper is to develop a model for integrated supply chain and energy planning for a multi-site pulp company treating energy not only as an input to the pulp process, but also as a saleable output from the production process.* The basic idea is that energy intensive raw materials not only give fibre to the pulp process but also generate an energy surplus that can be used in different ways to create additional value or revenues. The paper is based on a case study and a mixed integer linear programming model developed for the supply chain of this case-company. Decisions included in the model are purchase and transportation of raw materials, production allocation, energy mix, and distribution.

The results from the third paper are mainly from analyzing the output of eight different scenarios, where the first scenario represents the starting solution with basic settings. The results show a clear impact of involving the energy issues into the supply chain model. In a comparison between the basic scenario (including energy) and the second scenario (without energy prices), the profit and cost figures show a very different production schedule resulting in decreased cost for raw material and production but higher delivery costs. The impact on variations in electricity price also gives interesting results where the output of electricity strives to be maximized already at current prices. The possibility of holding inventory is furthermore proven to be useful in the scenario of seasonal variations of electricity price. A different use of raw materials due to their differences in energy content also becomes clear in scenarios of varying energy prices. The model moreover indicates that the use of energy per ton product produced is likely to increase if the supply chain planning is done without energy concerns. To sum up, the results show the feasibility of involving energy issues in this way and that the current production plan is not optimal with regard to energy considerations. The model thus reveals potential benefits with including energy issues in the supply chain planning.

### **4.3.2 Contributions with Including Energy in Supply Chain Planning**

Process industries can improve their planning in several different ways. One way is to include energy aspects into the production and supply chain planning. This is done in Paper 3 with a model analyzed through different scenarios that confirm its functionality, as well as providing interesting insights in how the supply chain and production system should react on different conditions. As such, a model useful for both planning and more strategic decision-making is composed and presented.

The connection of energy issues with planning issues is done in several ways along this thesis. To begin with, Paper 1 introduces the importance of energy issues in for instance investment problems that normally are heavily involved with traditional planning issues, especially within the capital intensive process industries. The issues concerning investments for new energy solutions mentioned in Paper 1 can also be viewed from the trade-off perspective given by Neto et al. (2009) as a balance between environmental and business concerns. Erenguc et al. (1999) argue that a similar discussion has historically taken place regarding trade-offs between competitive priorities such as flexibility, quality and cost in the field of operation strategy. Even though energy issues, or other environmental aspects, yet barely can be considered among the competitive priorities, decision making regarding these investment issues is still in the need of support for analyses and simulations, and its further development. For this, the model in Paper 3 provides a good starting point for such analyses.

In line with the poor usage of system support for planning among the case companies studied in Paper 2 there are at least some examples available in the literature that could be of their benefit (e.g. Mallya et al., 2001; Kallrath, 2005) On the one hand, involving energy from by-products into a commercial planning system seems to be difficult (e.g. Grunow and Günther, 2008) despite the increasing importance of systems such as APS (Stadtler and Kilger, 2008). Custom made planning support, as normally done among process industries, can on the other hand take care of the energy issue, as shown in Paper 3. In contrast to Grunow and Günther (2008) the allowed amount of produced by-products is in Paper 3 not constrained by the capacity of the energy transformation equipment, since this surplus is assumed to have the possibility to either be sold or stored for later purpose.

## **4.4 Purpose Reflection and General Conclusions**

*The purpose of this thesis is to investigate the most important energy management issues as well as to map the current state of art regarding production and supply chain planning in process industries, in order to integrate them into a common model for strategic and tactical planning, and thereby show the possible impact on profitability.*

Energy management, as well as production and supply chain planning, in process industries is reviewed and mapped in this thesis, mostly in the first, and second, paper and further on discussed in the frame of reference (Chapter 3). To complete and fulfil the purpose of this thesis, the integration part is done in the third paper where the profitability aspect of an innovative planning approach due to energy aspects is presented.

From an energy management point of view the studies in Paper 1 and Paper 3 can each be seen as an energy system analysis where the energy system is analyzed and critically examined. As such, the energy systems in Paper 1 and Paper 3 are analyzed from a utilization perspective with respect to the laws of thermodynamics. The analysis of planning processes in Paper 2, and its description of the current practice among process industries, also contributes in its collective way. The model in Paper 3 moreover shows some benefits with using a mathematical programming approach. All papers therefore contribute to the literature by showing an additional example of these theoretical and methodological approaches and its problematic issues. The aim of the thesis is thus consistent.

Since the energy issue is not only a cost issue driven by supply and demand, but also a political issue due to its environmental aspects, it is likely to believe that political influence and especially continuity (as discussed in Paper 1) will have escalating effects on the energy intensive process industry sector focused on in this thesis. The need for improved production and supply chain planning and the lack of planning support for process industries is still an issue (as reviewed in Paper 2). In combination there are reasons to believe that planning and optimization models that take energy aspects in consideration (as made in Paper 3) will contribute in interrelated decision-making processes.

## 5 Further Research Ideas

There are a lot of interesting issues around this thesis to dig deeper into. All of the questions in the discussion that follows might not be on the future path for the author of this thesis, but is still addressed for inspirational purposes.

As long as energy is important regarding cost and/or environmental impact there is going to be a strategic dimension around it. Aspects connected to costs or wastes affecting the environment such as emissions of greenhouse gases, use and purification of water and air, or other emissions and pollutants from industrial activities, are more or less important from a strategic point of view. For instance, the restrictions of using chlorofluorocarbon (freons) or mercury had vast impact on many industries not that long ago. To be prepared for future regulations might therefore provide benefits, even though they are difficult to predict. The complexity of governmental regulations on chemicals, pollutants, and other emissions makes this issue more complicated, yet still necessary to involve for a full scale model. How to best manage these issues, or how to create a more holistic and general model of such issues, is however left for further research to figure out.

The lack of planning support for process industries mentioned in Paper 2 is despite all recent progress in the field of planning and system support still an important task to solve. Whereas general manufacturing industry can be satisfied with an Enterprise Resource Planning (ERP) system or an Advance Planning Systems (APS), many of the process industries stand aside. In this topic there are plenty of research opportunities in developing such system applicable for the process industry leading to the following Further Research Questions (FRQ):

*FRQ 1. In what ways and from which planning perspectives (strategic, tactic operational) can process industries be treated as a homogenous group?*

*FRQ 2. What are the main obstacles for making a generalized and suitable system support, handling strategic, tactical, and operational planning issues, for process industries?*

*FRQ 3. What tools and methods are available today for this purpose, as well as for handling divergent flows, and what are their advantages?*

The model presented in Paper 3 is more on a tactical level and does not yet fully support the strategic long term decision-making processes as previously discussed. By increasing the horizon of the model presented in Paper 3 the strategic support asked for in the first research question in this thesis, can gain additional momentum. A longer horizon would however request more long term forecasts of market conditions. Summing up with previous discussion as well, the following questions arise:

*FRQ 4. Can the model in Paper 3 be modified in order to become more generalizable as previously requested and to make it more useful for other process industries by making it more generally applicable?*

*FRQ 5. Can the model in Paper 3 be modulated and compared by using other tools for simulation and/or similar analysis?*

The discussion and questions presented above roughly represent three recommended fields; Environmental Management (as initially discussed), Process Industry Planning Systems (as composed in FRQ 1 – FRQ 3), and Process Industry Planning Modelling (as composed in FRQ 4 – FRQ 5). These are some examples of many interesting issues to move forward with, even though the chosen path for further research is not fully determined. The approach is however to remain a production economic stance, and per se most business is about making profit and ensuring a positive cash flow, no matter if it is raw materials, water, air, or energy that complicates in managing the operations. Nevertheless, due to the complexity of energy, planning, and process industry characteristics as well as its many issues discussed in this thesis, the need for a robust strategy and planning support comprehending these issues is important and seems necessary. As such, this thesis takes one step forward towards improved energy and production planning for process industry supply chains.

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