How energy price changes can affect production- and supply chain planning – A case study at a pulp company

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Abstract

The process industry in general is very energy-intensive, and therefore models focusing on energy can be very important in order to reach higher profitability. In this study, an optimization model of the supply chain in a pulp company, where energy is included with respect to its revenue generating capabilities, is used. Using real company data, and through an analysis of the model's results, we show that higher profitability can be achieved when integrating energy into the planning process. Our findings show that when energy-intensive raw materials not only provide fibre to the pulp process but also generate an energy surplus, there is room for different planning approaches in order to maximize the total profit. This paper reveals promising changes that can be made for improving current planning process. The scenarios considered involve market changes for energy demand and price, and also alternative production opportunities. A cross-analysis compares the scenarios in order to reveal additional relations that are important to consider. Depending on a price change of energy, the model prioritizes in its selection of pulp products to produce. From this we provide guidelines on where and when to increase or decrease pulp production. The model shows that the company can increase its total profit no matter which of the included energy parameters that increase in price. The paper contributes to previous research by enhancing the usefulness of this model for not only the case company as such, but also by illustrating and describing how the approach applied can be useful for other cases within the energy intensive industry.

Keywords:
Supply chain planning; Energy revenues; Energy-intensive production systems; Mixed Integer Linear Programming (MILP) model; Process industry.

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1.1 HOW ENERGY PRICE CHANGES CAN AFFECT PRODUCTION- AND SUPPLY CHAIN PLANNING

- A case study at a pulp company

Abstract

The process industry in general is very energy-intensive, and therefore models focusing on energy can be very important in order to reach higher profitability. In this study, an optimization model of the supply chain in a pulp company, where energy is included with respect to its revenue generating capabilities, is used. Using real company data, and through an analysis of the model's results, we show that higher profitability can be achieved when integrating energy into the planning process. Our findings show that when energy-intensive raw materials not only provide fibre to the pulp process but also generate an energy surplus, there is room for different planning approaches in order to maximize the total profit. This paper reveals promising changes that can be made for improving current planning process. The scenarios considered involve market changes for energy demand and price, and also alternative production opportunities. A cross-analysis compares the scenarios in order to reveal additional relations that are important to consider. Depending on a price change of energy, the model prioritizes in its selection of pulp products to produce. From this we provide guidelines on where and when to increase or decrease pulp production. The model shows that the company can increase its total profit no matter which of the included energy parameters that increase in price. The paper contributes to previous research by enhancing the usefulness of this model for not only the case company as such, but also by illustrating and describing how the approach applied can be useful for other cases within the energy intensive industry.

Keywords: Supply chain planning; Energy revenues; Energy-intensive production systems; Mixed Integer Linear Programming (MILP) model; Process industry

Highlights:

- Energy price sensitivity analysis using a supply chain optimization model.
- A MILP model, using real data, suggests which pulp products to produce and where.
- Energy effectiveness shifts production allocation between different sites.
- Product price should reflect embedded energy and accumulated resource intensity.
- Alternative revenue from energy-intense raw materials enhances production planning.

1 INTRODUCTION

Energy is of great strategic importance for process industries (Rudberg et al., 2013). Some of the most important energy efficiency decisions are made in production planning and product design (Biel and Glock, 2016; Kalenoja et al., 2011), in designing energy efficient production systems, and by evaluating solutions on a higher level (Wolters et al., 1995). In addition, both the raw materials needed, as well as the finished goods process industries produce, are in general considerably large and heavy, resulting in high transportation costs. And since many companies have several different production facilities in different places to support the need of their customers, it is important to examine the whole supply chain. Advanced process models for improving production networks towards a more environmentally friendly direction have as such become more important (Geldermann et al., 2007). Energy-intensive industries and their long term investments are influenced by not only energy prices but also prices on greenhouse gas emissions (Rentizelas et al., 2012). Process industries, that normally use large amounts of energy, have previously been the target of supply chain optimization (e.g. Papageorgiou, 2009) and for developing decision support systems (e.g. Bakhrankova, 2010), but energy has then often been considered as a cost to be minimized (Özdamar and Birbil, 1999). Other optimization approaches can also be found in the literature where, for instance, energy issues in the pulp and paper industry have been studied (e.g. Marshman et al., 2010; Xiaoyan et al., 2012), or where by-products in the steel industry have been in focus (e.g. Zhao et al., 2015). In addition, the emerging bioenergy business area is believed to provide plenty of opportunities for the forest sector and its “green gold” (Pätäri et al., 2011).

In our study, we consider the many different contents of this “green gold”, not only in terms of wood as the traditional raw material for the pulp production, but also the energy-intensive co-products it provides as a source for additional revenues. As such, we value each product from its specific characteristics by looking at what is needed in terms of raw materials and energy input, as well as what is provided in terms of co-products (and possible use of these co-products as energy carriers). By adding these energy related dimensions to the contribution of each product, the energy price fluctuations are integrated in the total profit. Moreover, in the literature concerning the pulp process industry, there is, to the best of our knowledge, a lack of planning models and practical guidance that aim for profit maximization, while taking on energy price fluctuations or changes, in dealing with the supply chain planning and production planning problem. This paper hence aims to contribute in filling out this gap in the literature.

One starting point for this research is a model for integrated production and distribution planning developed for a pulp company by Gunnarsson et al. (2007). In that model the supply chain planning is a strategic one-period (one year) problem, including decisions about supply of materials, production, and distribution. Waldemarsson et al. (2013) simplified the distribution problem but extended and developed the model by Gunnarsson et al. (2007). This extension includes decisions about the energy mix and by choosing the energy input at the pulp mills. They also introduced the output of energy as revenue generating products. Furthermore, influenced by Gunnarsson and Rönnqvist (2008), Waldemarsson et al. (2013) extended the model to use monthly time periods over a one year planning horizon. As a result, Waldemarsson et al. (2013) show that there is room for different planning approaches to maximize the total profit when energy-intensive raw materials not only provide fibre for the pulp process but also generate an energy surplus. They also show that considering energy matters affects profitability, and the problem is thus important to further analyse. However, their analysis of the model includes some extreme market price changes, such as if the energy prices go up by 50%, but does not reveal what happens in between current state and such change. In this paper we refine the model presented in Waldemarsson et al. (2013) in order to analyse the whole spectra of energy price fluctuations, and not just its edges of each scenario price change. A single case study provides additional real company data as input for the model, refining the data set.

To sum up, the purpose of this paper is to analyse the impact of energy price changes on the supply chain planning and the production planning at a pulp company. As such, we reveal how different kinds of energy price changes are handled by the model and analyse the consequences the model then suggests for the supply chain planning and the production planning solution. Since the energy characteristics among the products produced differ among different types of products, we also discover whether changes in energy conditions can make some products preferable to others. To connect such issues to energy efficiency and effectiveness at each mill, we therefore show that some products and/or pulp mills are more competitive than others, and that they can contribute to the overall energy effectiveness of the company, when energy prices change. By analysing different scenarios of energy price changes, we enhance the applicability and the industrial usefulness of the planning model.

2 RELATED LITERATURE

On a strategic level, decisions should have a holistic perspective and should involve the entire plant when considering energy related issues (e.g. Bengtsson et al., 2002; Tari and Söderström, 2002; Karlsson, 2011). However, important energy efficiency decisions are also made in the production planning process (Biel and Glock, 2016; Modarres and Izadpanahi, 2016), making the energy efficiency of a supply chain dependent on everything from detailed scheduling to the overall operations strategy

(Kalenoja et al., 2011). The idea is rather simple, increased energy efficiency will set free some energy that could be used for other purposes and create additional revenues. For the pulp industry, such strive for energy efficiency is of great importance and could result in large savings on both heat and electricity (e.g. Klugman et al., 2007a; Klugman et al., 2007b). Managing energy demand, aiming for demand responsiveness, through production planning and scheduling is becoming more and more important as risks increase with more fluctuating energy prices (Mulhall and Bryson, 2014; Tong et al., 2015). Another approach for improving energy efficiency is to develop key performance indicators for such purpose (May et al., 2015), indicating the importance of integrating energy aspects into production planning. A literature review of decision support models for energy efficient production planning can moreover be found in Biel and Glock (2016). However, similar cases as considered in this paper, where most of the energy demand is supplied from internal sources, are delimited from the scope of the literature review by Biel and Glock (2016), calling for further investigation in cases as considered in this paper.

Whereas planning is to set goals and to determine how to utilize resources in order to accomplish these goals (Taylor et al. (1981b, p. 23), the context of supply chain planning can be described as "the determination of a set of policies and procedures that govern the operation of a supply chain" (APICS, 2008, p. 135). In this paper we investigate how to deal with such supply chain planning problems, together with the related production planning problems, using quantitative models. As such, using linear programming, Grunow and Günther (2008) developed a decision support tool for both strategic and operational decisions in the supply network planning of a chemical industry. Their optimization model handles use of alternative production resources and the production of by- or co-products. Zhao et al. (2015) also look at the by-product planning problem and present a MILP model for the short-term planning in the iron and steel making process. Kallrath (2002a) shows how cost savings can be achieved by combining both strategic and operative planning aspects in one mixed integer linear programming (MILP) model. Furthermore, Kallrath (2005) states that mixed integer linear programming is a common way to solve supply chain planning problems in the process industry. An example of such a problem is given by Paiva and Morabito (2009) who include the choice of production processes, quantities, inventory levels, suppliers, and transportation in their model. MILP models are also suitable for handling energy-mix problems (Arivalagan et al., 1995) and process industries often tailor their own planning system by combining different tools (Ashayeri et al., 2006).

The pulp and paper industry has been studied by, for example, Tari and Söderström (2002) as well as Karlsson (2011). They looked at the problem of energy storage from a system optimization perspective, where material storage is included in the MILP model used in the Method for analysis of INDustrial energy systems (MIND). Bredström et al. (2004) have also developed a mixed integer model with a planning horizon of three months in which the daily supply chain decisions for a pulp company are determined. The supply chain for the case company in this paper has also been studied several times before. A general overview is presented by Carlsson and Rönnqvist (2005) who discuss the decision support tools used for the company's supply chain planning. The distribution planning problem is also analysed by Gunnarsson et al. (2006) who include routing issues as well as terminal locations in a mixed integer programming model. Gunnarsson et al. (2007) later consider the whole supply chain, and present a model with a one year planning period. This model is further developed by Gunnarsson and Rönnqvist (2008) to also consider multiple time periods and the use of heuristics. Lidestam and Rönnqvist (2011) developed a mixed integer linear programming model, where a Lagrangian heuristic method based on Lagrangian decomposition was used to solve the supply chain planning problem. However, none of these studies at this case company have taken any special consideration of energy issues per se into account.

3 RESEARCH DESIGN

In this chapter, we describe the case, the methodological approach, a conceptual data structure, and introduce the scenarios that are analysed later.

3.1 Case description

The case company, Södra Cell AB, is a large pulp producer and part of a forestry group owned by 51,000 members in Sweden. The pulp operations consist of four mills producing about two million tons of paper pulp each year.

The supply chain for the case company can be divided into three parts: procurement, production and sales. Raw materials are transported to the pulp mills mainly by trucks from saw mills or forests districts. As illustrated in Fig. 1, three mills are located in Sweden and one is located in Norway. The supplying forestry land in the forests districts is mainly privately owned by members of Södra, but raw materials can also be imported from external sources. The raw materials consist of pulp wood and wood chips and are classified into different assortments, depending on their unique properties.

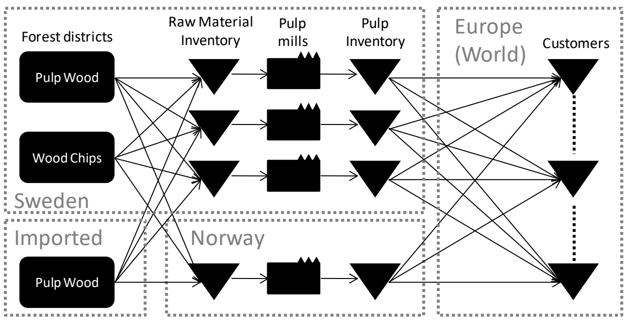

Fig. 1. The pulp supply chain for the case company investigated.

The pulp production uses a varying combination of different raw materials following different recipes. This mix depends on the properties of the raw materials which are included in the different kinds of recipes for producing different pulp products. The specific levels of raw materials needed or allowed for producing one unit of pulp of a particular kind are prescribed by a certain recipe. The pulp mills can run one recipe at a time, and accordingly producing one or two pulp products, with the exception of one Swedish pulp mill which can run two recipes simultaneously since it has two production lines. There are restrictions on what kinds of recipes that can be used at the pulp mills because of different processes at the mills, and also due to which specific chemicals are used for producing the pulp.

Depending on what kind of recipes that can be used at the pulp mills, different so-called production alternatives are presented. The main production decision is to decide which of the production alternatives to choose. Each production alternative gives a plan for what kind of recipes to use at each pulp mill, and that in turn decides which products are to be produced at each mill. A production cost is connected to each production alternative. These production costs represent the change-over costs related to the current production alternative settings at the mills (later referred to as Alternative 1).

Compared to the original model presented in Gunnarsson et al. (2007), our model is simplified with respect to the transportation possibilities. These transportation possibilities are aggregated in order to only represent one type of arc to each customer and this is based on the least cost perspective.

Customer demand is expressed in orders. Each order defines the type of products and the amount of products. The amounts are expressed within limits; a minimum and a maximum level for each product. Most orders are connected to contracts and if such contract is accepted, all the orders included have to be fulfilled. Orders not attached to any contract are optional to choose. If the revenues related to each order are considered to be attractive, the order will, if possible regarding to production capacities, be accepted.

How the procurement of raw materials and the production of pulp moreover connects to the energy supply at a typical case company pulp mill, is illustrated in Fig. 2. The energy supply at the pulp mills is generally self-sufficient, since the pulp is produced through the sulphate process. Large amounts of the energy-rich content of the raw materials are thus separated from the fibres and collected in the different co-products, hereafter referred to as the energy products. The amounts of these energy products produced, for example black liquor, liquid rosin and bark, are connected to specific characteristics of each recipe. Thus, the possible output of energy products is limited by the corresponding properties of the raw materials used for each recipe. The energy products are later the major contributors for the production of energy carriers such as steam and electricity that are needed in the pulp processes. The energy products can either be sold on the market, used in the boilers to create the energy carriers, or be stored for later use (see Fig. 2).

The conversion of energy products into energy carriers follows the rules of thermodynamics. The exergy content (or energy quality) of the energy products is vital and reflected in the quality of the energy carriers produced, limiting the output of electricity and low or medium pressure steam. The energy conversion also relates to the efficiencies of the boilers and turbines, which also have limited capacities, although they are not considered to be any bottlenecks for the pulp production today.

The energy market is limited with a maximum demand on steam and with no demand on black liquor. However, there is also a minimum demand on steam for district heating purposes, since steam is used to complement excess heat.

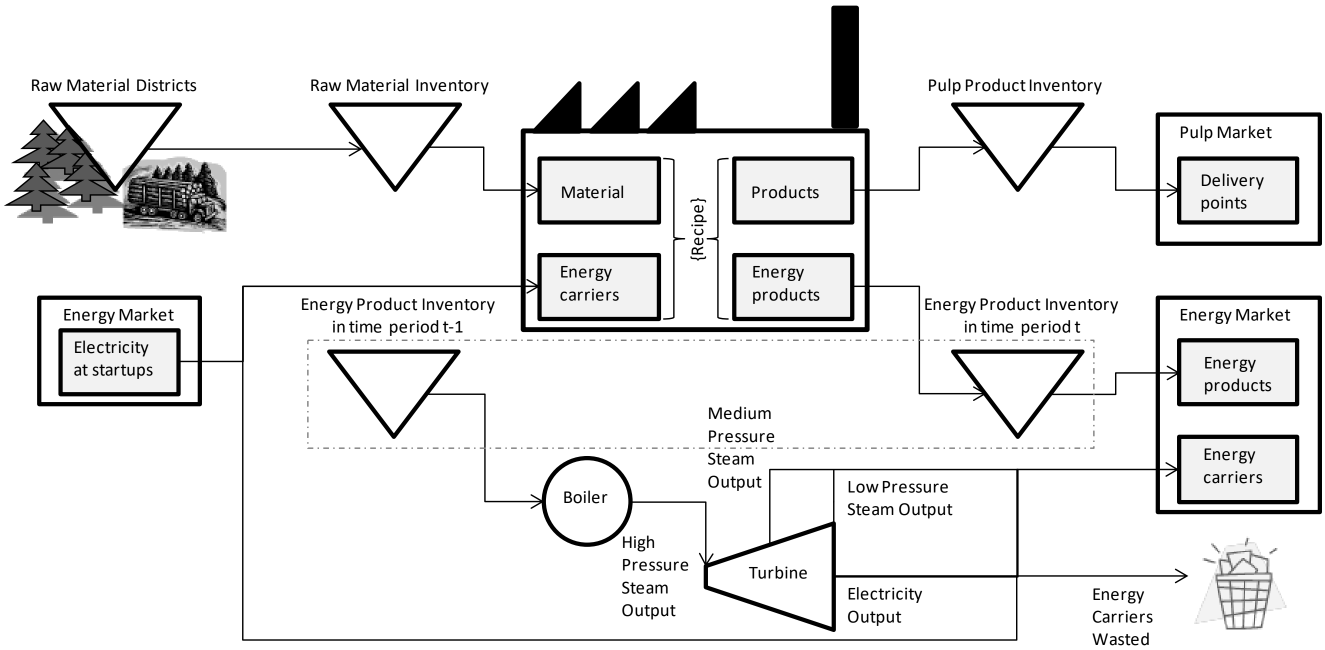

Fig. 2. An illustration of the supply chain structure and the energy system at a typical case company pulp mill.

3.2 Method

A mathematical model with the purpose of maximizing the profit is built. The model is summarized below and the complete version of the mathematical model can be found in the Appendix.

The model includes binary variables for choosing production alternatives and for choosing which contracts to accept. The continuous variables are variables that relate to how much raw material, pulp-related as well as energy-related, that should be used. This is done by choosing recipes and the necessary amount of these raw materials. There are also variables for how much energy products and carriers to use internally and how much of these to sell on the market. In addition, there are variables that represent the distribution of pulp products to the customers and the storage of both energy products and pulp products. The model takes different kinds of constraints into consideration. There are constraints for; supply and demand; capacity; making sure that the production follows the possible recipes, and balance of storage and flows. The model maximizes the profit, and the objective function includes costs for transportation, purchasing, storing, production, and distribution, and revenues from pulp products, energy products, energy carriers and green certificates. Green certificates are a tradable commodity whose purpose is to increase the incitement to produce electricity from renewable energy sources such as wind, solar, wave, gravitational (e.g. tidal), geothermal, hydro, or as in this case from biomass.

This model is based on the model presented in Waldemarsson et al. (2013) and is extended and refined according to the following considerations: Additional real data from the case company is used and has been refined in order to better represent the circumstances of the company. Different production-alternatives have been added. The capacities of the production facilities have been updated. Revenues from green certificates are also updated and separated from the electricity price. In this way, revenues from green certificates derive from electricity production, instead of from the electricity sold as in the previous model. An update of the possible output of energy products can be seen in constraint (20) and the new constraint (40) in the Appendix. This update is necessary for increased accuracy, since the measurements on the output of bark, for instance, are sometimes decoupled from when the production runs the recipe. The efficiencies of the boilers and turbines are refined and are now adapted to the differences between the different facilities. The capacities of the boilers and turbines are also added (see constraints (41)-(42) in the Appendix). The previously developed model presented in Gunnarsson et al. (2007) has been used in practice and is therefore validated. The new model presented in this paper is to some extent similar, but in order to ensure reliability the results have been presented and discussed with the company personnel. Thus, the changes made in this new model have been validated in several steps. New data, and the results obtained from the model using this data, have been validated through e-mails, interviews, and phone calls.

The problem is solved through a Mixed Integer Linear Programming (MILP) model with continuous and binary variables. The solution approach was to use the commercial linear programming solver CPLEX 10.0 directly, with default settings. The modelling language AMPL was used to model the problem. All the different scenarios were each solved in less than one minute on an Intel E5310 (4 core, 1.6 GHz) with 8 GB RAM. The solution time thus allows plenty of runs for scenario analysis within decent time limits.

Input data for the model has been collected in a case-based process in line with the procedures suggested by Yin (2009), involving meetings, interviews, e-mail conversations, and telephone meetings with several key informants within the company, all documented in a case study protocol. However, most of the data has been taken directly from the company's own budgeting data from 2011. Additional energy-related data has been collected from the company's own data base with historical measurements of the energy flows and parameters we are considering. By connecting these flows to historical data (on a yearly basis with daily intervals) on actual production (that is active recipes), we have calculated the weighted average key ratios for the possible energy exchanges in each recipe. One example of key ratio concerns the use of energy carrier per unit produced product.

The analysis phase was performed after running several different scenarios with the model and collecting the results in an Excel-based environment. For comparative reasons, all results were then converted to percentage change in relation to the scenario with the basic data settings.

3.3 Data

The problem consists of 40 different raw material districts supplying the four pulp mills with eleven different types of raw material which then are combined in different ways into twelve different raw material groups. From each raw material group, 20 different recipes combine the raw materials according to a given structure (see Table 1).

Table 1
Example of the needed raw materials for a specific recipe

Raw Material Group	Min content	Max content
Softwood	87%	94%
Wooden chips	6%	13%

Each of the mills can produce some of the total 15 products, which product depends on certain chemical and technological characteristics at each site. There are in total three production alternatives, and Alternative 1 is presented in Table 2. By choosing Alternative 1, for example, Product 1 (P1) can only be produced in Mill 4 whereas Line 1 at Mill 1 only produces Product 7 (P7) and so on.

Table 2
Alternative 1 for production at the pulp mills (and production lines).

Product	Mill1(1)	Mill1(2)	Mill2	Mill3	Mill4
P1					1
P2		1			
P3					1
P4				1	
P5			1		1

P6			1		1
P7	1				
P9			1		
P10				1	
P11					1
P12				1	
P13			1		1
P14		1			
P15			1		1

The other two alternatives are proposed to enable smoother solutions for two mills, and are therefore associated with negative change-over costs. Alternative 2 is based on Alternative 1 but excludes P5 and P6 at Mill4. Alternative 3 is based on Alternative 1 but excludes P13 and P15 at Mill2.

The total annual capacity varies between 1.8 and 2 million tons, depending on the production chosen. Demand is given through 250 different orders that either stand alone or belong to one of the 31 different contracts and originates from 142 different customers. The planning horizon of one year is divided into twelve periods.

On the output side we also find the energy products in a mix depending on the recipe chosen (see Table 3). This mix moreover depends on the limitations from its used raw materials seen in Table 4.

Table 3
Example of two recipes (R1 and R2) and their output of energy products (in MWh/ton pulp produced).

	Bark	Black Liquor	Methanol	Liquid Rosin	Turpentine
R1	3.092	5.842	0.045	0.439	0.000
R2	0.000	6.831	0.050	0.197	0.011

Table 4
Example of output of energy products depending on the raw materials used; M04 and M12 (in MWh/m^3).

	Bark	Black Liquor	Methanol	Liquid Rosin	Turpentine
M04	0.000	1.326	0.154	0.154	0.154
M10	0.124	1.409	0.301	0.301	0.301

The energy products are then either sold or used as fuel in the boilers in order to produce the energy carriers medium pressure steam (MPS), low pressure steam (LPS), and electricity through the turbine. The need for these energy carriers varies depending on the recipe chosen (see Table 5).

Table 5
Example of two recipes (R1 and R2) and their required input of energy carriers (in MWh/ton pulp).

	Electricity	MPS	LPS
R1	0.742	0.865	3.403
R2	0.630	0.459	3.271

In this paper, data regarding the input of energy carriers and output of energy products for each recipe is complemented with data from two additional mills, whereas the lack of data representing the fourth mill is instead replaced by weighted averages from similar recipes used at the others. This makes the recipes more unique regarding their energy conditions than the corresponding recipes in the previous study presented in Waldemarsson et al. (2013).

Revenues from electricity are divided into two parts: one based on the electricity market price at Nord Pool Spot (monthly average), and one based on the green certificates (monthly average). All price data is from 2011. The interest rate is based on a yearly rate of 10% (monthly 0.8%) and applied to inventories at both sites and further downstream in the supply chain. The interest rate is derived from the discount rate for the company at the time for the study. For raw materials at the forest districts, an annual interest rate of 0.5% is used, since it is outside the company's system but within the owner's preferences. In this paper the characteristics in the energy conversion is individual for each site (see Table 6).

Table 6
Characteristics for the energy conversion.

	Boiler efficiency [b_i]	Max electricity output [h_i^{max}]*
Mill1	0.896	0.180
Mill2	0.803	0.300
Mill3	0.853	0.176
Mill4	0.850	0.180

* Electricity production output in relation to steam input.

The problem consists of 27 binary and 31655 linear variables and 7851 constraints. Input data is verified and validated through the company personnel. For more details about the problem size and the model validation see Waldemarsson et al. (2013).

3.4 Scenario description

Since the purpose is to analyse the impact of energy price changes on the supply chain planning and the production planning, we want to reveal the consequence, due to each price change, that the model suggests for the planning solution. Hence, the modelled problem is analysed using different scenarios presented in Table 7. These scenarios are chosen partly because of previous results (Waldemarsson et al., 2013), and also because they are in line with discussions in both the research community and the case company. The design of the set of scenarios is made in order to enable investigations on how the model behaves under certain energy price conditions, and in order to be able to reveal cause- and effect relations relevant for the planning problem considered. The scenarios can be categorized into four groups: basic settings and alternatives (A) (described in the section "Data"), energy relaxation and alternatives (B), energy price changes (C), and open energy capacity and demand (D). Hence, scenario A0 represents the current state or basic scenario using the basic data settings in which the model suggests a solution without the influence of any price changes, market adjustments, or forces to select a specific production alternative.

Table 7
List of different scenarios.

	Scenario description.
A0	Basic data settings.
A1	Only Alternative 1 is allowed.
A2	Only Alternative 2 is allowed.
A3	Only Alternative 3 is allowed.
B0	Energy is relaxed from the objective function.
B1	Energy is relaxed from the objective function and only Alternative 1 is allowed.
B2	Energy is relaxed from the objective function and only Alternative 2 is allowed.
B3	Energy is relaxed from the objective function and only Alternative 3 is allowed.
B4	Price on all energy is 0.
C1	Electricity price change from -50% to +50%.
C2	Price on green certificates change from -50% to +50%.
C3	Both electricity price and price on green certificates change from -50% to +50%.
C4	Price on co-products (referred to as energy products) change from -50% to +50%.
C5	Price on all energy parameters change from -50% to +50%.
D0	Unlimited demand on all energy products and carriers, and unlimited capacity in boilers and turbines.

When relaxing energy from the objective function, the costs and revenues for energy are separately calculated, and after optimization, included in the total profit. The change of a parameter, between the end-points from -50% to +50%, is made in 20 steps of 5% each.

4 ANALYSIS OF RESULTS

Considering the size of the model, there are plenty of data results to analyse. An overview of some selected results from the scenarios can be seen in Table 8, where the results are given in percentage difference from the basic data settings (A0). In the first part of this chapter, overview of results, all scenarios are analysed, whereas the remainder part of the chapter focuses on analysing the results from scenarios C1- C5.

4.1 Overview of results

In Table 8, the results from scenarios A1, A3, B0-B4, C1-C5 end points (-50% and +50%), and D0 are presented. For analytical purposes, profit is divided into two parts: PulpProfit and EnergyProfit, as seen in Table 8. These parts are the normalized profits according to the revenue (rev.) from pulp and energy respectively, and are presented to more clearly locate the impact of each change. Similarly, revenues are divided into four parts: pulp (Rev. Pulp), energy products (Rev. EnProd), energy carriers (Rev. EnCarr), and green certificates (Rev. GreenC). The solution for A2 is the same as the one for A0, since the model selects Alternative 2 in the basic scenario A0, and is thus not shown in Table 8. In fact, the model selects Alternative 2 in all scenarios, unless the scenario forces another Alternative. The solution for B2 is not the same as B0 except for the pulp part. Production and sales of energy products and energy carriers differ in B0-B3, which is natural when the model has the possibility to randomly choose a solution for the aspects not involved in the objective function. Also note that only the results for the end-points in scenario C1-C5 are presented in Table 8. How the result appears in-between these end-points is further investigated later in this paper.

As can be seen in Table 8, the use of energy carriers; Electricity, MPS, and LPS decreases by about 0.5% to 4% when energy is relaxed from the objective function or set to zero (scenario B1-B4). At the same time, the production of pulp decreases by about 2% which indicates a different production mix in which pulp products of less energy importance have been chosen. One of the reasons is that the model lacks the incitement to increase the production of electricity for the purpose of internal use and thereby increase revenues from green certificates among these scenarios. This will be further investigated in the next part of our analysis, where we focus on the results of energy price changes (scenarios C1-C5), in order to reveal how various energy price changes are handled by the model. In Fig. 3 to Fig. 15 the results are presented in terms of relative change to the base setting (vertical axis) as a function of the changed parameter in the corresponding scenario (horizontal axis). As such, the consequence that the model suggests for the supply chain planning and the production planning solution, due to each price change is analysed. First, we look at the price change effect on the objective function (Fig. 3 to Fig. 7). This is followed by an analysis of how the total pulp production volumes change for each pulp mill (Fig. 8 to Fig. 11). Thereafter we look at the energy carrier production and the use of energy per ton pulp produced (Fig. 12 and Fig. 13). Finally, we analyse how energy price changes affect the incitement to produce specific products at a specific pulp mill (Fig. 14 and Fig. 15) as well as how the model suggests sales to differ, and how the scheduling of a single product is suggested to change (Fig. 16 and Fig. 17).

Table 8
Overview on the results from scenarios A1, A3, B0-B4, C1-C5 end points (-50% and +50%), and D0. The results are presented as relative difference, in percent, from scenario A0 (Basic data settings) where the largest anomalies are marked in green (positive) or red (negative).

(Diff. in %)	A1	A3	B0	B1	B2	B3	B4	C1		C2		C3		C4		C5		D0
								-50%	+50%	-50%	+50%	-50%	+50%	-50%	+50%	-50%	+50%	
Total Profit	-0.13	-0.36	-18.02	-18.23	-17.81	-18.82	-20.69	-3.34	4.04	-1.34	1.38	-4.57	5.52	-4.77	5.84	-10.73	11.28	1.76
PulpProfit	-0.14	-0.45	-8.44	-8.51	-8.24	-9.12	-8.75	-1.23	1.49	0.05	-0.02	-1.12	1.46	-2.35	2.88	-4.25	3.61	1.01
EnergyProfit	-0.07	0.24	-81.62	-82.75	-81.32	-83.22	-100.00	-17.39	20.93	-10.61	10.65	-27.52	32.47	-20.81	25.49	-53.73	62.24	6.73
Rev. Pulp	-0.01	0.10	-1.42	-1.39	-1.42	-1.56	-1.42	-0.92	-1.33	-0.19	-0.04	-1.35	-1.36	-1.97	0.34	-1.77	-1.58	0.17
Rev. EnProd	0.01	-1.34	-99.41	-97.70	-94.28	-98.28	-100.00	6.11	-9.49	4.89	-0.48	5.81	-12.98	-73.86	61.30	-51.93	57.09	-18.70
Rev. EnCarr	-0.62	2.71	-85.07	-89.20	-89.39	-89.82	-100.00	-53.67	64.59	-6.41	0.45	-55.17	68.53	28.57	-9.60	-54.47	62.57	46.55
Rev. GreenC	0.09	0.73	-36.31	-38.94	-38.80	-38.91	-100.00	-8.95	6.77	-51.93	51.56	-55.80	63.53	14.49	-4.69	-53.38	55.25	-4.92
Total Costs	0.04	0.46	-2.89	-2.85	-2.94	-2.79	-3.15	-1.88	-1.72	-0.34	-0.05	-2.69	-1.76	-3.45	0.53	-3.40	-1.23	0.20
El. use/ton pulp	0.17	-0.65	-0.54	-0.43	-0.54	-0.94	-0.54	-0.20	0.67	-0.09	0.21	-0.47	0.88	0.56	-0.13	-0.41	0.04	0.26
LPS use/ton pulp	0.07	-0.60	-3.68	-3.66	-3.68	-4.17	-3.68	-0.93	0.97	-0.01	0.13	-1.35	1.09	0.30	-0.24	-1.33	0.45	-0.36
MPS use/ton pulp	0.20	-0.82	-1.55	-1.35	-1.55	-1.99	-1.55	-0.54	0.90	-0.07	0.18	-0.92	1.09	0.41	-0.14	-0.92	0.59	0.03
Pulp production	-0.03	0.21	-1.96	-1.96	-1.96	-1.96	-1.96	-1.09	-1.59	-0.22	-0.02	-1.59	-1.61	-2.07	0.30	-1.99	-1.14	0.15
El. production	-0.13	0.91	-29.65	-29.34	-30.75	-31.07	-29.65	-6.33	4.37	-2.12	0.27	-7.90	5.60	10.92	-2.68	-5.10	2.81	-5.20
MPS production	0.17	-0.61	-2.50	6.47	-0.10	3.58	-2.50	-1.63	-0.71	-0.29	0.16	-2.49	-0.55	-1.67	0.16	-2.90	-0.56	65.42
LPS production	0.17	-0.36	-6.39	-5.38	-6.22	-7.04	-6.39	-0.96	-0.12	-0.40	0.31	-1.64	0.19	1.92	0.07	-1.84	-1.03	-5.00

4.2 Price change effect on the objective function

In order to see some changes in profit, costs, and revenues among the scenarios C1 to C5, their results, as relative difference, in percent, from scenario A0, are plotted in Fig. 3-Fig. 7 (vertical axis), as a function of the changed parameters (horizontal axis). The parameters for each scenario are previously stated in Table 7 to: electricity (C1), green certificates (C2), both electricity and green certificates (C3), energy products (C4), and all energy parameters (C5).

There is a clear connection between the revenues from energy products and the revenues from energy carriers, although their behaviour is not totally linearly dependent as seen in Fig. 3 and Fig. 5, their trade-offs are clearly illustrated in Fig. 4. Both the total costs and the pulp revenues increase at first to later decrease as a reaction to the changed price of electricity and green certificates (Fig. 3 and Fig. 5), but their reaction to the changed price of energy products is to increase stepwise all the way (Fig. 6). In scenario C5, where all energy price parameters increase from -50% to +50%, the pulp related profit increases all the way while the pulp related revenues first increase and later decrease (Fig. 7). This indicates that the energy related revenues have a proportionally greater leverage effect on the total profit than the pulp revenues when the energy prices increase above the current level.

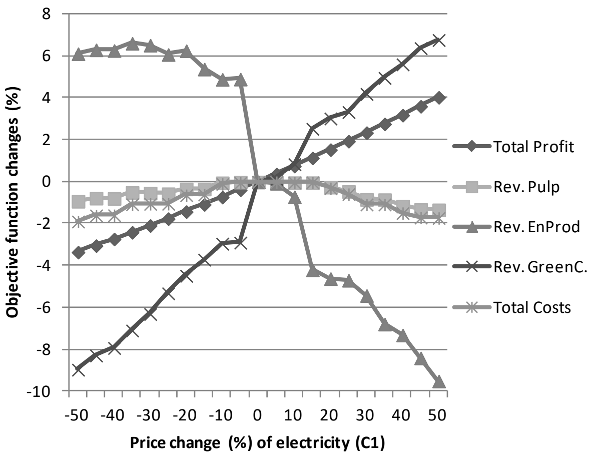

Fig. 3. Results from scenario C1: influence on the objective function (as relative difference, in percent, from scenario A0), when the *electricity price* parameters change between -50% to +50% (the end points). Due to visual aspects of the diagram, Rev. EnCarr is not plotted since its change from -54% to +65% is practically linear between the end-points of scenario C1.

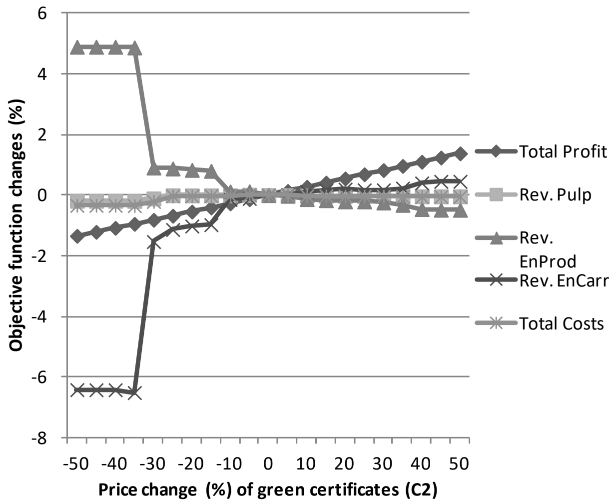

Fig. 4. Results from scenario C2: influence on the objective function (as relative difference, in percent, from scenario A0), when the *green certificate price* parameters change between -50% to +50% (the end points). Rev. GreenC is not plotted since its change from -52% to +52% is practically linear between the end-points.

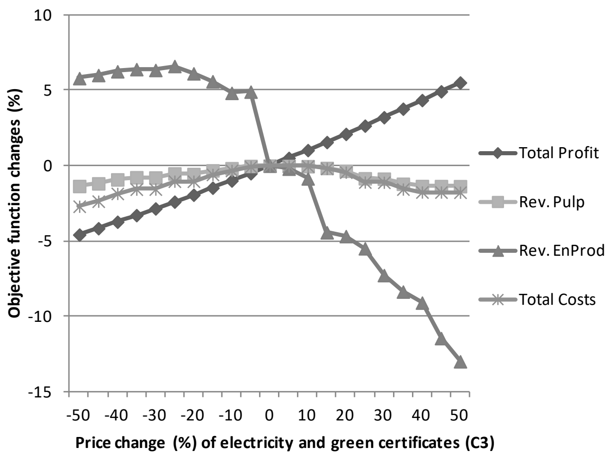

Fig. 5. Results from scenario C3: influence on the objective function (as relative difference, in percent, from scenario A0), when the *electricity price* and *green certificate price* parameters changes between -50% to +50% (the end points). Neither Rev. EnCarr, nor Rev. GreenC, are not plotted since their change from -55% to +69%, as well as from -56% to +64%, is practically linear between the end-points.

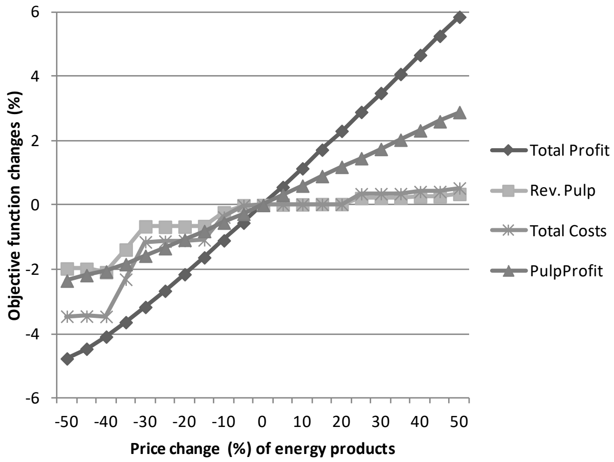

Fig. 6. Results from scenario C4: influence on the objective function (as relative difference, in percent, from scenario A0), when the *energy product price* parameters change between -50% to +50% (the end points). Rev. EnProd changes almost linearly from -74% to +61%, whereas Rev. EnCarr drops gradually from about 29% and then fade out at around -10%. These are not plotted due to visual aspects of the diagram.

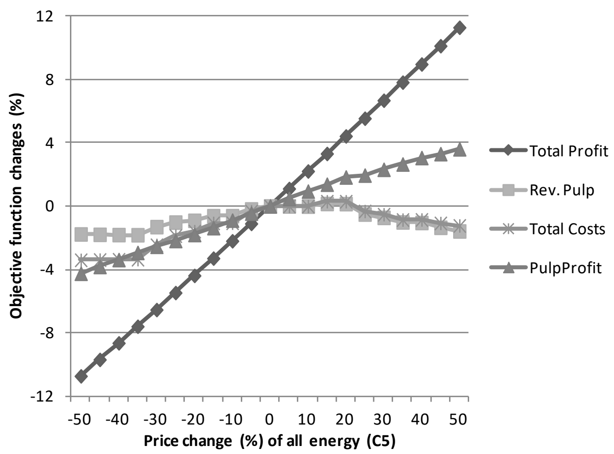

Fig. 7. Results from scenario C5: influence on the objective function (as relative difference, in percent, from scenario A0), when *all energy price* parameters change between -50% to +50% (the end points). Due to visual aspects of the diagram, the following parts of the objective function [and their change between the end-points] are not plotted: EnergyProfit [-54% to +62%], Rev. EnProd [-52% to +57%], Rev. EnCarr [-54% to +63%], and Rev. GreenC [-53% to +55%], since their respective change is practically linear.

4.3 Production volumes at each pulp mill

The model suggests what volumes to produce at the pulp mills when the price of energy carriers and energy products changes. The pulp production results for Mill1, Mill2 and Mill4 for scenarios C1-C5 are presented in Fig. 8-Fig. 10 where they are plotted in relation to the price changes of each scenario. The model suggests no change of the pulp production volumes for Mill3 to these scenario changes, and this is therefore not plotted in its own figure. The results indicate the conditions under which a specific mill is preferred to be utilized the most. To exemplify, an increasing price of electricity and green certificates makes the production allocation to shift among the Mills; it seems to shift mostly from Mill1 to Mill4 during a price increase, but also from Mill2 to Mill1 and Mill4 during a price decrease. This is presented in Fig. 8-Fig. 10 but can be seen more clearly in Fig. 11. A price change for energy products, however, reverses the shift, as can be seen by comparing the C4 scenario results in Fig. 8-Fig. 10. Price changes for energy carriers and green certificates seem to have a higher impact on the production volume than the price changes for energy products, as can be seen in the results of C5, where all energy price parameters change. Mill1 shows sensitivity to an increased price of electricity and green certificates, but also to a decrease in energy product prices. The production volume at Mill2 is by the model suggested to decrease if energy prices drop beyond 20% (compared to the prices in 2011), in which the scenario for a price drop for all energy (C5) has the highest impact. On the contrary, Mill4 is suggested to increase its volumes for the most extreme price drops, except for a price drop in green certificates.

The capacity utilization for the studied mills is rather high, which is normal for process industries where production mostly runs around the clock all year around. The data used is for yearly budgeting purposes and the production normally covers about 90% of the total capacity, which therefore allows the total production volumes to increase further. For minor price changes, the overall capacity utilization remains more or less the same, but increase or decrease for some pulp mills when the energy price changes are pushed to their extremes.

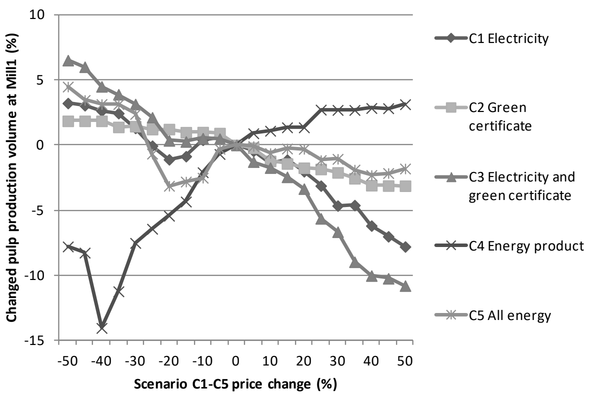

Fig. 8. Results from scenario C1-C5: changed pulp production volumes at Mill1 (as relative difference, in percent, from scenario A0), when *each scenario price* parameter change between -50% to +50% (the end points).

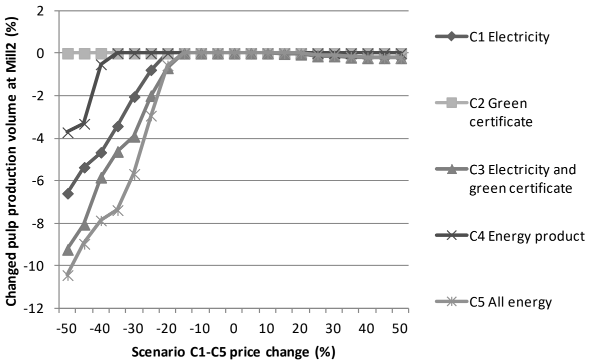

Fig. 9. Results from scenario C1-C5: changed pulp production volumes at Mill2 (as relative difference, in percent, from scenario A0), when *each scenario price* parameter change between -50% to +50% (the end points).

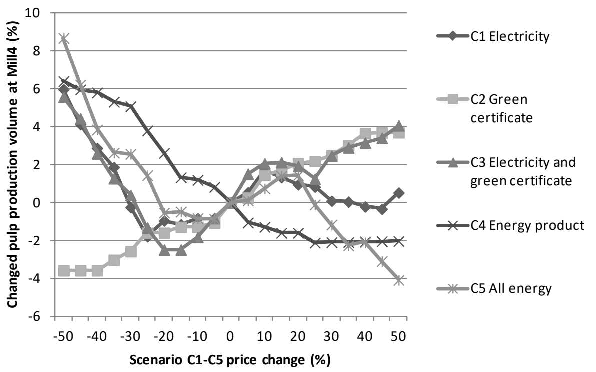

Fig. 10. Results from scenario C1-C5: changed pulp production volumes at Mill4 (as relative difference, in percent, from scenario A0), when *each scenario price* parameter change between -50% to +50% (the end points).

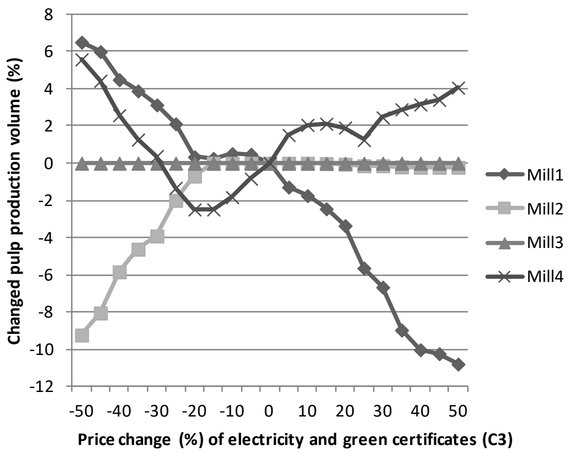

Fig. 11. Results from scenario C3: changed pulp production volumes at Mill1-Mill4 (as relative difference, in percent, from scenario A0), when the *electricity price and green certificate price* parameters change between -50% to +50% (the end points).

4.4 Use of energy

The relationship between pulp produced and produced energy carriers as well as the use of energy carriers per ton produced pulp is also analysed in this paper. As such, analysing results from scenario C1 and C2 is somewhat embedded in the analysis of scenario C3 results. Meanwhile, as scenario C5 involves all energy parameters an analysis of its results provides us small possibilities to distinguish differences between the energy carrier (consumption) side and the energy product (production) side of this analysis. Therefore, results from two scenarios are chosen for this analysis: C3 representing changes on energy carrier prices (Fig. 12); and C4 representing changes on energy products prices (Fig. 13). Energy use per ton increases when the prices of electricity and green certificates increase. This is contrary to some of the results in Waldemarsson et al. (2013) but also natural when there are incitements to increase electricity production due to revenue possibilities on green certificates. On the other hand, for a price increase in energy products, the use of energy per ton is more stable and shows a slight decrease at first and less change for further price increases. A lower price of energy products also has a clear, but not linearly proportioned, impact on the electricity production. However, although electricity production increases all the way in C3, pulp production first increases to later decrease (also seen in Fig. 5 for pulp revenue). This indicates that a different production mix is used, allowing more electricity production with a slight increase of energy use per ton pulp. In other words, there are products that require a higher energy use per ton but that also provide a larger surplus of energy for the market and thus increase total profitability. This reveals the importance of each product's uniqueness and how it relates to both the company's profit and its energy effectiveness.

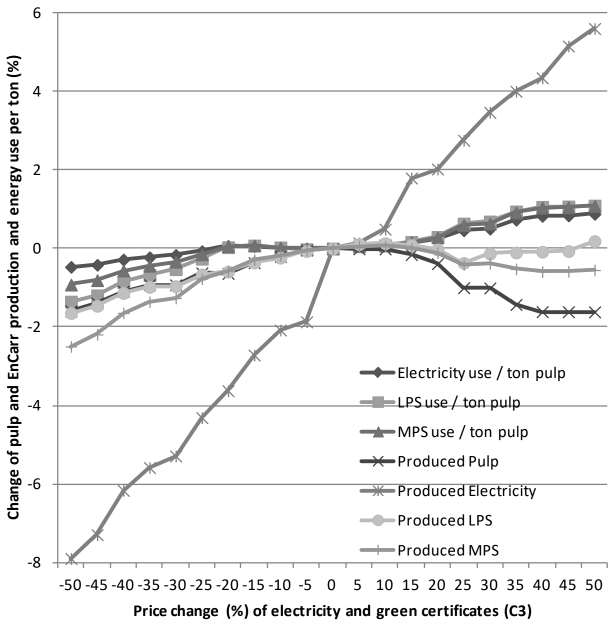

Fig. 12. Results from scenario C3: use of energy (as relative difference, in percent, from scenario A0), when the *electricity price* and *green certificate price* parameters change between -50% to +50% (the end points).

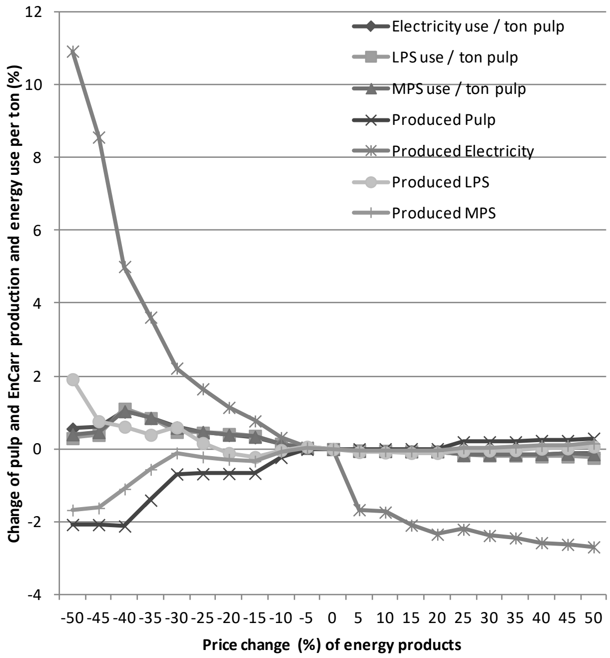

Fig. 13. Results from scenario C4: use of energy (as relative difference, in percent, from scenario A0), when the *energy product price* parameters change between -50% to +50% (the end points).

4.5 Production mix and scheduling

The production mix chosen also varies among the scenarios as exemplified in Fig. 14 (results from C3) and Fig. 15 (results from C4), where the production volume for some products differs. Production of product 2 (P2) at Mill1 shows dramatic changes in both scenarios, where the model suggests to increase its production due to higher energy product prices but decrease its production along rising prices of electricity and green certificates. The production of P13 at Mill2 is first suggested to decrease and thereafter increase along with rising energy product prices. Moreover, production of P13 at Mill2 volume is suggested to increase along decreasing prices on electricity and green certificates, whereas only a smaller volume decrease is suggested for additional price increase. The model also suggests that the production of P1 at Mill4, P5 at Mill2, and P14 at Mill1 increases slightly at higher prices of electricity and green certificates as well as to decrease slightly at higher energy product prices. Moreover, the production of P1 at Mill4 is suggested to increase, whereas the production of P5 at Mill2 and P14 at Mill1 are both suggested to decrease, at the extremes of price decrease in both scenarios C3 and C4. Each product's uniqueness and how it relates to the company's profit and energy effectiveness is thus also shown to be related to each mill and its energy efficiency.

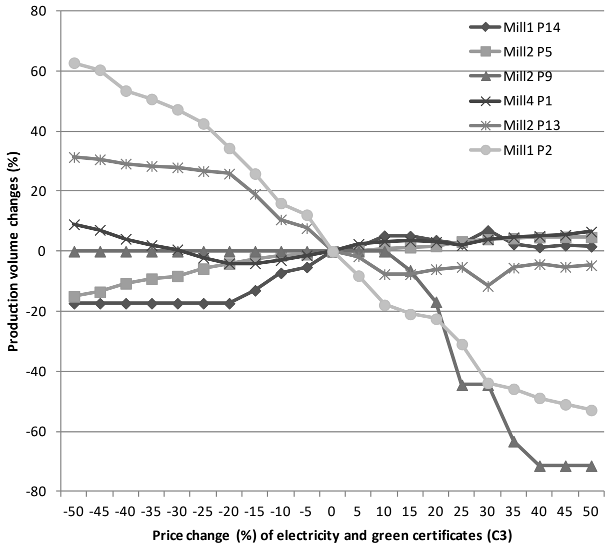

Fig. 14. Results from scenario C3: production volume changes for some products (as relative difference, in percent, from scenario A0), when the *electricity price* and *green certificate price* parameters change between -50% to +50% (the end points).

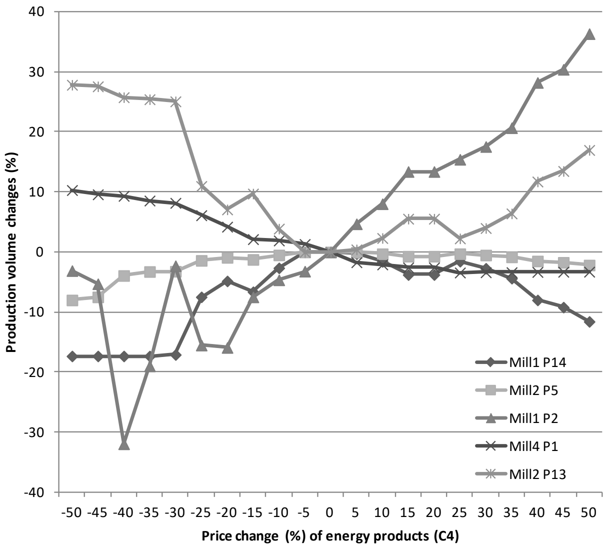

Fig. 15. Results from scenario C4: production volume changes for some products (as relative difference, in percent, from scenario A0), when the *energy product price* parameters change between -50% to +50% (the end points).

Looking at the sales and order fulfilment, we can also conclude that the model provides different suggestions for the production volumes that should be accepted for each order and consequently also the volumes to be delivered to a specific delivery point. One example of this change is provided in Fig. 16 (results from C5) where the yearly pulp deliveries are provided for a representative selection of orders and delivery points. Note that several different orders can be connected to the same delivery point. We can also see in Fig. 17 (results from C5) a different suggested scheduling at each extreme edge of the price changes. From this we can conclude that not only the total volume changes, but also the time period in which it is suggested to be produced, since several different products compete for a limited capacity. For this analysis results from scenario C5 are chosen in order to investigate how both the production mix and the scheduling are affected by changed energy prices in general. It is reasonable to assume that there are correlations between the energy prices at both the energy carrier (consumption) side as well as the energy product (production) side of the supply chain. By analysing the results from scenario C5 in this matter, such correlation is considered, and we can hence conclude that changed energy prices in general are enough for the model to suggest a different solution with a different sales plan and a different production schedule.

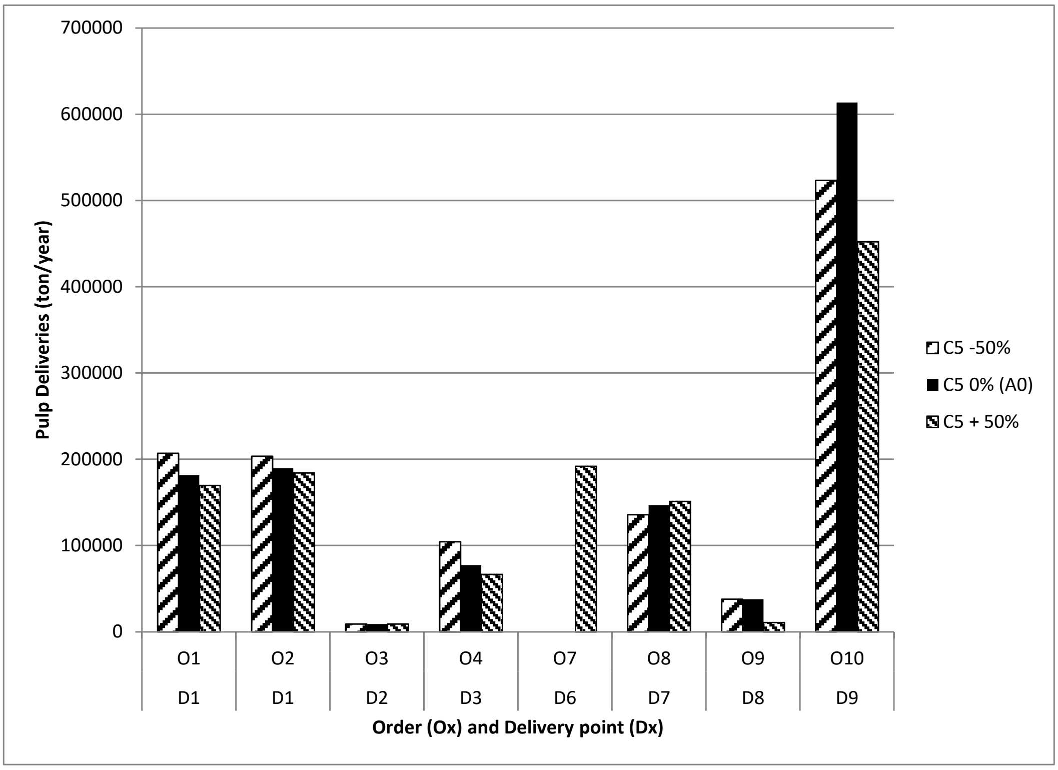

Fig. 16. Results from scenario C5: illustrating how sales according to some orders and deliveries to some delivery points (in ton/year) occur at the end points where *all energy price* parameters change with -50% or +50%, as well as the corresponding sales in the scenario with no change (0%), that is the basic setting (scenario A0).

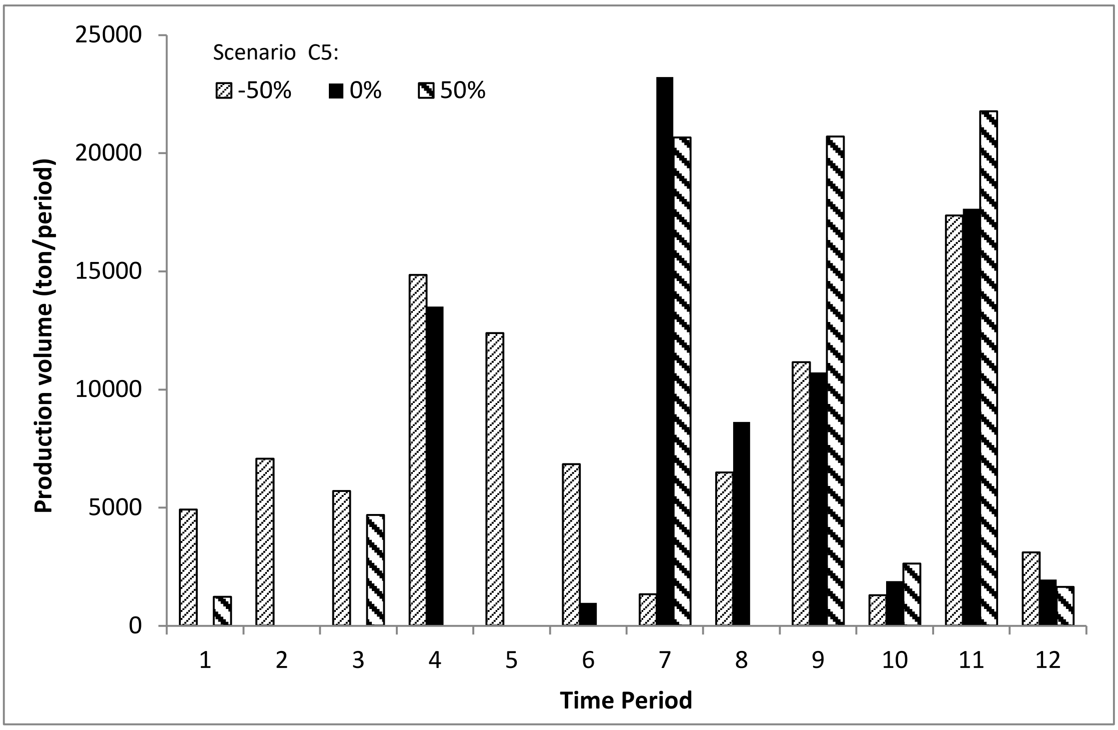

Fig. 17. Results from scenario C5: illustrating the suggested scheduling of a single product at the end points where *all energy price* parameters change with -50% or +50%, as well as the suggested scheduling in the scenario with no change (0%), that is the basic setting (scenario A0).

4.6 Industrial applicability

Changing the planning in a large company requires decisions founded on good underlying analyses that are based on hard facts and evidence. Our analysis is based on real data from the company, although the measurement of the data and the data mining have to some extent been beyond the direct control of the researchers. Decisions made based on such analyses are thus directly connected to the reliability of the data used in the model. This calls for a more in-depth control and verification of the results before any major decision is made. However, from the analysis of the results, and given the market conditions provided, it is recommended that the case company considers the guidelines presented in Table 9 and Table 10. In Table 9, suggestions are provided for where and when pulp production should be increased or decreased at each mill, in the case of a specific scenario. In Table 10, a similar suggestion is provided for some pulp products at a specific site for situations when prices on electricity and green certificates or energy products increase or decrease.

Table 9
Guidelines for decision-making on pulp production volume allocations per pulp mill.

Scenario price changes	Unit of Analysis	Mill1 (Fig. 8)	Mill2 (Fig. 9)	Mill3	Mill4 (Fig. 10)
C1: Electricity	drop	less[1]	-[3]	-	less[1]
	rise	less	-	-	more
C2: Green certificates	drop	more	-	-	less
	rise	less	-	-	more
C3: Electricity and green certificates (Fig. 11)	drop	more	-[3]	-	less[1]
	rise	less	-	-	more
C4: Energy products	drop	less	-[4]	-	more
	rise	more	-	-	less
C5: All Energy	drop	less[1]	-[3]	-	less[2]
	rise	less	-	-	more[5]

[1] Increase production if the prices drop with more than 30%.
[2] Increase production if the prices drop with more than 25%.
[3] Decrease production if the prices drop with more than 20%.
[4] Decrease production if the prices drop with more than 40%.
[5] Decrease production if the prices rise with more than 25%.

Table 10
Guidelines for decision-making of pulp production volume allocations per pulp mill and product.

Scenario price changes	C3: Electricity and green certificates (Fig. 14)		C4: Energy products (Fig. 15, except P9)	
Unit of Analysis	drop	rise	drop	rise
P1 Mill4	less[1]	(more)	more	(less)
P2 Mill1	more	less	less	more
P5 Mill2	less	(more)	less	(less)
P9 Mill2	-	less	less	less
P13 Mill2	more	(less)	more	more
P14 Mill1	less	(more)	less	less

[1] Increase production beyond a price change of -30%.

To generalize the suggestions and guidelines provided for the case company, presented in Table 9 and Table 10, into industrial applicability in a broader context requires further investigations and more cases to study. However, this paper contributes with an example of how such guidelines can be developed for other cases with a similar industrial planning problem. The underlying analysis for these guidelines is taken from a cause-and-effect perspective on how the supply chain planning model reacts on different parameter changes of, in this paper, several different scenarios with energy price changes. As future research opportunities in such matter, it could be possible to consider other parameter changes, such as prices or costs related to different kinds of emissions, especially with regards to the transportation costs for procurement of raw materials and distribution of finished goods. There are also scheduling aspects, involving set-up costs and batch sizes, which are worth considering for evolvement of the model while striving for industrial applicability.

5 CONCLUDING REMARKS

In this paper we analyse the possible impact of energy price changes on supply chain planning and production planning at a pulp company. A MILP model (presented in Appendix) has been built based on the model presented in Waldemarsson et al. (2013), from which it is extended and refined. It considers not only pulp products but also the energy-intensive raw material for the pulp production, from both the raw material and a revenue generating perspectives. Using our model, the impact of energy price changes is analysed through several different scenarios, presented in Table 7, involving changes in production alternatives and energy prices. This is done in order to analyse the whole spectra of energy price fluctuations, and not just the end-points of each scenario price change, as done in Waldemarsson et al. (2013). Triggered by a scenario price change, our model suggests a different planning solution for the supply chain of the pulp company, and our analysis shows that the results are mostly non-linearly dependent on the change of input parameters.

Findings show that the model chooses Alternative 2 unless otherwise forced by constraints, indicating that the change-over cost for using Alternative 2 is small enough to promote this choice among the scenarios analysed. However, the case company made an announcement in the final stage of this study that its supply chain structure, as well as its production alternatives, are likely to change in the near future, thus calling for a different structure with different change-over costs among the alternatives. Nevertheless, the energy aspects analysed here have shown a great impact on the supply chain planning and the production planning. There is a trade-off between revenues from energy products and energy carriers, when the prices change, but these changes are not always linear. This shows that in its selection of pulp products to produce, the model considers not only costs for procurement, production and distribution, but also the pulp products influence on energy product output and its resulting energy possibilities. In other words, the embedded energy in the raw material, falling out as co-products (referred to as energy products), is considered important enough to change the planning of the company. Consequently, it is reasonable to map the contribution from each product based on its true structure of costs and revenues, as could be enhanced using our model.

The use of energy carriers decreases when the energy prices are set to zero or relaxed from the objective function. This can be explained by the lack of incitements to produce more electricity for internal use and thus increase revenues from green certificates. Moreover, the energy use per ton is higher when the prices for electricity and green certificates increase, but electricity production also increases (Fig. 12) along with the different production mixes (Fig. 14), resulting in higher profit and showing the complexity of balancing economic and environmental considerations. However, since a higher use of renewable resources also results in more green electricity on the market, it might still be more environmentally friendly from a global perspective.

Biel and Glock (2016) call in their literature review for further investigation in planning models that consider energy prices that significantly change over time. Our model somewhat responds to this request by considering seasonal variations of energy prices, such as electricity prices based on monthly average. Moreover, the sensitivity analysis in our paper throughout the scenarios with different energy price changes also further contributes to the field of developing decision support models in this context. For example, triggered by energy price changes the model suggests to shift production between the different production facilities, and there are also changes in production volumes suggested for some products. The different characteristics of the products and how they are produced thus certainly impact the supply chain and production when energy price changes are considered. This is also connected to the energy efficiency of each pulp mill and is therefore an important part of the overall energy effectiveness of the company.

To conclude, through our findings, we argue to emphasize the importance of pricing the final products on the basis of not only their pulp characteristics but also their embedded energy characteristics. As such we can conclude that, at least for the energy intensive process industry segment, there is a large potential in developing planning and scheduling applications where such embedded characteristics are taken into account, which calls for future research to follow up. Another future research possibility is to generalize the model and make it more useful for other process industries. All things considered, our research shows that different energy aspects affect the supply chain planning and the production planning in a number of ways and should therefore be considered in such decision making processes.

6 ACKNOWLEDGEMENTS

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APPENDIX

In this appendix the mathematical model with the purpose of maximizing the profit is presented.

Objective function:

$$
\begin{aligned}
max \sum_{i\in I}\sum_{p\in P}\sum_{s\in S}\sum_{q\in Q}\sum_{t\in T} p_p^{SP} p_{pq}^{Q} y_{ipsqt}^{SP} + \sum_{n\in N}\sum_{i\in I}\sum_{t\in T} p_{nt}^{N} y_{nit}^{SN} \\
+ \sum_{e\in E}\sum_{i\in I}\sum_{t\in T} p_{eit}^{E} y_{eit}^{SE} + \sum_{i\in I}\sum_{t\in T} p_i^{GC} k_i^{GC} w_{it}^{El} \\
- \sum_{d\in D}\sum_{m\in M}\sum_{i\in I}\sum_{t\in T} (c_{dmi}^{TM} + c_{dm}^{M}) w_{dmit}^{FM} - \sum_{i\in I}\sum_{l\in L}\sum_{p\in P}\sum_{r\in R}\sum_{t\in T} c_r^{R} u_{ilprt}^{P} - \sum_{a\in A} c_a^{A} z_a^{A} \\
- \sum_{i\in I}\sum_{p\in P}\sum_{s\in S}\sum_{q\in Q}\sum_{t\in T} c_{is}^{TM} y_{ipsqt}^{SP} - \sum_{d\in D}\sum_{m\in M}\sum_{t\in T} c_{dm}^{FMstor} L_{dmt}^{FM} \\
- \sum_{m\in M}\sum_{i\in I}\sum_{t\in T} c_{mi}^{MMstor} L_{mit}^{MM} - \sum_{i\in I}\sum_{p\in P}\sum_{t\in T} c_{ip}^{MPstor} L_{ipt}^{MP} - \sum_{m\in M}\sum_{i\in I}\sum_{t\in T} c_{ni}^{MNstor} L_{nit}^{MN}
\end{aligned}
$$

Constraints:

$$\sum_{i\in I}\sum_{t\in T} w_{dmit}^{FM} \leq s_{md} + L_{dm0}^{FM}, \quad \forall m \in M, d \in D \tag{1}$$

$$L_{dmt-1}^{FM} + s_{mt}^{S} s_{md} - \sum_{i\in I} w_{dmit}^{FM} = L_{dmt}^{FM} \qquad \forall d \in D, m \in M, t \in T \tag{2}$$

$$L_{mit-1}^{MM} + \sum_{d\in D} w_{dmit}^{FM} - \sum_{l\in L}\sum_{p\in P}\sum_{r\in R} w_{milprt}^{MM} = L_{mit}^{MM} \qquad \forall m \in M, i \in I, t \in T \tag{3}$$

$$\sum_{m\in M_{GL}}\sum_{p\in P} w_{milprt}^{MM} / a_{mil}^{M} \geq m_{m_g r}^{min} \sum_{p\in P} u_{ilprt}^{P} \qquad \forall\, m_g \in M_{GRL}, i \in I, l \in L, r \in R, t \in T \tag{4}$$

$$\sum_{m\in M_{GL}}\sum_{p\in P} w_{milprt}^{MM} / a_{mil}^{M} \leq m_{m_g r}^{max} \sum_{p\in P} u_{ilprt}^{P} \qquad \forall m_g \in M_{GRL}, i \in I, l \in L, r \in R, t \in T \tag{5}$$

$$\sum_{m\in M_{RL}}\sum_{p\in P} w_{milprt}^{MM} / a_{mil}^{M} = \sum_{p\in P} u_{ilprt}^{P} \qquad \forall i \in I, l \in L, r \in R, t \in T \tag{6}$$

$$\sum_{r\in R}\left(\left(\sum_{p\in P} u_{ilprt}^{P}\right) \Big/ \sum_{p\in P} r_{pr}^{P}\right) \leq g_{il}^{C} / |T| \qquad \forall i \in I, l \in L, t \in T \tag{7}$$

$$\left(\sum_{p\in P} u_{ilprt}^{P}\right) \Big/ \sum_{p\in P} r_{pr}^{P} \leq g_{il}^{C} / |T| \sum_{a\in A} e_{ra}^{R} z_a^{A} \qquad \forall i \in I, l \in L, r \in R, t \in T \tag{8}$$

$$\left(\sum_{p\in P}\sum_{t\in T} u^{P}_{ilprt}\right)\Big/\sum_{p\in P} r^{P}_{pr} \leq \sum_{a\in A} e^{R}_{ra} z^{A}_{a} g^{max}_{ilr} \tag{9}$$
$\forall i \in I, l \in L, r \in R$

$$\left(\sum_{p\in P}\sum_{t\in T} u^{P}_{ilprt}\right)\Big/\sum_{p\in P} r^{P}_{pr} \geq \sum_{a\in A} e^{R}_{ra} z^{A}_{a} g^{min}_{ilr} \tag{10}$$
$\forall i \in I, l \in L, r \in R$

$$u^{P}_{ilprt} = \left(r^{P}_{pr}\Big/\sum_{p\in P} r^{P}_{pr}\right)\sum_{p\in P} u^{P}_{ilprt} \tag{11}$$
$\forall i \in I, l \in L, p \in P, r \in R, t \in T$

$$\sum_{a\in A} z^{A}_{a} = 1 \tag{12}$$

$$L^{MM}_{mit} \leq L^{MMmax}_{mi}, \quad \forall m \in M, i \in I, t \in T \tag{13}$$

$$\sum_{p\in P} L^{MP}_{ipt} \leq L^{MPmax}_{i}, \quad \forall i \in I, t \in T \tag{14}$$

$$\sum_{i\in I}\sum_{t\in T} y^{SP}_{ipsqt} \leq z^{C}_{c} d^{Pmax}_{pq} \tag{15}$$
$\forall p \in P, s \in S, c \in C, q \in Q_C \cap Q_S \cap Q_{CC}$

$$\sum_{i\in I}\sum_{t\in T} y^{SP}_{ipsqt} \geq z^{C}_{c} d^{Pmin}_{pq} \tag{16}$$
$\forall p \in P, s \in S, c \in C, q \in Q_C \cap Q_S \cap Q_{CC}$

$$\sum_{i\in I}\sum_{t\in T} y^{SP}_{ipsqt} \leq d^{Pmax}_{pq}, \quad \forall p \in P, s \in S, q \in Q_F \cap Q_S \tag{17}$$

$$\sum_{i\in I}\sum_{t\in T} y^{SP}_{ipsqt} \geq d^{Pmin}_{pq}, \quad \forall p \in P, s \in S, q \in Q_F \cap Q_S, \tag{18}$$

$$L^{MP}_{ipt-1} + \sum_{l\in L}\sum_{r\in R} u^{P}_{ilprt} - \sum_{s\in S}\sum_{q\in Q_S} y^{SP}_{ipsqt} = L^{MP}_{ipt} \tag{19}$$
$\forall i \in I, p \in P, t \in T$

$$u^{N}_{nilrt} \leq \left(\sum_{p\in P} u^{P}_{ilprt}\Big/\sum_{p\in P} r^{P}_{pr}\right) r^{N}_{nr} \tag{20}$$
$\forall n \in N, i \in I, l \in L, r \in R, t \in T$

$$L^{MN}_{nit-1} + \sum_{l\in L}\sum_{r\in R} u^{N}_{nilrt} - w^{B}_{nit} - y^{SN}_{nit} = L^{MN}_{nit} \tag{21}$$
$\forall n \in N, i \in I, t \in T$

$$\sum_{n\in N} w^{B}_{nit} b_i = w^{MPS}_{it} + w^{LPS}_{it} + w^{El}_{it}, \quad \forall\, i \in I, t \in T \tag{22}$$

$$\sum_{n\in N} w^{B}_{nit} b_i h^{max}_{i} \geq w^{El}_{it}, \quad \forall\, i \in I, t \in T \tag{23}$$

$$\sum_{n\in N} w^{B}_{nit} b_i h^{min}_{i} \leq w^{El}_{it}, \quad \forall\, i \in I, t \in T \tag{24}$$

$$\sum_{n\in N} w^{B}_{nit} b_i \geq w^{MPS}_{it} + w^{El}_{it}/h^{max}_{i}, \quad \forall\, i \in I, t \in T \tag{25}$$

$$\sum_{l\in L}\sum_{p\in P}\sum_{r\in R} w_{eilprt}^{ME} + y_{eit}^{SE} + x_{eit}^{WE} = w_{it}^{MPS} \quad (26)$$
$$\forall\, e \in E_{MPS}, i \in I, t \in T$$

$$\sum_{l\in L}\sum_{p\in P}\sum_{r\in R} w_{eilprt}^{ME} + y_{eit}^{SE} + x_{eit}^{WE} = w_{it}^{LPS} \quad (27)$$
$$\forall\, e \in E_{LPS}, i \in I, t \in T$$

$$\sum_{l\in L}\sum_{p\in P}\sum_{r\in R} w_{eilprt}^{ME} + y_{eit}^{SE} + x_{eit}^{WE} = w_{it}^{El} \quad (28)$$
$$\forall\, e \in E_{El}, i \in I, t \in T$$

$$\sum_{p\in P} w_{eilprt}^{ME} / a_{er}^{E} \geq e_{er}^{min} \left(\sum_{p\in P} u_{ilprt}^{P} \Big/ \sum_{p\in P} r_{pr}^{P} \right) \quad (29)$$
$$\forall e \in E, i \in I, l \in L, r \in R, t \in T$$

$$\sum_{p\in P} w_{eilprt}^{ME} / a_{er}^{E} \leq e_{er}^{max} \left(\sum_{p\in P} u_{ilprt}^{P} \Big/ \sum_{p\in P} r_{pr}^{P} \right) \quad (30)$$
$$\forall e \in E, i \in I, l \in L, r \in R, t \in T$$

$$L_{nit}^{MN} \leq L_{ni}^{MNmax}, \;\; \forall n \in N, i \in I, t \in T \quad (31)$$

$$L_{nit}^{MN} \geq L_{ni}^{MNout}, \;\; \forall n \in N, i \in I, t = T \quad (32)$$

$$L_{nit}^{MN} \geq k L_{ni}^{MNout}, \;\; \forall n \in N, i \in I, t \in T \quad (33)$$

$$y_{eit}^{SE} \leq d_{eit}^{Emax}, \;\; \forall e \in E, i \in I, t \in T \quad (34)$$

$$y_{eit}^{SE} \geq d_{eit}^{Emin}, \;\; \forall e \in E, i \in I, t \in T \quad (35)$$

$$\sum_{i\in I} y_{nit}^{SN} \leq d_{nt}^{Nmax}, \;\; \forall\, n \in N, t \in T \quad (36)$$

$$\sum_{i\in I} y_{nit}^{SN} \geq d_{nt}^{Nmin}, \;\; \forall\, n \in N, t \in T \quad (37)$$

$$\mathrm{x}_{\mathrm{eit}}^{\mathrm{WE}} \leq \gamma_{eit}^{Emax}, \;\; \forall e \in E, i \in I, t \in T \quad (38)$$

$$\mathrm{x}_{\mathrm{eit}}^{\mathrm{WE}} \geq \gamma_{eit}^{Emin}, \;\; \forall e \in E, i \in I, t \in T \quad (39)$$

$$u_{nilrt}^{N} \leq \sum_{m\in M}\sum_{p\in P} w_{milprt}^{MM} f_{mn}^{MN} f_{nit}^{NI} \quad (40)$$
$$\forall n \in N, i \in I, l \in L, r \in R, t \in T$$

$$\sum_{n\in N} w_{nit}^{B} \leq k_{i}^{BC}, \;\; \forall\, i \in I, t \in T \quad (41)$$

$$w_{it}^{El} \leq k_{i}^{TC}, \;\; \forall\, i \in I, t \in T \quad (42)$$

Variables:

z_a^A	$\begin{cases} 1 \text{ if production alternative } a \text{ is used,} \\ 0 \text{ otherwise} \end{cases}$
z_c^C	$\begin{cases} 1 \text{ if contract } c \text{ is accepted,} \\ 0 \text{ otherwise} \end{cases}$
L_{dmt}^{FM}	volume of raw material m stored at forest district d at the end of time period t
w_{dmit}^{FM}	volume of raw material m transported from forest district d to pulp mill i in time period t

L_{mit}^{MM} volume of raw material m stored at pulp mill i at the end of time period t

w_{milprt}^{MM} volume of raw material m used at line l in pulp mill i to produce product p according to recipe r in time period t

u_{ilprt}^{P} production of product p at line l in pulp mill i according to recipe r in time period t

L_{ipt}^{MP} storing of product p at pulp mill i at the end of time period t

y_{ipsqt}^{SP} flow of product p from pulp mill i to delivery point s according to order q in time period t

u_{nilrt}^{N} production of energy product n at line l in pulp mill i according to recipe r in time period t

L_{nit}^{MN} volume of energy product n stored at pulp mill i at the end of time period t

w_{nit}^{B} flow of energy product n to the boiler at pulp mill i in time period t

y_{nit}^{SN} flow of energy product n sold to the market at pulp mill i in time period t

w_{it}^{MPS} production of medium pressure steam at pulp mill i in time period t

w_{it}^{LPS} production of low pressure steam at pulp mill i in time period t

w_{it}^{El} production of electricity at pulp mill i in time period t

y_{eit}^{SE} flow of energy carrier e sold to the market from pulp mill i in time period t

w_{eilprt}^{ME} volume of energy carrier e used at line l in pulp mill i to produce product p according to recipe r in time period t

x_{eit}^{WE} waste of energy carrier e at pulp mill i in time period t

Sets:

D	District
M	Material
M_G	MaterialGroup
M_{GL}	MaterialGroupLink
N	Energy_prod
E	Energy_carr
E_{MPS}	MPSteam
E_{LPS}	LPSteam
E_{El}	Electricity
I	Pulpmills
L	Lines
A	Alternative
P	Products
R	Recipe

M_{RL} MaterialRecipeLink
M_{GRL} MaterialGroupRecipeLink
S Delivery points
C Contract
Q Order
Q_F Order_fix
Q_C Order_contract
Q_S Order_delivery
Q_{CC} Contract_order
T Time Periods

Parameters:

s_{md}	supply of raw material m at forest district d
s_{mt}^{S}	share of supply of raw material m in time period t
L_{dm0}^{FM}	ingoing inventory raw material m at forest district d
L_{mi0}^{MM}	ingoing inventory of raw material m at pulp mill i
a_{mil}^{M}	the amount of raw material m consumed at line l in pulp mill i to get one unit
$m_{m_g r}^{min}$	minimum level of allowed raw materials from material group mg used in recipe r
$m_{m_g r}^{max}$	maximum level of allowed raw materials from material group mg used in recipe r
r_{pr}^{P}	24h production volume of product p according to recipe r
g_{il}^{C}	yearly capacity in number of 24h production days at line l in pulp mill i
e_{ra}^{R}	$\begin{cases} 1 \text{ if the use of recipe } r \text{ is included in alternative } a \\ 0 \text{ otherwise} \end{cases}$
g_{ilr}^{max}	24h production max capacity at line l in pulp mill i according to recipe r
g_{ilr}^{min}	24h production min capacity at line l in pulp mill i according to recipe r
L_{mi}^{MMmax}	maximum storage capacity of raw material m at pulp mill i
L_{i}^{MPmax}	maximum storage capacity of products at pulp mill i
d_{pq}^{Pmin}	the minimum demand of product p according to order q
d_{pq}^{Pmax}	the maximum demand of product p according to order q
p_{p}^{SP}	price of sold product p
p_{pq}^{Q}	price quota of product p in order q
c_{dmi}^{TM}	transportation cost of material m from district d to pulp mill i
c_{dm}^{M}	purchasing cost of raw material m from district d
c_{r}^{R}	production cost according to recipe r
c_{a}^{A}	change over cost using alternative a
c_{is}^{TP}	transportation cost from pulp mill i to delivery point s
c_{dm}^{FMstor}	storage cost per volume unit of raw material m at district d per period
c_{mi}^{MMstor}	storage cost per volume unit of raw material m at pulp mill i per period
c_{ip}^{MPstor}	storage cost per volume unit of product p at pulp mill i per period
L_{ni}^{MNin}	ingoing inventory of energy product n at pulp mill i
L_{ni}^{MNout}	outgoing inventory of energy product n at pulp mill i

b_i	boiler efficiency at pulp mill i
h_i^{min}	minimum level of electricity output from the turbine at pulp mill i
h_i^{max}	maximum level of electricity output from the turbine at pulp mill i
a_{er}^{E}	use of energy carrier e while running recipe r for 24h
e_{er}^{min}	minimum level of needed energy carrier e used in recipe r
e_{er}^{max}	maximum level of allowed energy carrier e used in recipe r
r_{nr}^{N}	24h production volume of energy product n according to recipe r
L_{ni}^{MNmax}	maximum storage capacity of energy product n at pulp mill i
k	constant used for adjustment of safety stock
d_{nt}^{Nmin}	the minimum market demand of energy product n in time period t
d_{nt}^{Nmax}	the maximum market demand of energy product n in time period t
d_{eit}^{Emin}	the minimum market demand of energy carrier e at pulp mill i in time period t
d_{eit}^{Emax}	the maximum market demand of energy carrier e at pulp mill i in time period t
p_{nt}^{N}	price of energy product n in time period t
p_{eit}^{E}	price of energy carrier e at pulp mill i in time period t
c_{ni}^{MNstor}	storage cost per volume unit of energy product n at pulp mill i per period
γ_{eit}^{Emin}	minimum waste of energy carrier e at pulp mill i in time period t
γ_{eit}^{Emax}	maximum waste of energy carrier e at pulp mill i in time period t
f_{mn}^{MN}	potential output of energy product n from raw material m
f_{nit}^{NI}	seasonal index for output of energy product n at mill i in time period t
k_i^{GC}	proportion of electricity production that generates green certificates at pulp mill i
p_i^{GC}	price of green certificates in time period t
k_i^{BC}	boiler capacity at pulp mill i
k_i^{TC}	turbine capacity at pulp mill i