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Modeling an integrated market for sawlogs, pulpwood and forest bioenergy

BY

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Modeling an integrated market for sawlogs, pulpwood and forest bioenergy

[2011 Working Paper]

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Abstract

Traditionally, most applications in the initial stage of forest supply chain deal with sawlogs to sawmills, pulpwood to pulp or paper mills and forest residues to heating plants. However, in the past decades, soaring prices of fossil fuel, global awareness about CO_2 emission and increasing attention to domestic resource security have boosted the development of alternative renewable energy, among which forest bioenergy is the most promising and feasible choice for medium- and large-scale heating and electricity generation. Different subsidies and incentive policies for green energy further promote the utilization of forest bioenergy. As a result, there is a trend that pulpwood may be forwarded to heating plants as complementary forest bioenergy. Though pulpwood is more expensive than forest residues, it is more efficient to transport and has higher energy content. The competition between traditional forest industries and wood-energy facilities, expected to grow in the future, is very sensitive for the forest companies as they are involved in all activities. In this paper, we develop a model that all raw materials in the forest, i.e. sawlogs, pulpwood and forest residues, and byproducts from sawmills, i.e. wood chips and bark, exist in an integrated market where pulpwood can be sent to heating plants as bioenergy. It represents a multi-period multi-commodity network planning problem with multiple sources of supply, i.e. pre-selected harvest areas, and multiple kinds of destination, i.e. sawmills, pulp mills and heating plants. The decisions incorporate purchasing the raw materials in harvest areas, reassigning byproducts from sawmills, transporting those assortments to different points for chipping, storing, wood-processing or wood-fired, and replenishing fossil fuel when necessary. Moreover, different from the classic wood procurement problem, we take the unit purchasing costs of raw materials as variables, on which the corresponding supplies of different assortments linearly depend. With this price mechanism, the popularity of harvest areas can be distinguished. The objective of the problem is to minimize the total cost for the integrated market including the purchasing cost of raw materials. Therefore, the model is a quadratic programming (QP) problem with a quadratic objective function and linear constraints. A large case study in southern Sweden under different scenario assumptions is implemented to simulate the integrated market and to study how price restriction, market regulation, demand fluctuation, policy implementation and exogenous change in price for fossil fuel will influence the entire wood flows. Pair-wise comparisons show that in the integrated market, competition for raw materials between forest bioenergy facilities and traditional forest industries pushes up the purchasing costs of pulpwood. The results also demonstrate that resources can be effectively utilized with the price mechanism in supply market. The overall energy value of forest bioenergy delivered to heating plants is 23% more than the amount in the situation when volume and unit purchasing cost of raw materials are fixed.

Keywords: Forest supply chain, integrated market, bioenergy, wood procurement, wood distribution, quadratic programming

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1 Introduction

Forest supply chain provides original forest resource for divergent final uses. It can be viewed as a large network of production units that gradually process the raw materials, i.e., sawlogs, pulpwood and forest bioenergy, into consumer products, i.e., wood products, pulp and paper products, and energy and electricity (D'Amours et al. 2008). The difference between sawlogs and pulpwood is defined by the length, diameter and quality of the timber. Traditionally, the lower part of the tree, which has a larger diameter with higher value, is sent to sawmill as sawlogs. The upper, thinner part with a lower value is best suited for pulp and paper mills as pulpwood. The remaining tops and branches with least value, treated as residues, are left in the forest as soil nutrient or forwarded to heating plants as forest bioenergy. Sawlogs and pulpwood can be transported by the same type of trucks while forest residues have to be shipped by special trucks and chipped before final delivery.

The energy crisis in 1970’s and later soaring prices of fossil fuel boosted the development of alternative renewable energy, among which forest bioenergy is the most promising and feasible choice for medium- and large-scale heating and electricity generation (Figure 1). Since trees capture and store carbon as part of photosynthesis, the net release of carbon dioxide (CO_2) into the atmosphere caused by the combustion of forest bioenergy is zero. It means that using forest bioenergy instead of fossil fuel can reduce fossil-based CO_2 emissions from existing power production plants. As to the countries that own abundant forest resources, appropriate exploitation of forest bioenergy complies with the environmental commitments regarding “green” energy as well as relieves their dependence on the import of energy. Therefore, many countries, such as Sweden (Gunnarsson et al. 2004), Belgium (Van Belle et al. 2003), Austria (Gronalt and Rauch 2007), Ireland (Murphy et al. 2010) and USA (Conrad et al. 2011), have established sustainable energy goals and implemented various subsidies and incentive policies to encourage energy generation from forest-based biomass.

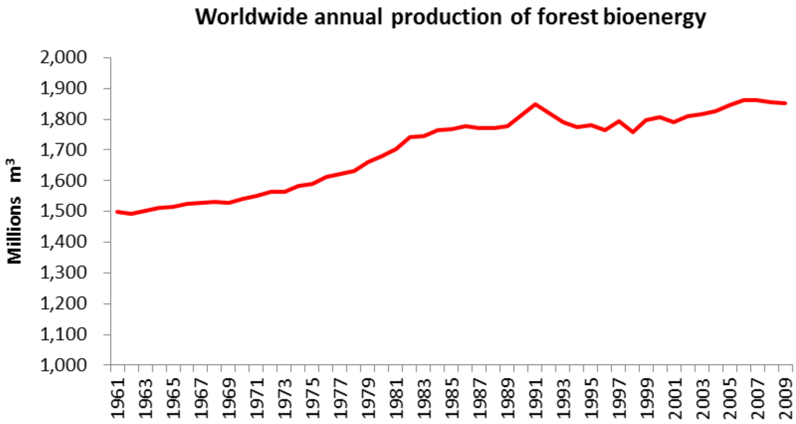


Figure 1 Worldwide annual production of forest bioenergy from 1961 to 2009 (*Source*: FAOSTAT 2011)

Forest bioenergy normally refers to forest residues that are trivial tree parts left onsite after final felling or thinning, poorly formed logs that cannot be further processed, stubs on the ground, and byproducts that are generated from the wood-processing industries. However, due to the accelerating promotion of wood energy and relatively lower price for forest fuel compared with fossil fuel, directly using pulpwood for power production is becoming attractive. Though pulpwood is more expensive than forest residues, it is more efficient to transport and has higher energy content.

Definitely this trend will affect other conventional timber consumers, especially the pulp and paper industry, and lead to competition for forest raw materials. Through a mail survey in the U.S. south, Conrad et al. (2011) found that though the wood-energy facilities and traditional forest industries are not competing for raw materials on a large scale at present, 32% of pulp and paper mills expect that a wood-fired power planting will be their largest competitor over the next decade and 55% of wood-energy facilities already count pulp and paper mills as their main rivals. As the real price of paper is decreasing over time, the pulp and paper producers, like other manufacturers, have strong desire to reduce the production cost and are thus not willing to pay more for the pulpwood as raw material (Carlgren et al. 2006). However, Lundmark (2006) indicated that in Sweden if the wood-energy consumption exceeds the break-point (21TWh), it will be more economical to directly use pulpwood as bioenergy than to further extract forest residues, putting upward pressure on the price for pulpwood. Moreover, Galik et al. (2009) suggested that there will be a dramatic spike in pulpwood price if the demand for bioenergy exceeds the supply of forest residues, which will squeeze out marginal pulpwood consumers. Therefore, concerns increase about competition for forest resources and interaction among traditional forest industries and emerging forest bioenergy facilities. Gunnarsson (2007) hence believed that it will be a new and exciting challenge to establish a mathematical model for both forest fuel and pulp products in the forest supply chain.

Numerous models based on operational research (OR) have been developed to optimize forest supply chain planning and to understand the complex functioning of the systems for the last half century. Rönnqvist (2003), Bettinger and Chung (2004), Weintraub and Romero (2006), D'Amours et al. (2008) and Carlsson et al. (2009) reviewed the applications and contributions of OR to the forestry industry from different perspectives on the forest supply chain.

Recent years have witnessed growing interest in integrating the different planning problems, i.e., synchronizing the procurement, production, distribution and sales activities throughout a set of independent business units or within large international companies that have many interrelated forest products supply chains. Gunnarsson et al. (2004) studied a problem that a supplying company is obliged to deliver a certain amount of forest fuel to several heating plants, involving procurement, conversion, transportation and terminal location planning. Beaudoin et al. (2007) introduced a centralized annual model to manage the wood flow from the forest to end market for an integrated forest company that own many sawmills. Gunnarsson and Rönnqvist (2008) solved an integrated planning of the overall supply chain for one of the world's largest suppliers of market pulp.

In addition to integrating the divergent activities, it is of increasing importance to integrate different levels of decision-making, ranging from aggregated strategic forest management to detailed operational tasks. Although the consistency and feasibility occur as problems, there are many successful implementations both in theory and in practice. Cea and Jofre (2000) considered the strategic investment and tactical planning decisions to assist forestry companies. Forsberg et al. (2005) developed a decision support system for strategic and tactical transportation planning in Swedish forestry.

Plentiful articles that simultaneously deal with various planning problems or link different decision levels are mostly focus on one specific forestry industry, that is, wood processing industry, pulp and paper industry, and heating or power generation. Relatively few exist on how to integrate the whole market. In the case study of central Ireland, Murphy et al. (2010) demonstrated that modeling and planning tools can optimize allocation of wood fiber in a non-traditional market where both forest bioenergy and logs are supplied.

In this paper, we integrate two value chains, round wood and forest biomass, in an optimization model. That is, all the raw materials in the forest, i.e. sawlogs, pulpwood and forest residues, and byproducts from sawmills, i.e. wood chips and bark, exist in an integrated market where pulpwood can be sent to heating plants as bioenergy (Figure 2). It represents a multi-period multi-commodity network planning problem with multiple sources of supply, i.e. pre-selected harvest areas, and multiple kinds of destination, i.e. sawmills, pulp mills and heating plants. The planning horizon is one year and monthly time periods are considered to account for the seasonality, which has a great influence on the whole supply chain. For example, during the summer in the Nordic countries, operations in forest often focus on silvicultural management and harvest capacity decreases due to holidays, hence affecting the supply of logs. On the demand side, the consumption of heating energy during January-February is much higher than June-July. All of these imply the need for advance planning. The decisions in the model therefore incorporate purchasing the raw materials in harvest areas, reassigning byproducts from sawmills, transporting those assortments to different points for chipping, storing, wood-processing or wood-fired, and replenishing fossil fuel when necessary.

A combined wood procurement and distribution problem requires a supplying company to determine how to obtain the wood required by mills and how to deliver from sources to destinations, both distributed geographically. If the supplying company owns forest, the decisions involve which blocks to harvest (Beaudoin et al. 2007), what kinds of harvesting methods to use (Burger and Jamnick 1995), how to allocate the crews (Karlsson et al. 2004), whether to buck trees into logs of specific dimensions in the woods (Carlgren et al. 2006) and how many types of logs to produce onsite (Chauhan et al. 2009). The volume of assortments at supply nodes will be affected by these factors, but the related harvesting or purchasing cost is normally pre-defined as a parameter.

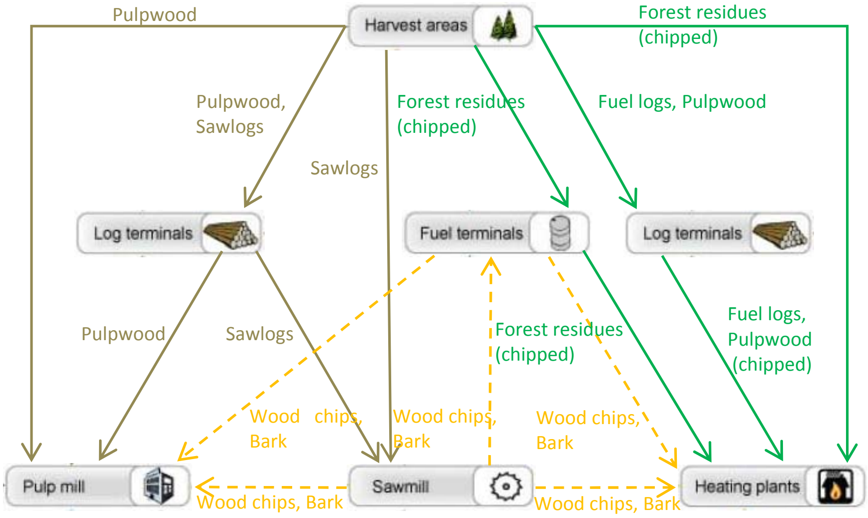


Figure 2 An integrated market for raw materials in the forest supply chain

Because the total cost of harvesting is usually a non-continuous linear function with 0-1 variables, analysts use mixed integer programming (MIP) models to balance the supply of raw materials and demand for specific products. However, to our knowledge, so far no attempt has been made to take the unit purchasing cost as variable, on which the corresponding supply of different raw materials linearly depends. In our paper, we assume that the supplying company purchases raw materials directly from the pre-selected harvest areas. The higher unit purchasing cost the supplying company offers, the more volume, if possible, the forest owners will provide under constrictions of harvest nature. With this price mechanism, the popularity of harvest areas can be distinguished. Given the demands in mills and delivery prices for assortments are specified, the objective is to minimize the total costs for the integrated market including the purchasing cost of raw materials. Therefore, the model is a quadratic programming (QP) problem with a quadratic objective function and linear constraints.

We use the data from the Forestry Research Institute of Sweden to simulate the integrated market and separated market, respectively. The difference in these two markets is whether or not pulpwood can be used in heating plants as forest bioenergy. The harvest areas, located in southern Sweden, can annually supply 1.6 – 2.2 million cubic meters (m^3) required wood assortments to sawmills, pulp mills and heating plants. We generate 16 instances to test the proposed model and make 7 different scenario comparisons to analyze the results. The main purpose is to study how price restriction, market regulation, demand fluctuation, policy implementation and exogenous change in price for fossil fuel will influence the entire wood flows. Pair-wise comparisons show that in the integrated market, competition for raw materials between forest bioenergy facilities and traditional forest industries pushes up the unit purchasing costs of pulpwood. The results also demonstrate that resources can be effectively utilized with the price mechanism in supply market. The overall energy value of forest bioenergy delivered to heating plants is 23% more than the amount in the situation when volume and unit purchasing cost of raw materials are fixed. The results also indicate the strong connection and high dependency among all forest-related industries.

The main contribution of this paper is twofold: Firstly, we innovatively integrate two value chains of roundwood and forest biomass, including decisions about procurement, transportation, chipping and inventory planning. Secondly, we take the unit purchasing cost as variable and assume the supply of raw materials is linear with respect to the unit cost. This allows for the study that to what extent market prices can be relaxed to make the value chain more efficient. The remainder of this paper is as follows: in the following section, a detailed problem description will be given. We then formulate the mathematical model in Section 3. In Section 4, a case study based on real-world data is provided, with numerical results and scenario analysis. The paper ends with some concluding remarks and suggestions for further work in Section 5.

2 Problem description

2.1 Supply of raw materials in harvest areas

Forest in a district is divided into harvest areas which vary in size and in available volumes of assortments. The assortments of raw materials can be classified according to their use. Sawlogs, pulpwood and forest residues are the major parts of the assortments. Each part can be further divided into several subgroups according to their species, qualities and dimensions.

The harvesting operation in Sweden, as well as in many other countries, fells trees and delimbs stems. The stems are directly bucked into logs by the harvesters under the optimized bucking decisions. Top and limb portion of the tree is left as residues. The high-quality sawlogs and the lower-quality pulpwood are forwarded to storage locations adjacent to forest roads by forwarders. They will be piled temporally and then transported to wood-processing factories. The residues are left for around a year in the woods or adjacent to roads in large piles and then chipped before final delivery. In addition, during the felling operation, defect wood, i.e., decayed or damaged, will be found. These logs cannot be further processed either in sawmills or in pulp mills, but used as fuel logs for energy generation. They will also be left in the forest for drying, the same as forest residues, and then transported to terminals for storage and chipping.

Seasonality has great influence on harvesting operations. In the Nordic countries, for example, because most sawmills are closed for holiday in July, a relatively small proportion of the annual harvesting is done during this period. Operations instead deal with such silvicultural management as regeneration and cleaning activities, which will reduce the supply of logs and consequently affect the availability of byproducts. This implies the need for better inventory planning overall the year.

In this paper, we assume that the supplying company has selected a potential number of harvest areas from where to purchase forest raw materials. The respective ranges of acceptable unit purchasing cost and corresponding supply for each assortment are also pre-defined. The volume supplied or harvested linearly depends on the unit purchasing cost offered (Figure 3). Additionally, the unit cost ranges of the same assortment are the same in all the harvest areas, but the supply ranges of that assortment depend on the production level in the area. Table 1 gives typical data for four areas in the case study. Therefore, one of the crucial decisions for the supplying company is to determine what the unit costs should be in order to obtain enough raw materials to satisfy demands while minimizing the total procurement cost.

It is also necessary to mention that, since forest residues and fuel logs are already available in the forest after the harvesting of logs from the previous year, the actual supply is simply determined by the unit purchasing cost the supplying company is willing to pay. However, the actual supply of sawlogs and pulpwood in certain harvest area is not only decided by the unit cost, but also limited by the harvest nature. Because a harvest area is usually composed of several tree species, the harvest of one area will result in the co-production of various assortments. That is, the more one kind of logs are harvested, the more other logs in this area will also be produced and vice versa.

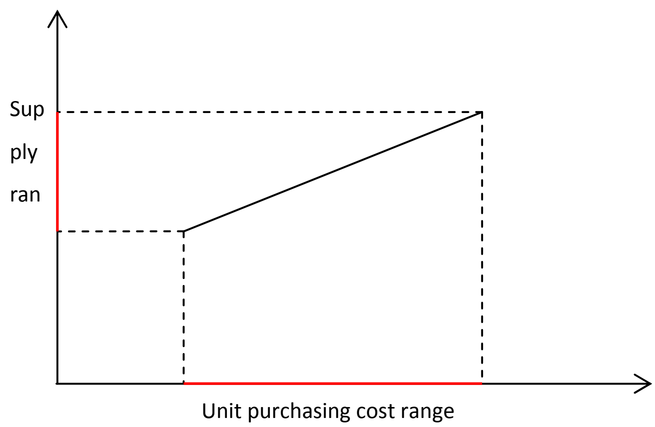


Figure 3 Linear dependence between unit purchasing cost and corresponding supply of raw material in harvest areas

Table 1 Unit purchasing cost ranges (*unit: SEK/m^3*) and supply ranges (*unit: m^3*) for forest raw materials in four harvest areas

	Sawlogs		Pulpwood			Fuel logs	Forest residues	
	Pine	Spruce	Pine	Spruce	Birch	Decayed wood	Branches	Tree parts
Unit cost range								
All areas	383-518	383-518	213-288	225-305	225-305	128-173	43-58	85-115
Supply range								
Area-H1	1822-2464	1240-1678	1034-1400	1138-1540	64-86	189-255	--	--
Area-H2	138-186	95-129	102-138	--	44-60	111-151	--	--
Area-H3	757-1025	672-909	943-1275	46-62	218-294	117-159	1018-1378	1676-2268
Area-H4	23-31	--	201-273	--	17-23	--	141-191	83-113

2.2 Supply of byproducts in sawmills

Sawlogs sent to sawmills are transformed into boards to produce lumber and dimension parts or into flakes to produce panels. The process will produce byproducts such as bark, wood chips and sawdust (Figure 4). Traditionally, except that some byproducts are directly burned to generate steam for wood dryers in sawmills, most of the byproducts, especially wood chips and sawdust, are further transported to pulp mills as raw material for pulp. However, since forest fuel becomes increasingly attractive alternative for heating plants, wood chips can also be shipped to heating plants.

The supplying company delivers sawlogs to several sawmills. The byproducts with specified price are then transported, if needed, to the pulp mills or heating plants for further use. We assume that the wood products and different types of byproducts are proportionally produced. That is, once the sawlogs processed in sawmills are known, the volumes of different byproducts generated can be exactly measured in each time period. The supplying company is responsible to continuously move away the byproducts since there is a limited storage capacity for chips and sawdust in sawmills.

The making of pulp also produces byproducts, such as bark. Besides the internal use for steam generation and cooking of chips as a part of the paper-making process, these byproducts can be forwarded to heating plants as fuel. We do not include this wood flow in our model because it is very similar to the flow of byproducts from sawmills and could easily be added if required.

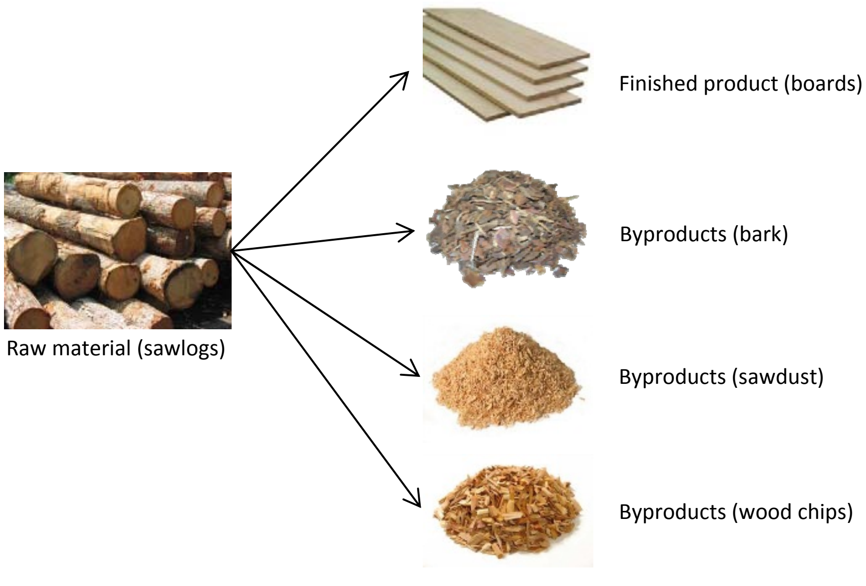


Figure 4 The process of sawlogs converted into finished wood products and byproducts

2.3 Chipping and storage

The residues and fuel logs are piled at the landing until they are chipped for direct delivery or transported to terminals for further process or storage. In this paper, we assume that chipping of residues is carried out in the forest by the mobile machinery. Though chipping onsite is very costly, it is more economical for later transportation since the loading capacity of bulky tree tops and branches is too low. Yet chipping of fuel logs and pulpwood, if any, typically occurs at terminals by industrial chippers before they are eventually sent to heating plants.

Since byproducts from sawmills are already chipped, no chipping needs to be taken into account. Furthermore, all the sawlogs sent to sawmills or pulpwood to pulp mills involve no chipping. They are transported as logs all the way from sources to terminals or directly to final destinations.

Storage in locations plays an important role in the whole supply chain. It is used to balance the seasonal fluctuation of supply and demand. Our formulation considers two types of storage: roadside in the forest and at terminals. Both locations have certain capacity constraints. However, due to higher quality degradation in the forest, it is typically more expensive to store harvested raw materials in the forest than in the terminals. Furthermore, once forest residues are chipped, they have to be shipped to the terminals or heating plants immediately since there are no chip storage bins in the forest. In addition, the variation in production of sawlogs has a direct impact on supply of byproducts. We thus assume that byproducts can also be transported to terminals with chip storage bins for temporary storage.

It is true that not all the terminals have chipping ability or storage capacity for chipped forest fuel. In this paper, instead of introducing new sets of variables and constraints to separate the terminals of different types, we model these possibilities by prohibiting the flow of logs sent to heating plants from terminals without chipping equipment or preventing the flow of chipped bioenergy via terminals without chip storage bins.

2.4 Demand at heating plants

Heating plants usually supply residential and industrial sectors with hot water for heating. Therefore, the demand for energy fluctuates with seasons. Figure 5 depicts the total demand of 22 heating plants during the whole planning period in the case study. We notice that in contrast to the supply of forest fuel given in terms of volume (m^3), the demand at the heating plants is specified in energy value (MWh). Therefore, conversion from volume to energy is necessary in the flow conservation constraints. The energy values of assortments depend on their species, moisture content and the portion of the tree being used, i.e., stem, branches, or bark.

Since the energy generation in heating plants cannot be suspended, if the supplying company fails to deliver enough forest bioenergy to heating plants in some period, we assume that the missing volumes could be obtained through the purchasing of fossil fuel, for example, heating oil or coal. However, under the pressure from environmental concerns, there is a certain maximal proportion of fossil fuel in the total energy composition.

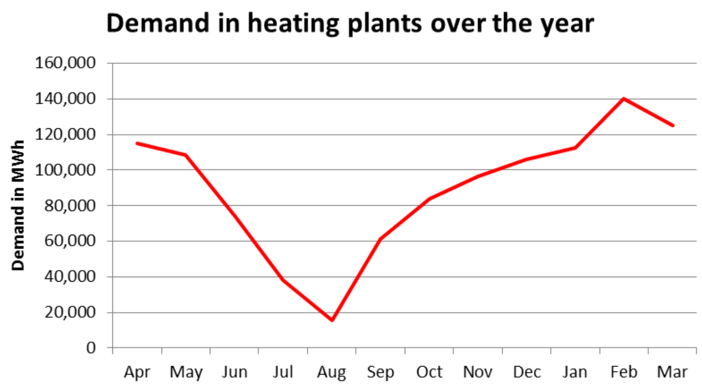


Figure 5 Total demand of 22 heating plants during the whole planning period

2.5 Demand in sawmills and pulp mills

The sawmills and pulp mills for which the supplying company is obliged to provide raw materials are all contract-based. Log types and their delivery prices are pre-defined. Volumes of sawlogs and pulpwood are in specified amount. Differently, the demand of byproducts in pulp mills is flexible, within certain interval based on the consumption of pulpwood. The proportion of pulpwood and byproducts used can be adjusted according to the production recipes for specific pulp.

2.6 Transportation

The supplying company is responsible for delivering all the wood assortments required by different facilities. As far as the different assortments are concerned, the density will limit the quantity that a truck can load. A weight limit of 60 tons for trucks corresponds to a maximal loading weight of about 40 tons and a length restriction of 24 meters cannot be violated. Typically loading capacity of logs is limited by weight and that of other assortments is by volume. The transportation cost is thereby associated with types of assortments. With regard to the same assortment in different form, i.e., chipped or non-chipped fuel logs and pulpwood, it is cheaper to transport chips yet costs more in loading and unloading. As the balanced result, the transportation costs, including loading and unloading, are similar. As to the distance factor, we use the common assumption that the unit transportation cost is linear with the distance between two points, which is the case in transportation agreements. It is possible to control the flow between any two locations under various assumptions. Table 2 lists the normal flows in an integrated forest raw material market.

Table 2 All the assortments and possible flows in the model

Assortment	Source	Destination
Sawlogs, pulpwood, fuel logs, forest residues (chipped)	Harvest area	Terminal
Forest residues (chipped)	Harvest area	Heating plant
Sawlogs	Harvest area	Sawmill
Pulpwood	Harvest area	Pulp mill
Fuel logs (chipped), pulpwood (chipped), forest residues (chipped), byproducts	Terminal	Heating plant
Sawlogs	Terminal	Sawmill
Pulpwood, byproducts	Terminal	Pulp mill
Byproducts	Sawmill	Terminal
Byproducts	Sawmill	Heating plant
Byproducts	Sawmill	Pulp mill

3 Mathematical formulation

In this section we present the mathematical model of an integrated market for sawlogs, pulpwood and forest bioenergy. First the sets used in the model are introduced.

A Set of harvest areas
K Set of terminals
H Set of heating plants
S Set of sawmills
M Set of pulp mills
R_S Set of sawlog assortments
R_P Set of pulpwood assortments
R_{F} Set of fuel log assortments
R_G Set of forest residue assortments

R Set of raw materials, $R = R_S \cup R_P \cup R_F \cup R_G$
P_S Set of finished wood products in sawmills
P_B Set of byproducts in sawmills
P Set of products processed in sawmills, $P = P_S \cup P_B$
W Set of fossil fuel alternatives
T Set of time periods

In the remainder of the paper, we will use index i for nodes of outbound flow (sources), j for nodes of inbound flow (destinations), a for harvest areas, k for terminals, h for heating plants, s for sawmills, m for pulp mills, r for raw materials, p for processed products in sawmills, w for fossil fuel and t for time periods.

The parameters used in the model are as follows. As mentioned in Section 2.6, transportation cost includes loading and unloading operational fee.

α_{pt} Proportion of sawlogs processed into product p in time period t, where $\sum_{p\in P} \alpha_{pt} = 1$
β_h Minimal percentage of forest bioenergy required to use at heating plant h
γ_{mpt}^L Minimal percentage of byproduct p demanded in pulp mill m in time period t, $p \in P_B$
γ_{mpt}^U Maximal percentage of byproduct p demanded in pulp mill m in time period t, $p \in P_B$
c_r^A Unit chipping cost of raw material r in harvest areas, $r \in R_G$
c_r^K Unit chipping cost of raw material r at terminals, $r \in R_F \cup R_P$
c_{ijr}^T Unit transportation cost of raw material r from source i to destination j, $i \in A \cup K$, $j \in K \cup H \cup S \cup M$, $r \in R$
c_{ijp}^T Unit transportation cost of byproduct p from source i to destination j, $i \in S \cup K$, $j \in K \cup H \cup M$, $p \in P_B$
d_{ht}^H Demand for converted energy at heating plant h in time period t
d_{srt}^S Demand for raw material r in sawmill s in time period t, $r \in R_S$
d_{mrt}^M Demand for raw material r in pulp mill m in time period t, $r \in R_P$
e_{rt} Energy value of one volume unit of raw material r in time period t, $r \in R_F \cup R_G \cup R_P$
e_{pt} Energy value of one volume unit of byproduct p in time period t, $p \in P_B$
f_{pt}^B Unit purchasing cost of byproduct p in time period t, $p \in P_B$
f_{wt}^E Unit energy purchasing cost of fossil fuel w in time period t
f_{art}^L Lower bound of unit purchasing cost in harvest area a of raw material r in time period t, $r \in R$
f_{art}^U Upper bound of unit purchasing cost in harvest area a of raw material r in time period t, $r \in R$
h_{art}^A Unit inventory cost in harvest area a of raw material r in time period t, $r \in R$
h_{krt}^K Unit inventory cost at terminal k of raw material r in time period t, $r \in R$
h_{kpt}^K Unit inventory cost at terminal k of byproduct p in time period t, $p \in P_B$
n_{srt}^S Unit penalty cost in sawmill s of raw material r in time period t, $r \in R_S$
n_{mrt}^M Unit penalty cost in pulp mill m of raw material r in time period t, $r \in R_P$
n_{mpt}^M Unit penalty cost in pulp mill m of byproduct p in time period t, $p \in P_B$
s_{art}^L Lower bound of supply in harvest area a of raw material r in time period t, $r \in R$
s_{art}^U Upper bound of supply in harvest area a of raw material r in time period t, $r \in R$
v_a^I Storage capacity in harvest area a
v_k^I Storage capacity at terminal k
v_t^C Total capacity of mobile chippers in harvest area in time period t
v_{kt}^C Chipping capacity at terminal k in time period t
v_k^G Maximal flow capacity at terminal k

The variables will be presented below, in the same order as they are illustrated in Figure 6. Note that the initial storage level, given by time index 0, in different districts is known.

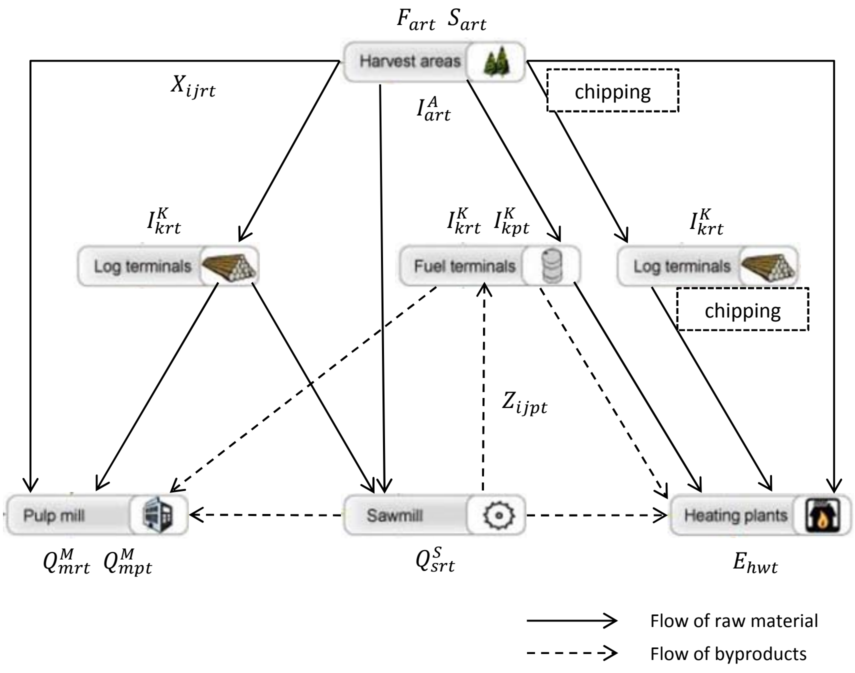


Figure 6 An illustration of the possible flows in an integrated market

F_{art} Unit purchasing cost in harvest area a of raw material r in time period t, $r \in R$
S_{art} Supply in harvest area a of raw material r in time period t, $r \in R$
X_{ijrt} Flow from source i to destination j of raw material r in time period t, $i \in A \cup K$, $j \in K \cup H \cup S \cup M$, $r \in R$
I^A_{art} Storage in harvest area a of raw material r at the end of time period t, $r \in R$
I^K_{krt} Storage at terminal k of raw material r at the end of time period t, $r \in R$
I^K_{kpt} Storage at terminal k of byproduct p at the end of time period t, $p \in P_B$
Z_{ijpt} Flow from source i to destination j of byproduct p in time period t, $i \in S \cup K$, $j \in K \cup H \cup M$, $p \in P_B$
E_{hwt} Fossil fuel w forwarded to heating plant h in time period t
Q^S_{srt} Unsatisfied demand in sawmill s of raw material r in time period t, $r \in R_S$
Q^M_{mrt} Unsatisfied demand in pulp mill m of raw material r in time period t, $r \in R_P$
Q^M_{mpt} Unsatisfied demand in pulp mill m of byproduct p in time period t, $p \in P_B$

The model is expressed as

$$\begin{aligned}\min TC = & \sum_{a\in A}\sum_{r\in R}\sum_{t\in T} F_{art}S_{art} + \sum_{s\in S}\sum_{j\in K\cup H\cup M}\sum_{p\in P_B}\sum_{t\in T} f^B_{pt}Z_{sjpt} + \sum_{h\in H}\sum_{w\in W}\sum_{t\in T} f^E_{wt}E_{hwt} \\ & + \sum_{a\in A}\sum_{j\in K\cup H}\sum_{r\in R_G}\sum_{t\in T} c^A_r X_{ajrt} + \sum_{k\in K}\sum_{h\in H}\sum_{r\in R_P\cup R_F}\sum_{t\in T} c^K_r X_{khrt} \\ & + \sum_{a\in A}\sum_{r\in R}\sum_{t\in T} h^A_{art}I^A_{art} + \sum_{k\in K}\sum_{r\in R}\sum_{t\in T} h^K_{krt}I^K_{krt} + \sum_{k\in K}\sum_{p\in P_B}\sum_{t\in T} h^K_{kpt}I^K_{kpt} \\ & + \sum_{i\in A\cup K}\sum_{j\in K\cup H\cup S\cup M}\sum_{r\in R}\sum_{t\in T} c^T_{ijr}X_{ijrt} + \sum_{i\in S\cup K}\sum_{j\in K\cup H\cup M}\sum_{p\in P_B}\sum_{t\in T} c^T_{ijp}Z_{ijpt} \\ & + \sum_{s\in S}\sum_{r\in R_S}\sum_{t\in T} n^S_{srt}Q^S_{srt} + \sum_{m\in M}\sum_{r\in R_P}\sum_{t\in T} n^M_{mrt}Q^M_{mrt} + \sum_{m\in M}\sum_{p\in P_B}\sum_{t\in T} n^M_{mpt}Q^M_{mpt}\end{aligned}$$

Subject to

$$S_{art} = s_{art}^{L} + \left(F_{art} - f_{art}^{L}\right) \cdot \frac{s_{art}^{U} - s_{art}^{L}}{f_{art}^{U} - f_{art}^{L}}, \quad \forall a \in A, \forall r \in R, \forall t \in T, \tag{1}$$

$$f_{art}^{L} \le F_{art} \le f_{art}^{U}, \quad \forall a \in A, \forall r \in R, \forall t \in T, \tag{2}$$

$$\frac{S_{ar_1t} - s_{ar_1t}^{L}}{s_{ar_1t}^{U} - s_{ar_1t}^{L}} = \frac{S_{ar_2t} - s_{ar_2t}^{L}}{s_{ar_2t}^{U} - s_{ar_2t}^{L}}, \quad \forall a \in A, \forall r_1 \in R_S \bigcup R_P, \forall r_2 \in R_S \bigcup R_P, \forall t \in T, \tag{3}$$

$$\alpha_{pt}\left(\sum_{i \in A \bigcup K} \sum_{r \in R_S} X_{isrt}\right) = \sum_{j \in K \bigcup H \bigcup M} Z_{sjpt}, \quad \forall s \in S, \forall p \in P_B, \forall t \in T, \tag{4}$$

$$I_{ar,t-1}^{A} + S_{art} = I_{art}^{A} + \sum_{j \in K \bigcup H \bigcup S \bigcup M} X_{ajrt}, \quad \forall a \in A, \forall r \in R, \forall t \in T, \tag{5}$$

$$I_{kr,t-1}^{K} + \sum_{i \in A} X_{ikrt} = I_{krt}^{K} + \sum_{j \in H \bigcup S \bigcup M} X_{kjrt}, \quad \forall k \in K, \forall r \in R, \forall t \in T, \tag{6}$$

$$I_{kp,t-1}^{K} + \sum_{i \in S} Z_{ikpt} = I_{kpt}^{K} + \sum_{j \in H \bigcup M} Z_{kjpt}, \quad \forall k \in K, \forall p \in P_B, \forall t \in T, \tag{7}$$

$$\sum_{i \in A \bigcup K} \sum_{r \in R_P \bigcup R_F \bigcup R_G} e_{rt} X_{ihrt} + \sum_{i \in S \bigcup K} \sum_{p \in P_B} e_{pt} Z_{ihpt} + \sum_{w \in W} E_{hwt} = d_{ht}^{H}, \quad \forall h \in H, \forall t \in T, \tag{8}$$

$$\sum_{i \in A \bigcup K} \sum_{r \in R_P \bigcup R_F \bigcup R_G} e_{rt} X_{ihrt} + \sum_{i \in S \bigcup K} \sum_{p \in P_B} e_{pt} Z_{ihpt} \ge \beta_h d_{ht}^{H}, \quad \forall h \in H, \forall t \in T, \tag{9}$$

$$\sum_{i \in A \bigcup K} X_{isrt} + Q_{srt}^{S} = d_{srt}^{S}, \quad \forall s \in S, \forall r \in R_S, \forall t \in T, \tag{10}$$

$$\sum_{i \in A \bigcup K} X_{imrt} + Q_{mrt}^{M} = d_{mrt}^{M}, \quad \forall m \in M, \forall r \in R_P, \forall t \in T, \tag{11}$$

$$\gamma_{mpt}^{L}\left(\sum_{r \in R_P} d_{mrt}^{M}\right) - Q_{mpt}^{M} \le \sum_{i \in S \bigcup K} Z_{impt} \le \gamma_{mpt}^{U}\left(\sum_{r \in R_P} d_{mrt}^{M}\right), \quad \forall m \in M, \forall p \in P_B, \forall t \in T, \tag{12}$$

$$\sum_{r \in R} I_{art}^{A} \le v_{a}^{I}, \quad \forall a \in A, \forall t \in T, \tag{13}$$

$$\sum_{r \in R} I_{krt}^{K} + \sum_{p \in P_B} I_{kpt}^{K} \le v_{k}^{I}, \quad \forall k \in K, \forall t \in T, \tag{14}$$

$$\sum_{a \in A} \sum_{j \in K \bigcup H} \sum_{r \in R_G} X_{ajrt} \le v_{t}^{C}, \quad \forall t \in T, \tag{15}$$

$$\sum_{h \in H} \sum_{r \in R_P \bigcup R_F} X_{khrt} \le v_{kt}^{C}, \quad \forall k \in K, \forall t \in T, \tag{16}$$

$$\sum_{i \in A} \sum_{r \in R} X_{ikrt} + \sum_{s \in S} \sum_{p \in P_B} Z_{skpt} \le v_{k}^{G}, \quad \forall k \in K, \forall t \in T, \tag{17}$$

$$X_{ijrt} \ge 0 \quad \forall i \in A \bigcup K, \forall j \in K \bigcup H \bigcup S \bigcup M, \forall r \in R, \forall t \in T, \tag{18}$$

$$Z_{ijpt} \ge 0 \quad \forall i \in S \bigcup K, \forall j \in K \bigcup H \bigcup M, \forall p \in P_B, \forall t \in T, \tag{19}$$

$$F_{art}, S_{art}, I_{art}^{A}, I_{krt}^{K}, I_{kpt}^{K} \ge 0 \quad \forall a \in A, \forall k \in K, \forall r \in R, \forall p \in P_B, \forall t \in T, \tag{20}$$

$$E_{hwt}, Q_{mrt}^{M}, Q_{mpt}^{M} \ge 0 \quad \forall h \in H, \forall m \in M, \forall w \in W, \forall r \in R_P, \forall p \in P_B, \forall t \in T, \tag{21}$$

$$Q_{srt}^{S} \ge 0 \quad \forall s \in S, \forall r \in R_S, \forall t \in T. \tag{22}$$

Because the delivery prices for forest raw materials and byproducts in the mills, as well as the energy prices for bioenergy at heating plants, are covered by pre-existing contracts, the revenues associated with the delivery are parameters of the problems and thus irrelevant to the decisions. Therefore, the objective for the supplying company is to minimize the total cost by procuring wood assortments and byproducts, complementing fossil fuel when necessary, chipping forest fuel, balancing the inventory and optimizing the wood flows.

The first line in the objective function is the procurement costs which constitute the purchasing cost of raw materials in harvest areas, the purchasing cost of byproducts from sawmills and the purchasing cost of fossil fuel. Since the supply of raw materials in harvest areas S_{art} linearly depends on the unit purchasing cost F_{art}, the purchasing cost of raw materials $\sum_{a\in A}\sum_{r\in R}\sum_{t\in T}F_{art}S_{art}$ makes the objective function nonlinear but quadratic. The next line represents chipping costs in the forest and at terminals, respectively. Note that residues in the forest will not be chipped until delivery to terminals or heating plants, the same as logs sent to heating plants as bioenergy. The third line corresponds to the storage costs in different locations. The fourth line is the transportation costs for the whole wood flows in this integrated market and the last line represents the deficit costs. Actually the unit penalty costs are large enough to assure that the demands in mills will be satisfied.

As mentioned earlier, in our model the supply of certain raw material in harvest areas is linear with its purchasing cost, which is expressed as constraint set (1). Constraint set (2) ensures that the actual unit purchasing cost must be within the cost bounds, together with the supply bounds, which are all pre-defined under binding contracts between the supplying company and forest owners. Constraint set (3) reflects the harvest nature that harvested volumes of fresh logs are proportional in any harvest area. As to the supply of byproducts in sawmills, the volume of byproducts available in each time period is based on the volume of sawlogs processed. Constraint set (4) stipulates that all kinds of byproducts will be delivered to different destinations for temporary storage or further use in the same time period when they become available.

Constraint sets (5) through (7) represent classical flow conservation constraints in harvest areas and at terminals. We assume that the chipping for forest fuel does not influence volumes and thus change in form of raw materials will not impact the inventory balance constraints in harvest areas for residues or those at terminals for logs.

The demand at the heating plant in each time period is specified in terms of energy (MWh), but all raw materials or byproducts transported to the heating plant are expressed in volume unit (m^3). We therefore introduce conversion factors, e_{rt} and e_{pt}, in constraint sets (8) to ensure that demand of converted energy is satisfied. Note that different assortment has different energy value that varies from one time period to another. The supplying company will decide how much raw materials and byproducts should be sent to heating plants. In the same period, the company can also provide such fossil fuel as heating oil or coal, specified in energy value, to adapt to the increasing demand during the winter. However, due to the environmental concerns, constraint set (9) guarantees that the minimal percentage of forest fuel β_h should be used as "green" energy at heating plants. In order to get a robust model, we introduce penalized variables to represent the deviation of the amount delivered from the amount demanded in one period, respectively, in sawmills (constraint set (10)) and pulp mills (constraint sets (11) and (12)). If these variables are not included in the model, we might not find any solution and then there is no possibility to identify the problem.

Constraint sets (13) and (14) refer to capacity restrictions regarding storing in each district. Constraint set (15) gives a restriction on the total volume of forest residues that can be chipped in each time period by the mobile chippers working at harvest areas. Similarly, at every terminal with permanent chipping equipment for fuel logs or pulpwood, the monthly amount that can be chipped is limited by constraint set (16). Constraint set (17) restricts the throughput or total flow handled at each terminal. All the variables are continuous and no less than zero, which are specified in last five constraints.

4 Case study and discussion

In this section, we apply the proposed model to a hypothetical but realistic case study, based on real-world data from the Forestry Research Institute of Sweden. All harvest areas, terminals and forest industries and wood-energy facilities are located in a region in southern Sweden. The geographical distribution of supply and demand nodes is given in Figure 7. These harvest areas, corresponding to aggregated standard areas used in Swedish forest industry, can annually supply 1.6 – 2.2 million cubic meters required wood assortments to sawmills, pulp mills and heating plants.

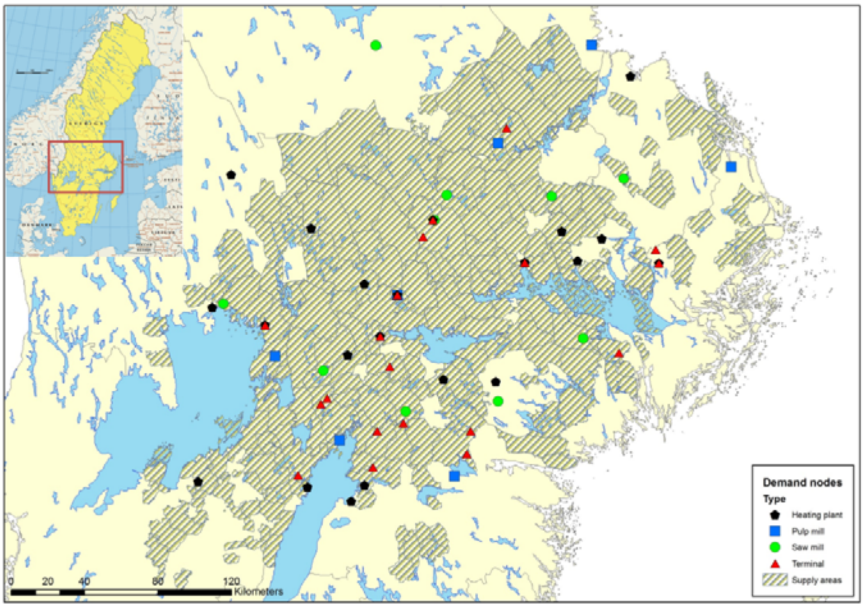


Figure 7 Geographical distribution of nodes for the case study

Table 3 lists the information of this case study. Monthly total supply of raw materials and byproducts and demand in sawmills, pulp mills and heating plants are illustrated in Figure 8. The volumes of raw materials and byproducts are measured in m^3 and energy value is in MWh. We notice that the demand (dashed line) for sawlogs in sawmills and pulpwood in pulp mills are all within the supply ranges (solid line) whereas the demand (dashed line) at heating plants exceeds the maximal available supply (stacked area) of forest bioenergy during the winter. Moreover, due to a relatively small proportion of the annual harvesting for sawlogs is done during the summer (July), the supply of byproducts in that period is lower than the minimum demand from pulp mills. These all imply the need for efficient inventory management during the year.

Table 3 The information of the case study

Number of harvest areas	234
Number of terminals	20
Number of heating plants	22
Number of sawmills	11
Number of pulp mills	7
Number of sawlog assortments	2
Number of pulpwood assortments	3
Number of fuel log assortments	1
Number of forest residue assortments	2
Number of types of fossil fuel	1
Number of types of finished wood products	1
Number of types of byproducts	2
Number of time period	12

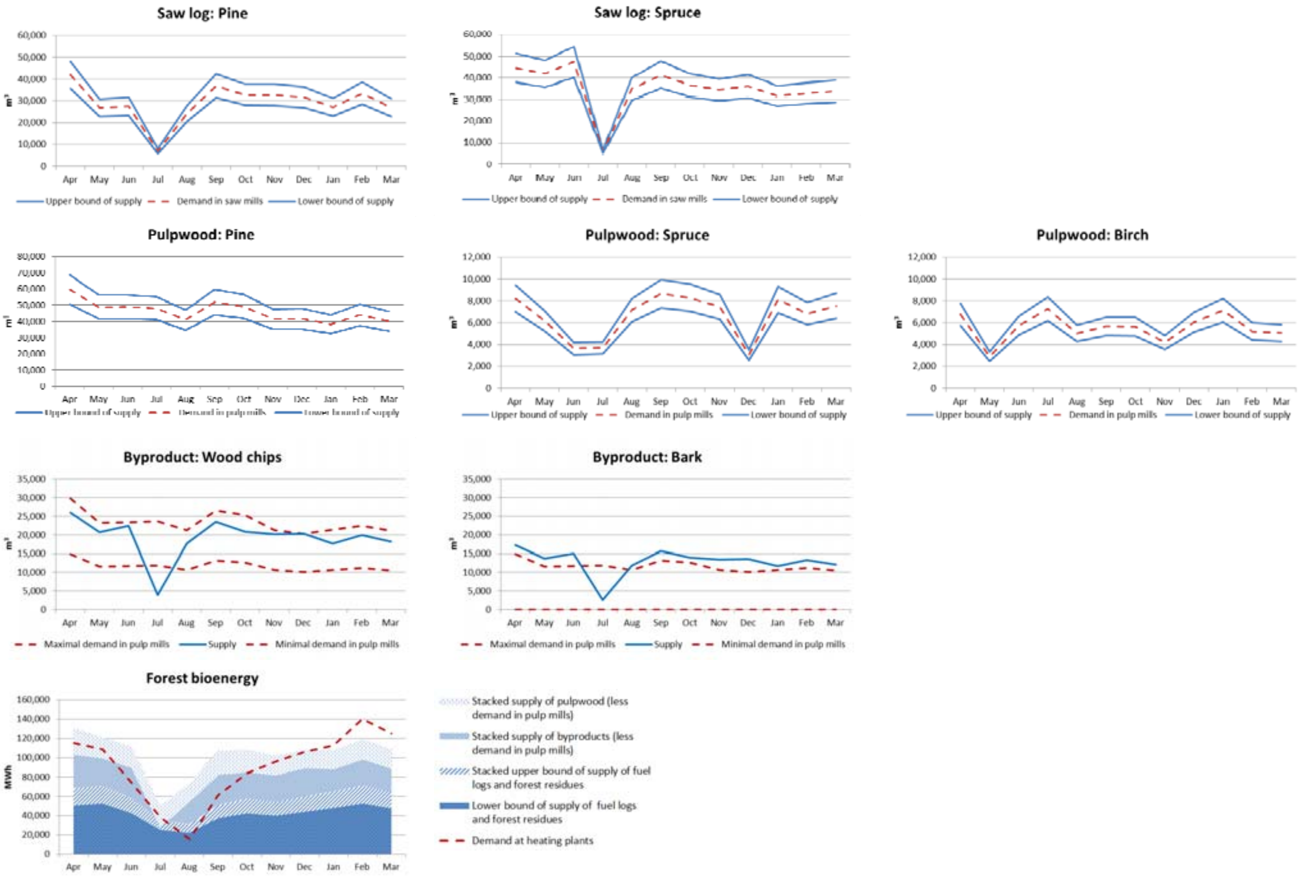


Figure 8 Monthly minimum and maximum total supply of raw materials in harvest areas, monthly total supply of byproducts in sawmills and monthly total demand for different assortments in sawmills, pulp mills and heating plants

We generate 16 instances to test the proposed model and make 7 different scenario comparisons to analyze the results. The main purpose is to investigate the change of wood flow in the whole forest raw material market under various assumptions. In the integrated market it is possible to use pulpwood as forest fuel whereas in the separated market it is not allowed to send pulpwood to heating plants as bioenergy. Table 4 gives a short description of each instance which will be addressed in more detail later. Though the costs of raw materials in the case study are set by the authors, they do reflect the relative value of different assortments based on real market prices. Total costs are in Sweden SEK and unit costs are in SEK per m^3. 10 SEK is about 1 Euro.

We use AMPL as the modeling language and CPLEX 10.0 as the solver. The instances have been solved on a T7300 2.00 GHz processor with 3 GB RAM. The number of variables and constraints and solution time of each instance are also included in Table 4. After AMPL's pre-solve phase reduces the size of the instances, the numbers of variables and constraints of each instance are still very large. However, since the proposed model is a typical QP problem, CPLEX 10.0 solves QP problems well within reasonable time.

Table 4 The basic information of the 7 comparions and 16 instances

Instance	Description	No. of variables	No. of constraints	Solution time (Seconds)
Comparison 1:				
Integrated market, different price restrictions				
S1	Free prices, integrated market	896,367	64,627	565
S2	Period-same prices, integrated market	896,367	93,268	771
S3	Area-same prices, integrated market	896,367	265,152	785

Instance	Description	No. of variables	No. of constraints	Solution time (Seconds)
S4	Fixed prices, integrated market	851,438	31,958	65
Comparison 2: Separated market, different price restrictions				
S5	Free prices, separated market	880,527	64,627	452
S6	Period-same prices, separated market	880,527	93,268	433
S7	Area-same prices, separated market	880,527	265,152	603
S8	Fixed prices, separated market	835,598	31,958	23
Comparison 3: Increased harvest flexibility				
S9	Based on S1, the constraints that assortments are proportionally harvested in any harvest area are relaxed	896,367	54,423	478
Comparison 4: Increased demand at heating plants				
S10	Free prices, separated market, demand at heating plants increases 10%	880,527	64,627	553
S11	Free prices, integrated market, demand at heating plants increases 10%	896,367	64,627	630
Comparison 5: Decreased demand in sawmills				
S12	Period-same prices, separated market, demand in sawmills decreases 10%	880,527	93,268	537
S13	Period-same prices, integrated market, demand in sawmills decreases 10%	896,367	93,268	784
S14	Based on S13, sawlogs can be sent to pulp mills	939,039	93,268	821
Comparison 6: Increased bioenergy proportion at heating plants				
S15	Based on S3, minimal percentage of bioenergy used in heating plants increases from 50% to 80%	896,367	265,152	842
Comparison 7: Change in price for fossil fuel				
S16	Based on S3, price of fossil fuel changes from 50% less to 50% more	896,367	265,152	796

4.1 Comparison 1: Integrated market, different price restrictions

Firstly, we will study the effect of various price restrictions in harvest areas where the supplying company purchases forest raw materials. It provides insights into the supply-market price behavior, which cannot be obtained by using conventional wood procurement assumption that volume and harvesting or purchasing costs of each assortment in every harvest area are fixed.

Instance S1: The model presented in Section 3 represents the scenario of free prices. That is, there are no temporal or spatial constraints on the unit purchase costs of different raw materials in one period or in any harvest area. In other words, all the assortments can be purchased at any price within the price range, regardless of the prices of the same assortment in other harvest areas or other periods.

Instance S2: The second instance includes the temporal constraints that in any harvest area the unit purchasing cost of certain assortment should be the same all over the year, short for scenario of period-same prices. It is common when the supplying company signs the annual procurement contract with forest owners. Then we add this constraint set into the proposed model:

$$F_{art_1} = F_{art_2} \quad \forall a \in A, \forall r \in R, \forall t_1, t_2 \in T \tag{23}$$

Instance S3: In the third scenario we introduce the spatial constraints that in any period of the planning year the unit purchasing cost of certain assortment should be the same among all the harvest areas. We call it scenario of area-same prices. This represents the supplying company itself has this kind of procurement rule. It is actually the current situation in Sweden. Consequently, we insert the following constraint set into the model:

$$F_{a_1rt} = F_{a_2rt} \quad \forall a_1, a_2 \in A, \forall r \in R, \forall t \in T \tag{24}$$

Instance S4: We also study the situation that the purchasing costs and volumes of raw materials are fixed, which is assumed by majority of models dealing with the wood procurement problem. In this scenario, variables F_{art} and S_{art} become parameters, that is, the mid-price of the cost range and average amount of the supply range, respectively. The total purchasing cost of raw materials turns into be parameter too. We also exclude constraint sets (1), (2) and (3) in the proposed model. Therefore, the original optimization model becomes a classic network linear program.

Table 5 and Table 6 list the computational results of these four scenarios. Firstly, we compare the results of Instance S1, Instance S2 and Instance S3. As we expect, the total cost of Instance S1 is the lowest with least constraints while that of Instance S3 is the highest with most constraints. Because of the temporal constraints in Instance S2 and spatial constraints in Instance S3, less are spent on raw materials in the forest, but much more fossil fuel are sent to heating plants than that in Instance S1. These changes are reflected by the facts that less pulpwood are purchased, and hence, less are forwarded to heating plants in Instance S2 and Instance S3, whereas more fuel logs and forest residues are supplied. Actually, the total supplies of fuel logs and forest residues all reach the upper bounds in Instance S3. Since unit chipping cost in harvest areas for forest residues is much higher than that in terminal for logs, the total chipping cost both increases in Instance S2 and Instance S3.

Table 5 Cost comparisons of Instance S1, Instance S2, Instance S3 and Instance S4 (*unit: SEK*)

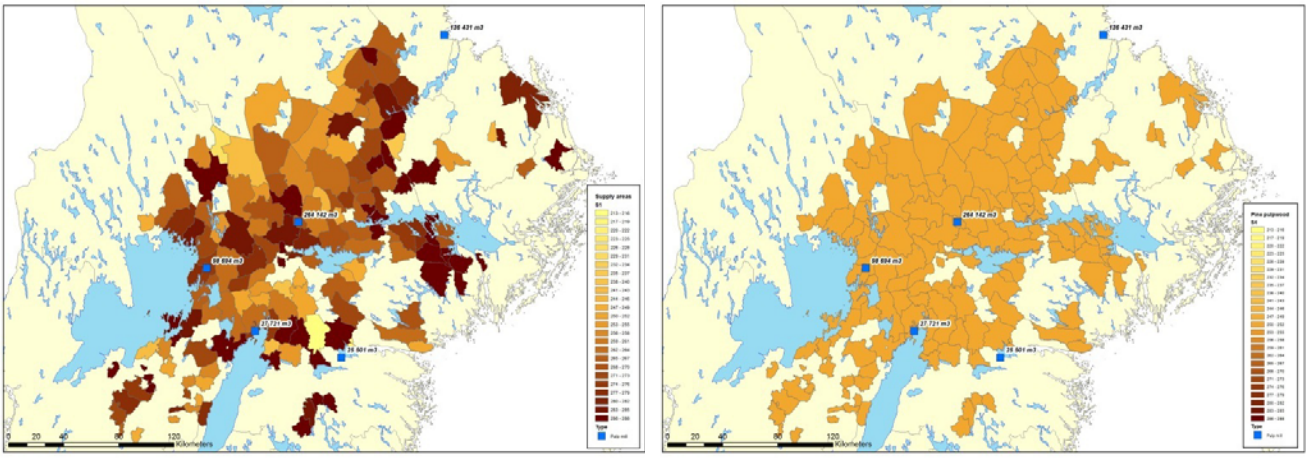
Instance	Purchasing Raw material	Purchasing Byproduct	Purchasing Fossil fuel	Chipping	Storage	Transport	Deficit	Total cost
S1	592,994,210	21,179,263	-	57,671,659	2,204,370	149,859,644	-	823,909,146
S2	589,271,005	21,179,263	5,045,729	59,426,347	2,136,040	151,702,497	-	828,760,880
S3	573,413,187	21,179,263	28,399,276	58,493,879	2,255,646	151,246,790	-	834,988,041
S4	557,821,700	21,179,263	69,518,122	50,614,924	1,236,913	148,733,657	-	849,104,577

Table 6 Actual total supply of raw materials of Instance S1, Instance S2, Instance S3 and Instance S4 (*unit: m^3*)

Instance	Sawlogs		Pulpwood			Fuel logs	Forest residues	
	Pine	Spruce	Pine	Spruce	Birch	Decayed wood	Branches	Tree parts
S1	348,548	421,607	589,803	83,165	70,833	71,490	351,306	103,486
S2	348,548	421,607	578,313	82,563	69,176	71,490	367,506	106,749
S3	348,548	421,607	558,757	79,229	67,476	71,490	367,523	106,749
S4	348,551	421,616	552,495	78,832	66,588	62,165	319,585	92,825

Now we focus on the comparison between Instance S1 and Instance S4. When the supply of raw materials can freely change within certain ranges and be decided according to the purchasing costs in Instance S1, the price mechanism will effectively allocate the resources and no other uneconomic resources, such as heating oil, are needed. For example, in the left map of Figure 9, the gradient colors indicate the popularity of the harvest areas for pulpwood “Pine”. The darker the colors, the higher unit purchasing costs in those areas reach, and thus more volumes are offered. The increase in purchasing cost of raw materials is justifiable as long as it can be offset by a reduction in total cost.

By contrast, in Instance S4, because the fixed volumes of supply of raw materials are slightly higher than the demand in final destinations, the excess or undesirable sawlogs have to be left in the forest and the few more pulpwood can be sent to heating plants. However, the limited supply of bioenergy cannot meet the requirements from heating plants. Therefore, all the shortage has to be complemented by relatively expensive heating oil. We note that the overall energy value of forest bioenergy delivered to heating plants in Instance S1 is 23% more than the amount in Instance S4.



Average unit purchasing cost in S1 (free prices) **Average unit purchasing cost in S4 (fixed prices)**

Figure 9 Average purchasing costs of pulpwood "Pine" in harvest areas and demand in pulp mills

We further investigate the transportation and chipping alternatives for Instance S1 and Instance S4. Table 7 gives the detailed proportions of raw materials and byproducts transported directly to final destinations or via terminals, as well as the proportions of forest bioenergy chipped in the forest areas or at terminals. Because of the practical reason that all the logs sent to heating plants should be first chipped at terminals, no fuel logs or pulpwood are directly transported to heating plants. Since the demand at heating plants fluctuated with seasons, the storage of forest bioenergy for heating at terminals is higher than that of sawlogs and pulpwood. Moreover, because the supply of forest residues is much higher than those of fuel logs and pulpwood as forest bioenergy, most chipping is done in harvest areas. It is very important to improve the efficiency of chipping in harvest areas and thus reducing the operational cost. Besides the above similarities of these two instances, it is also worth noting that since much less pulpwood are available in Instance S4, both the volumes of storage as transshipment and chipping as bioenergy at terminals decline.

Table 7 Transportation and chipping alternatives of Instance S1 and Instance S4 (*Unit: Percentage*)

	S1		S4	
	Directly	Via terminal	Directly	Via terminal
Sawlogs transported to sawmills	86	14	87	13
Pulpwood transported to pulp mills	61	39	72	28
Fuel logs transported to heating plants	0	100	0	100
Forest residues transported to heating plants	51	49	53	47
Total transportation of raw materials to final destinations	65	35	71	29
Byproducts from sawmills transported to pulp mills	55	45	83	17
Byproducts from sawmills transported to heating plants	41	59	46	54
Total transportation of byproducts to final destinations	46	54	59	41
	S1		S4	
Forest residues chipped in harvest areas	80		87	
Fuel logs and pulpwood chipped at terminals	20		13	

4.2 Comparison 2: Separated market, different price restrictions

All the instances in Comparison 1 are based on the assumption that it is allowed to send pulpwood to heating plants. It can be treated as an integrated market for the raw materials, which is the perfect market condition. However, several institutional restrictions in Sweden limit use of pulpwood in energy generation (Lundmark

2006). Therefore, we modify the assumption and it is now forbidden to transport pulpwood to heating plants, which represents a separated market. This change can be achieved by modification of the route design. The above four instances become *Instance S5*, *Instance S6*, *Instance S7* and *Instance S8*, correspondingly.

Similarly, Table 8 and Table 9 list the computational results of these four scenarios. Different from what we observed from Instance S1, Instance S2 and Instance S3, the gap among total costs of Instance S5, Instance S6 and Instance S7 are negligible. In Table 9, we see that the supplies of sawlogs and pulpwood are exact to the demand in sawmills and pulp mills. No extra pulpwood is sent to heating plants. As to the supplies of fuel logs and forest residues, they reach the upper bound and the shortfall in demand at heating plants is filled by fossil fuel.

Table 8 Cost comparisons of Instance S5, Instance S6, Instance S7 and Instance S8 (*unit: SEK*)

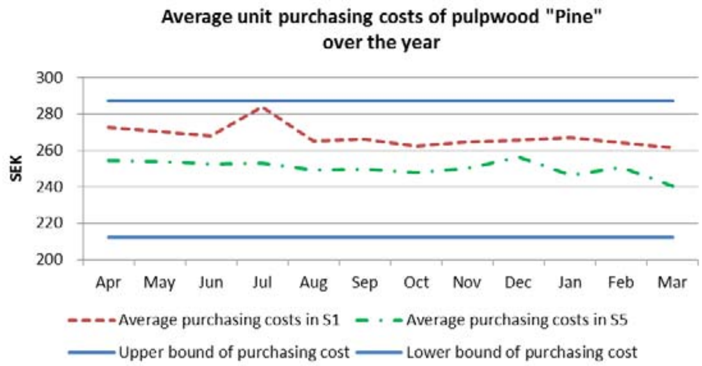
Instance	Purchasing Raw material	Purchasing Byproduct	Purchasing Fossil fuel	Chipping	Storage	Transport	Deficit	Total cost
S5	569,828,674	21,179,263	35,591,570	58,204,922	2,060,614	149,816,517	-	836,681,559
S6	569,552,898	21,179,263	35,590,499	58,205,252	1,807,814	150,905,306	-	837,241,032
S7	569,070,294	21,179,263	35,586,848	58,206,376	1,978,255	151,589,762	-	837,610,797
S8	557,821,700	21,179,263	69,535,222	50,614,240	1,237,285	148,732,526	-	849,120,236

Table 9 Actual total supply of raw materials of Instance S5, Instance S6, Instance S7 and Instance S8 (*unit: m^3*)

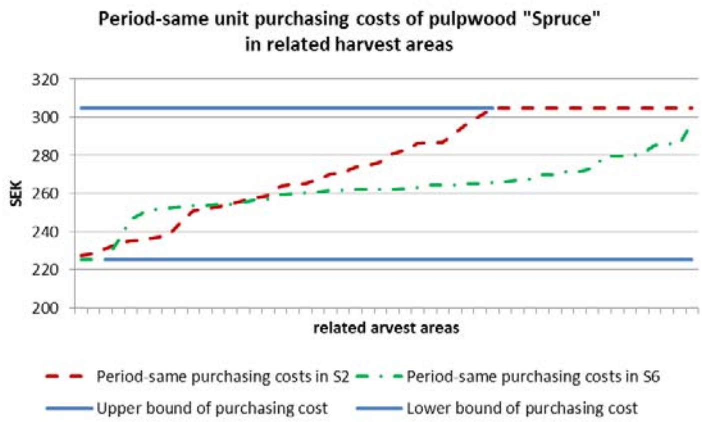
Instance	Sawlogs		Pulpwood			Fuel logs	Forest residues	
	Pine	Spruce	Pine	Spruce	Birch	Decayed wood	Branches	Tree parts
S5	348,548	421,607	552,489	78,824	66,584	71,490	367,510	106,749
S6	348,548	421,607	552,489	78,824	66,584	71,490	367,513	106,749
S7	348,548	421,607	552,489	78,824	66,584	71,490	367,523	106,749
S8	348,551	421,616	552,495	78,832	66,588	62,165	319,585	92,825

However, when we compare the results of Table 8 with those of Table 5, it is obvious that the total costs of these four instances in Comparison 2 are all higher than their counterparts in Comparison 1. It arises from the fact that more expensive fossil fuel, such as heating oil, has to be used to fulfill the demand at heating plant which can be totally or partially substituted by cheaper pulpwood in an integrated market. It confirms the hypothesis that if possible, pulpwood has comparative advantage to be combusted at heating plants than fossil fuel. Because more pulpwood is desired, no matter which kind of price restrictions is applied, the purchasing costs of pulpwood in the integrated market are higher than those in the separated market, which is illustrated by comparisons between Instance S1 and Instance S5 for average unit purchasing cost of pulpwood “Pine” over the year, Instance S2 and Instance S6 for period-same unit purchasing cost of pulpwood “Spruce” in related harvest areas, and Instance S3 and Instance S7 for area-same unit purchasing cost of pulpwood “Birch” over the year in Figure 10. It is in line with the concern that once it is acceptable to sell pulpwood to heating plants, competition for raw materials between forest bioenergy facilities and traditional forest industries is expected to occur (Conrad et al. 2011).

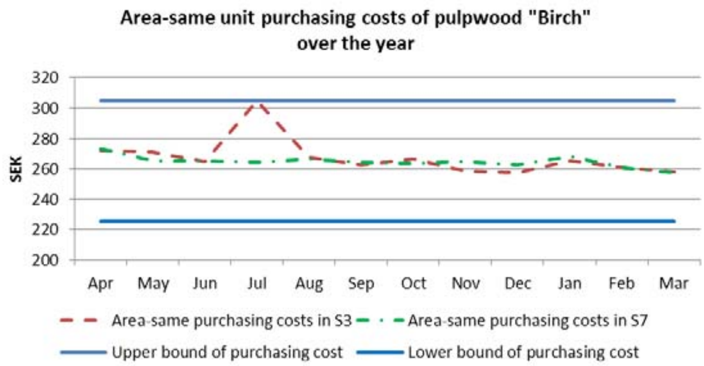
Last but not least, we have to point out that Instance S8 with fixed supply in a separated market actually represents the situation in the real world for some forest companies. The least flexible situation results in the highest total costs, 3% more than the total cost of an integrated market (Instance S1). This reinforces the benefit of integrating a market for all the forest raw materials and introducing the price mechanism in harvest areas.



Note: Average unit purchasing costs of S1 are all higher than those of S5



Note: More unit purchasing costs of S2 reach the upper bound than those of S6



Note: Unit purchasing costs of S3 are still slightly higher than those of S7

Figure 10 Comparisons of unit purchasing costs of pulpwood in an integrated market and those in a separated market

4.3 Comparison 3: Increased harvest flexibility

As we mentioned in Section 2.1, there are practical constraints in each harvest area that the proportion of assortments harvested, no matter sawlogs or pulpwood, should be the same. In other word, if a harvest area consist of 400 m^3 pine and 600 m^3 spruce and we want to harvest 50% volume of pine, we will end up with 200 m^3 pine and 300 m^3 spruce, respectively. However, it is also interesting to study the effect of what if the assortments to be harvested in one area are flexible through, for example, specialized final felling or thinning.

Instance S9: Based on Instance S1 with free prices in an integrated market, we simulate an instance that all the assortments can be freely harvested as needed. To achieve this purpose, we just take away the constraint set (3) in the proposed model.

Table 10 and Table 11 give the comparison between Instance S1 and Instance S9. The most distinct changes are that more pulpwood yet less forest residues are supplied for heating plants, which elevates the purchasing cost of pulpwood. However, this increase is fetched up by the decrease in chipping cost since chipping of logs at terminals as bioenergy is much more economic and efficient than chipping of residues in the forest.

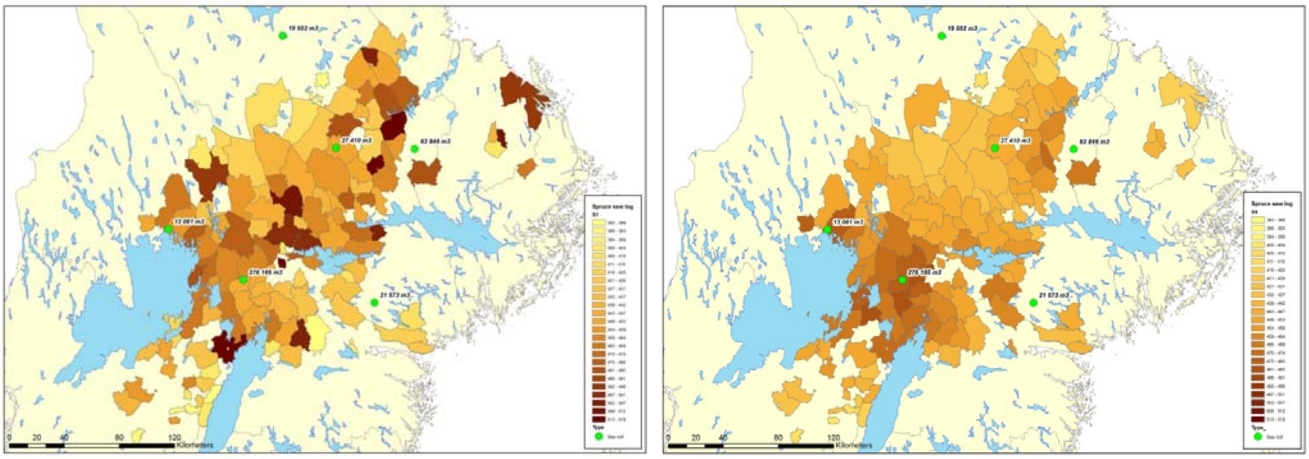
Table 10 Cost comparisons of Instance S1 and Instance S9 (*unit: SEK*)

Instance	Purchasing Raw material	Purchasing Byproduct	Purchasing Fossil fuel	Chipping	Storage	Transport	Deficit	Total cost
S1	592,994,210	21,179,263	-	57,671,659	2,204,370	149,859,644	-	823,909,146
S9	597,844,938	21,179,263	-	52,755,077	1,841,077	145,418,764	-	819,039,118

Table 11 Actual total supply of raw materials of Instance S1 and Instance S9 (*unit: m^3*)

Instance	Sawlogs		Pulpwood			Fuel logs	Forest residues	
	Pine	Spruce	Pine	Spruce	Birch	Decayed wood	Branches	Tree parts
S1	348,548	421,607	589,803	83,165	70,833	71,490	351,306	103,486
S9	348,548	421,607	606,042	87,685	72,066	71,486	313,756	91,873

It is also important to note that though the total volumes of sawlogs harvested are the same in both instances, the allocations of volumes are different, which is reflected by the color shifting of purchasing costs in different areas and illustrated in Figure 11. Because the assortments can be ideally harvested as needed in Instance S9, regardless of the harvesting of other assortments in the same area, the allocation of harvesting can be more efficient according to the demand for different raw material from final destinations. Then the distance from one harvest area to mills determines the prices of the assortments in that area. The closer to the demand nodes, the higher purchasing cost will be (Left map of Figure 11). This will definitely improve the efficiency of transportation and reduce inventory. It also proves the possibility that profitability gains can be achieved by greater coordination among local forest companies in a context characterized by shared procurement areas and co-production of assortments. The interested reader is referred to Beaudoin et al (2010).



Average unit purchasing cost in S1 (constrained by harvest nature) **Average unit purchasing cost in S9 (freely harvested)**

Figure 11 Average purchasing costs of sawlog "Spruce" in harvest areas

4.4 Comparison 4: Increased demand at heating plants

Now we would like to check the impact of demand changes on the whole wood flows. We assume that demand at all heating plants increases 10% during the planning period. It represents an unexpected change of weather occurs or the heating plants have to expand their production capacity for unprecedented energy consumption. *Instance S10* with free prices in a separated market is established under this new demand assumption while *Instance S11* is all the same but in an integrated market.

Table 12 and Table 13 show the comparisons between Instance S10 and Instance S11. When the demand at heating plants increases, in a separated market where pulpwood can only be delivered to pulp mills, the supplying company has no other choices but to use up all the available resources of fuel logs and forest residues. The remaining demand gap has to be filled by fossil fuel, leading to dramatic increase in the purchasing cost of substitute energy. The severe situation is alleviated in an integrated market. Besides fuel logs and forest residues, more pulpwood are forwarded to heating plants to meet the surging demand, which is demonstrated by the comparison of monthly total amount of pulpwood sent to heating plants between Instance S1 and Instance S11 in Figure 12. Again, it emphasizes that an integrated market is more flexible to respond to external changes than a separated market. Figure 13 shows proportion of overall forest bioenergy, byproducts, fossil fuel and pulpwood consumed at heating plants in Instance S10 and Instance S11. It should be mentioned that because cost minimization trends to minimize volume, the byproducts sent to heating plants always just meet the minimum requirements.

Table 12 Cost comparisons of Instance S10 and Instance S11 (*unit: SEK*)

Instance	Purchasing Raw material	Purchasing Byproduct	Purchasing Fossil fuel	Chipping	Storage	Transport	Deficit	Total cost
S10	569,829,401	21,179,263	76,543,309	58,205,702	1,766,594	149,039,640	-	876,563,908
S11	604,309,076	21,179,263	20,936,894	60,428,911	2,068,770	151,376,049	-	860,298,964

Table 13 Actual total supply of raw materials of Instance S10 and Instance S11 (*unit:* m^3)

	Sawlogs		Pulpwood			Fuel logs	Forest residues	
Instance	Pine	Spruce	Pine	Spruce	Birch	Decayed wood	Branches	Tree parts
S10	348,548	421,607	552,489	78,824	66,584	71,490	367,517	106,749
S11	348,548	421,607	600,489	83,935	72,011	71,490	367,507	106,749

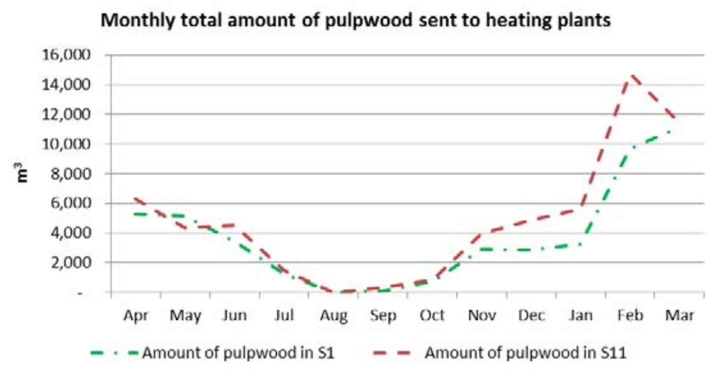


Figure 12 Monthly total amount of pulpwood sent to heating plants

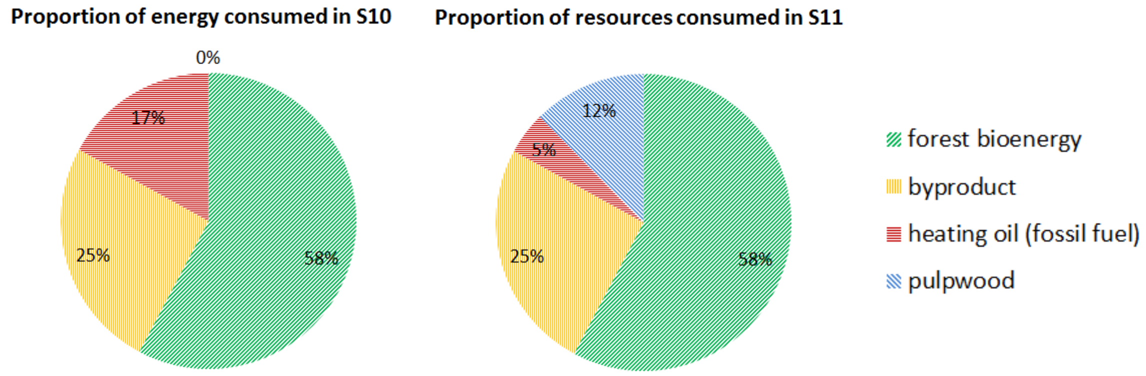


Figure 13 Proportion of overall forest bioenergy, byproducts, fossil fuel and pulpwood consumed in heating plants in a separated market and in an integrated market

4.5 Comparison 5: Decreased demand in sawmills

Since activities in the forest supply chain are highly inter-connected, for example, the decline in exports of finished wood products will influence the demand for sawlogs as raw material, and then cut down the availability of byproducts as bioenergy and reduce the wood flow to other facilities. How this chain reaction evolves certainly merits special attention.

Instance S12: With period-same prices in a separated market, we assume that demand for sawlogs in all sawmills decrease 10% during the whole planning period.

Instance S13: The same assumption is applied to the instance in an integrated market.

Instance S14: Because the difference between sawlogs and pulpwood of the same types is just the diameter of the timber, if possible, sawlogs actually can be used as pulpwood. Therefore, based on Instance S13, we now assume that if sawlogs and pulpwood are originally the same timber, sawlogs then can be sent to pulp mills as substitution of pulpwood. We hence modify the flow-conservation constraint set (11) in pulp mills in the proposed model as:

$$\sum_{i \in A \cup K} X_{imrt} + Q^{M}_{mrt} = d^{M}_{mrt}, \quad \forall m \in M, \forall r \in R_P \setminus R_S, \forall t \in T \tag{25}$$

$$\sum_{i \in A \cup K} X_{imr_1t} + \sum_{i \in A \cup K} X_{imr_2t} + Q^{M}_{mr_1t} = d^{M}_{mr_1t}, \quad \forall m \in M, \forall r_1 \in R_P \cap R_S, \forall r_2 \in R_S, r_1 = r_2, \forall t \in T \tag{26}$$

Specifically, in our case study, sawlog “Pine” and sawlog “Spruce” can replace pulpwood “Pine” and pulpwood “Spruce”, but not pulpwood “Birch”.

Table 14 and Table 15 give the comparison between Instance S12, Instance S13 and Instance S14. As expected, the declining demand in sawmills consequently brings about the decrease in availability of byproducts and thus aggravating the consumption of fossil fuel at heating plants. However, it is interesting to notice that pulpwood are no longer sent to heating plants even in an integrated market, ending up that the results of Instance S12 and Instance S13 are exactly the same. It arises from the fixed harvesting proportion of sawlogs and pulpwood, which has already been discussed in Comparison 3. Therefore, when the demand of sawlogs decrease by 10%, the amount of pulpwood purchased is also influenced and drops to the minimum level that just satisfies the demand in pulp mills. However, because of the fixed harvesting proportion, the actual supply of sawlogs still exceeds the demand in sawmills and the remaining logs have to be left in the forest or at terminals as storage. This is also the reason that the storage costs of Instance S12 and Instance S13 increase more than 60% when we compare them with their counterparts, namely Instance S6 and Instance S2. In fact, it complies with the real-world phenomena, that is, strong sawlog markets can stimulate more harvesting and feed more low-grade wood into the pulp and biomass markets whereas weak sawlog market will make many landowners hold off harvesting, reducing the flow of wood to the other markets. From this viewpoint, the forest raw material market is highly interacted.

Table 14 Cost comparisons of Instance S12, Instance S13 and Instance S14 (*unit: SEK*)

Instance	Purchasing Raw material	Purchasing Byproduct	Purchasing Fossil fuel	Chipping	Storage	Transport	Deficit	Total cost
S12	534,971,383	19,061,336	53,587,806	58,205,626	2,898,760	141,902,028	-	810,626,939
S13	534,971,383	19,061,336	53,587,806	58,205,626	2,898,760	141,902,028	-	810,626,939
S14	553,535,469	19,061,336	-	59,259,619	1,895,263	140,147,763	-	773,899,451

Table 15 Actual total supply of raw materials of Instance S12, Instance S13 and Instance S14 (*unit: m^3*)

Instance	Sawlogs		Pulpwood			Fuel logs	Forest residues	
	Pine	Spruce	Pine	Spruce	Birch	Decayed wood	Branches	Tree parts
S12	326,826	395,701	552,489	78,824	66,584	71,490	367,516	106,749
S13	326,826	395,701	552,489	78,824	66,584	71,490	367,516	106,749
S14	339,275	408,254	557,784	79,947	67,045	71,490	359,145	104,229

Once it is allowed to forward sawlogs to pulp mills as substitutions of pulpwood, the entire wood flows become more efficient and cost-saving. Figure 14 contrastingly shows the different allocation of sawlogs and pulpwood in Instance S13 and Instance S14. In Instance S13, the undesirable sawlogs caused by fixed harvesting proportion have to be left in the forest and all the pulpwood purchased is only transported to pulp mills. By contrast, in Instance S14, excess harvested sawlogs are delivered to pulp mills while pulpwood are again sent to heating plants as economical bioenergy and no fossil fuel are needed. These benefits are undoubtedly attributed to a highly integrated market for raw materials.

Figure 14 Different allocation of sawlogs and pulpwood in Instance S13 and Instance S14

4.6 *Comparison 6: Increased bioenergy proportion at heating plants*

With the growing emphasis on environmental issues, it is believed that government policies such as tax breaks, subsidies and targets will drive the wood fuel market and stir competition between forest products industry and forest bioenergy facilitates. In this section, we simply investigate whether government policies play a significant role in the raw material market.

Instance S15: Based on Instance S3 with area-same prices in an integrated market, we assume that a new policy is imposed that the share of forest fuel used in heating plants increase from 50% to 80%.

Table 16 and Table 17 indicate the comparison between Instance S3 and Instance S15. We find that there is no significant difference in costs between these two problems. Only 0.12% less fossil fuel is purchased. Actually, in both Instance S3 and Instance S15, among 22 heating plants during 12 planning periods, most slack of the proportion constraints is positive. Only 6 constraints' slack is zero in Instance S3 and 31 in Instance S15. Indeed, the positive slack implies that these constraints do not bind; hence changing the proportion of forest fuel used in heating plants somewhat does not obviously affect the optimum. That is, in our case study, the consumption of forest fuel in most heating plants in most periods is under regulation. It should be note that the results can be sensitive to a change in the value of parameters, such as the price of fossil fuel. Anyway, the amount that forest raw materials can be used for energy generation is not only encouraged by the policies, but also by the harvest nature and trade-off between costs of other assortments, as discussed above.

Table 16 Cost comparisons of Instance S3 and Instance S15 (*unit: SEK*)

Instance	Purchasing Raw material	Purchasing Byproduct	Purchasing Fossil fuel	Chipping	Storage	Transport	Deficit	Total cost
S3	573,413,187	21,179,263	28,399,276	58,493,879	2,255,646	151,246,790	-	834,988,041
S15	573,436,139	21,179,263	28,364,869	58,495,255	2,285,565	151,471,404	-	835,232,495

Table 17 Actual total supply of raw materials of Instance S3 and Instance S15 (*unit: m*^{3})

	Sawlogs		Pulpwood			Fuel logs	Forest residues	
Instance	Pine	Spruce	Pine	Spruce	Birch	Decayed wood	Branches	Tree parts
S3	348,548	421,607	558,757	79,229	67,476	71,490	367,523	106,749
S15	348,548	421,607	558,772	79,249	67,478	71,490	367,523	106,749

4.7 Comparison 7: Change in price for fossil fuel

Nowadays the high price volatility of fossil fuel, such as heating oil, is very common. In the last comparison, we concentrate on how the change in heating oil price has an impact on supply market of raw materials and the wood flows in the network. Based on Instance S3 with area-same prices in an integrated market, we assume that the price of heating oil changes from 50% less to 50% more, by every 10%.

On the left side of Figure 15, the total energy values of forest bioenergy and fossil fuel sent to heating plants with the changes in the price of heating oil are bi-dimensionally displayed. The variation on average purchasing costs of corresponding forest bioenergy is illustrated on the right side. Obviously, the consumption of bioenergy in heating plants is driven by prices of possible substitute sources, i.e. heating oil.

At the beginning, when the price of heating oil is relatively low, heating oil is preferred and not all the available fuel logs and forest residues are forwarded to heating plants. Some purchased forest residues are even left in the forest. At the same time, little pulpwood is used as bioenergy. Most purchasing costs of forest bioenergy are around or lower than the mid-price of the range. However, with the steady increase of heating oil price, situation changes dramatically. Supply of fuel logs and forest residues quickly reach the upper bound with the soaring increase in corresponding purchasing costs. The higher price of heating oil, the less heating oil is purchased and more pulpwood is sent to heating plants. The purchasing costs of pulpwood are also pushed up. Because of the harvest nature that the supply of pulpwood are proportional to those of sawlogs, when the price of heating oil rises to 40% or higher, even more sawlogs than required will be purchased in order to increase the availability of pulpwood as bioenergy. The trade-off between increase in costs of forest raw materials (i.e., purchasing cost, chipping cost, transportation cost and storage cost) and decrease in consumption of heating oil should be taken into consideration.

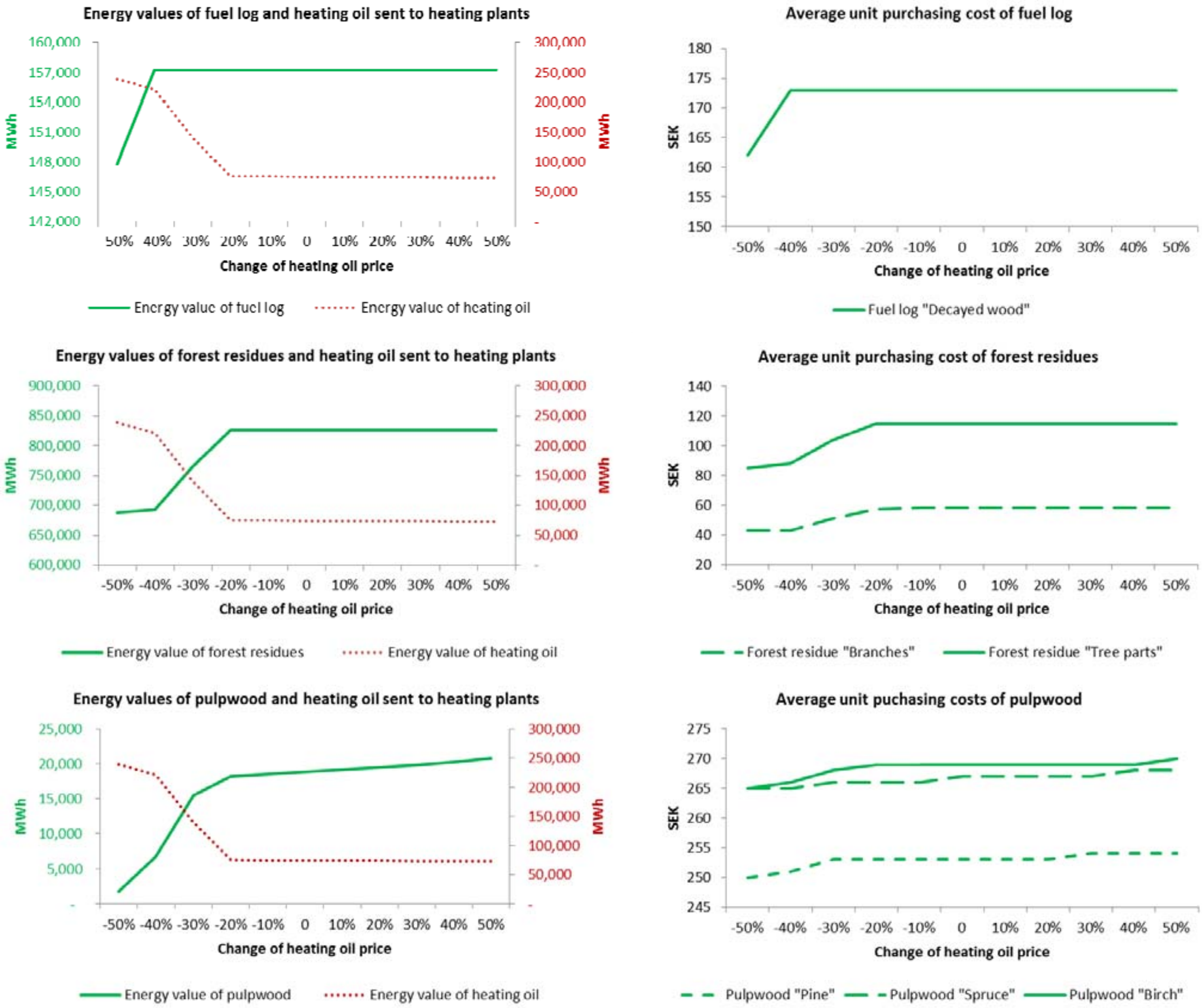


Figure 15 Total energy values of forest bioenergy sent to heating plants and corresponding average unit purchasing costs under the changes in price for heating oil

5 Concluding remarks and future work

Most studies in the past have addressed integration either for various planning problems or for different decision levels, concentrating on one specific forest products industry. This paper was unique because, for the first time, it dealt with an integrated market for all the forest raw materials in the initial stage of the supply chain. The objective of the proposed problem is to purchase adequate amount of raw materials in harvest areas and byproducts from sawmills in order to satisfy the diverse demands in sawmills, pulp mills and heating plants at the minimum combined costs of procurement, chipping, inventory and transportation.

We also include the possibility to decide the unit purchasing cost for different assortments so as to dynamically change the corresponding supply of raw materials, which linearly depends on the unit cost. This innovative implementation allows the forest companies to make in-depth analysis of the supply market and generate geographic maps with price difference. They can use this information to negotiate with forest owners for better rebates when signing annual supply contracts.

Though the proposed model is developed from a supplying company's perspective, similar modeling approaches could also be applied for 1) a forest owner who harvests logs and residues and sell to different customers or 2) a forest association who own all kinds of mills and heating plants and want to meet all the specific demands and balance needs for byproducts among its subsidiaries.

The integrated market for all the forest raw materials was simulated with the data from the Forestry Research Institute of Sweden. The proposed model is a typical QP problem of large size, but it can be efficiently solved by CPLEX as a solver. 16 instances under different assumptions are generated. Pair-wise comparisons demonstrate that resources can be effectively utilized with the price mechanism in supply market. No other uneconomic resources, such as heating oil, are needed to replenish the shortage in winter for heating plants. The overall energy value of forest bioenergy delivered to heating plants is 23% more than the amount in the situation when volume and unit purchasing cost of raw materials are pre-defined.

The results also indicate that because, in the integrated market, pulpwood can be used both as raw material for pulp process and as bioenergy for heat generation, the unit purchasing costs of pulpwood in harvest areas are pushed up. This is in line with the concern that once it is acceptable to sell pulpwood to heating plants, competition for raw materials between forest bioenergy facilities and traditional forest industries is expected to occur. However, an integrated market leads to a considerable cost saving potential in total cost and is more flexible to respond to external changes, i.e., demand fluctuation, than a separated market.

Harvest nature that the harvest of one area will result in the co-production of various assortments is an important factor that makes the whole market highly interacted. If the assortments can be ideally harvested, regardless of the harvesting of other assortments in the same area, the distance from one harvest area to mills turns out to be the main factor that determines the purchasing costs of the assortments in that area. Additionally, the amount that forest raw materials can be used for energy generation is not only encouraged by the policies, but also by the harvest nature and trade-off between costs of other assortments. Nevertheless, the exogenously increasing price for possible substitute sources, i.e., heating oil, will obviously boost the consumption of bioenergy in heating plants.

The next step of this research will introduce the binary variable in the supply market to exclude the real "unpopular" harvest areas and relax the specified volume and delivery prices in the demand market. We will estimate how these new changes influence the whole market and have a more comprehensive view about the impact of an integrated market on the competition between wood-energy facilities and traditional forest industries. These issues are currently being investigated.

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