

Interdependence of the Sawlog, Pulpwood and Sawmill Chip Markets: an Oligopsony Model with an Application to Finland

A. Maarit I. Kallio

Kallio, A.M.I. 2001. Interdependence of the sawlog, pulpwood and sawmill chip markets: an oligopsony model with an application to Finland. *Silva Fennica* 35(2): 229–243.

The interdependence of the markets for pulpwood, sawlogs and sawmill chips is analysed using a short-run model, which accommodates the alternative competition structures of wood buyers. We propose that imperfect competition in the pulpwood market tends to make the sawmills owned by the pulp and paper companies larger than the independent ones, even in the absence of transactional economies of integration. The impact of the wood market competition pattern on the profits of the forest owners and forest industry firms depends upon a firm-capacity structure, wood supply elasticities, and business cycles in the output markets. The numerical application of the model to the Finnish softwood market suggests that inflexibility of production capacities tends to make the wood demand rather insensitive with respect to price. Only the large firms, which all produce both pulp and sawnwood, may have oligopsony power under some conditions. Integrated production can increase competition in the sawlog market via the wood chip market.

Keywords wood market, oligopsony, forest industry

Author's address Helsinki School of Economics, Department of Economics and Management Science, P.O. Box 1210, FIN-00101 Helsinki, Finland **E-mail** maarit.kallio@hkkk.fi

Received 9 October 2000 **Accepted** 23 January 2001

1 Introduction

Forestry and the forest industry are of considerable economic importance in many countries, not the least because they provide income and important job opportunities in rural areas. Hence, there is a need for efficient wood markets. The spatial oligopsony power of the wood buyers

has often been recognised as a possible source of wood market inefficiency. Due to the land-intensive character of forestry and scale economies in pulpwood processing, pulpwood suppliers in particular often have relatively few potential buyers for the product. Despite the possibility of small-scale production in sawmilling, the sawlog market can also be concentrated. Diversification

by pulp and paper producers into sawnwood production is one source of sawlog market concentration. The incentives for integrated production of pulp and sawnwood can be many. If stumpage sales are the dominant sales pattern in the wood market, integration facilitates allocation of the different wood types from a sales lot to alternative end-uses. Integration may also reduce the transaction costs affiliated with the exchange of an important raw material of the pulp industry, sawmill chips. But as we will discuss in this paper, this integration may be also motivated by imperfect competition in the wood market.

Competition in the wood market has been studied in countries with a significant forest sector. Some studies have aimed to explicitly quantify the impacts of imperfect competition in the wood market on social welfare. Brännlund (1989) suggests a considerable social loss, given the assumed monopsony in the Swedish pulpwood market. Murray (1995a) estimates the welfare effects of a pulpwood market oligopsony and partial vertical integration of the pulp industry with roundwood resources in the U.S. His results indicate very small welfare distortions, but considerable distributional impacts. Regarding studies on the degree of market power, Murray's (1995b) study on the U.S. markets for pulpwood and sawlogs indicates a mild but statistically significant level of oligopsony power in the pulpwood market, but competitive sawlogs markets. Bergman and Brännlund (1995) suggest that the Swedish pulpwood market has been more oligopsonistic during recessions than booms. Størdal and Baardsen (2000) propose that the Norwegian sawlog market has been non-competitive. Ronnila and Topinen (2000) do not reject the competitive market hypothesis for the Finnish pulpwood market, but present some evidence for a non-competitive sawmill chip market. Simulations of the Finnish pulpwood market from 1988 to 1997 in Kallio (2001) suggest that the market may have been non-competitive during the recession years.

The wood market studies typically examine the markets for pulpwood and sawlogs separately, while they may consider the interrelation of these two markets through cross-price effects (e.g., Kuuluvainen et al. 1988, Brännlund 1989). Despite sawmill chips being an important raw material source for the pulp industry¹⁾, the role

of the chip market as a link between the two roundwood markets has attracted little attention. In this paper, we examine wood market competition while accounting for the interaction of the markets for sawlogs, pulpwood and chips. Our goal is to gain a better understanding of how the use of chips is reflected in roundwood prices, quantities traded and the performance and sizes of the market players under alternative competition hypotheses. We will first address this issue by analysing a theoretical market model where the wood buyers are divided into firms producing sawnwood only and into firms that produce both pulp and sawnwood. We will show, for instance, that when sawmill chips are an important input in the pulp industry, the pulpwood price should be nested in the sawlog price. We will also suggest that under the non-competitive wood markets, pulp producers integrated with sawnwood tend to choose a larger sawnwood output than independent sawmills. To explore the real-world implications of the model and the phenomena that can emerge due to the wood market interactions, the model is applied to recent data on the Finnish softwood market. In this context, we also discuss the implications for the market competition of the current buyer structure in the Finnish wood market.

In Section 2, we present and analyse a wood market model where the demand side consists of vertically integrated and non-integrated forest industry firms. In Section 3, the model is tailored to represent the Finnish softwood market. The results of the numerical experiments are presented in Section 4. Section 5 concludes.

2 Model

Consider an industry with two types of firms. For the firms $i \in I$, pulp is a principal product, but to diversify and to obtain flexibility in wood procurement, they also produce sawnwood. The firms $i, e \in E$ produce sawnwood only. A fixed input a_s of sawlogs is required to produce one unit of sawnwood. As a by-product, share r of

¹⁾ In Finland, for instance, sawmill chips accounted for 25% of the total wood use in the pulp industry in 1998 (The Finnish Forest Research... 1999). In Sweden the respective figure for 1997 was 30% (Skogsstatistisk årsbok... 1999).

sawlog input a_s is converted to sawmill chips, i.e., one unit of sawnwood output gives an output of ra_s units of chips. To produce pulp, firms use a fixed amount a_m of pulpwood or chips per one unit of pulp output. In the short run, the production of sawnwood and pulp by a firm is limited by the firm's production capacity. Due to the assumption of fixed wood input proportions, these production capacities can also be expressed as maximal wood processing capacities. We denote the pulpwood processing capacity of firm i by K_m^i and sawlog processing capacity by K_s^i .

In addition to wood and capital, the industry uses energy, labour and other materials in pulp and sawnwood production. The marginal unit costs of firm i due to the use of these non-wood inputs are assumed constant and they are denoted c_m^i in pulp production, and c_s^i in sawnwood production. The firms are assumed to take sawnwood and pulp prices, p_s and p_m respectively, given. Hence, there is perfect competition in the market for outputs.

Roundwood is supplied to the industry by numerous private forest owners. Their willingness to sell roundwood is assumed to depend on the stumpage price of wood and on factors Z , which are exogenous to the forest industry. The stumpage price for sawlogs w_s can be expressed by the inverse supply function $w_s = w_s(X_s, Z)$, where X_s denotes the total supply of sawlogs. Respectively, the stumpage price for pulpwood w_m is determined as $w_m = w_m(X_m, Z)$, where X_m denotes the total supply of pulpwood. Assume that these inverse supply functions are increasing in quantity, i.e., $w_m' = \partial w_m / \partial X_m > 0$, and $w_s' = \partial w_s / \partial X_s > 0$.

In addition to stumpage price, other wood-related costs are incurred from harvesting the wood and transporting it to mill. We denote the difference between the mill price and stumpage price of pulpwood by d . Furthermore, we assume that the mill price of chips w_h is tied to the mill price $(w_m + d)$ of pulpwood so that $w_h = w_m + d - b$. Assuming sawmill chips to be a perfect substitute for roundwood, $b \geq 0$ is a possible mark-down term, which results from pulp mills paying a non-competitive price for chips. The net unit price of chips received by independent sawmills is given as $w_h - l$, where l is the unit

cost of transporting chips from a sawmill to a pulp mill.

For $i \in I$, let x_m^i , x_h^i and x_s^i denote the input of pulpwood, the input of chips purchased from the independent sawmills, and the input of sawlogs by producer i , respectively. Similarly, for $e \in E$, let x_s^e be the sawlog input. In a market clearing equilibrium, the pulpwood supply X_m equals the total pulpwood demand, i.e., $X_m = \sum_{i \in I} x_m^i$, and the supply of sawlogs X_s equals the demand for sawlogs by integrated and independent sawmills, i.e., $X_s = X_s^I + X_s^E$, where $X_s^I = \sum_{i \in I} x_s^i$ and $X_s^E = \sum_{e \in E} x_s^e$. The total input of purchased wood chips $\sum_{i \in I} x_h^i$ is denoted by X_h . We assume that the market for chips clears, i.e., we require that $X_h = rX_s^E$.

A firm may recognise that its own wood demand has an impact on the total wood demand and thereby on the market price. We denote the firm's conjectured impact of its own input decision on the total wood demand in the markets for pulpwood by $\partial X_m / \partial x_m^i = \gamma_m^i$ and for sawlogs by $\partial X_s / \partial x_s^i = \gamma_s^i$. In a competitive pulpwood market firms act like price takers. In this case $\gamma_m^i = 0$ for all $i \in I$. For a competitive sawlog market $\gamma_s^i = 0$ for all i respectively. In a quantity setting Cournot oligopsony $\gamma_m^i = 1$ for all $i \in I$, and $\gamma_s^i = 1$ for all $i \in I$ and for all $i \in E$ for pulpwood and sawlogs, respectively. Hence, under the Cournot conjecture, each firm considers only its own impact on the total pulpwood or sawlog demand.

Let us now formulate the mathematical models for the wood buying firms and discuss the alternative wood market equilibria.

We assume that all the firms maximise their profits. To simplify notation, we include the non-stumpage costs of sawlogs directly in the marginal costs c_s^i of sawnwood production, but keep the respective unit cost d for pulpwood apart from c_m^i . For an integrated firm $i \in I$, profit V^i is given by

$$V^i = (p_s - c_s^i) \frac{x_s^i}{a_s} + (p_m - c_m^i) \left(\frac{x_m^i + x_h^i + rx_s^i}{a_m} \right) - w_s x_s^i - (w_m + d)x_m^i - (w_m + d - b)x_h^i. \tag{1}$$

Note that x_s^i/a_s is the sawnwood output and $(x_m^i + x_h^i + rx_s^i)/a_m$ is the pulp output of firm i . To further simplify notation, we denote $(p_s - c_s^i)/a_s = \pi_s^i$ and $(p_m - c_m^i)/a_m = \pi_m^i$. Then the profit

maximisation problem of the firm $i \in I$ is:

$$\begin{aligned} \text{Max}_{x_m^i, x_h^i, x_s^i} V^i &= (\pi_s^i + r\pi_m^i - w_s)x_s^i \\ &+ (\pi_m^i - w_m - d)x_m^i \\ &+ (\pi_h^i - w_m - d + b)x_h^i \end{aligned} \quad (2)$$

s.t.

$$x_s^i \leq K_s^i \quad (3)$$

$$x_m^i + x_h^i + rx_s^i \leq K_m^i \quad (4)$$

$$x_h^i \leq rX_s^E - \sum_{j \neq i} x_j^i \quad (5)$$

The wood inputs are constrained by the wood processing capacities as given by Eqs. (3) and (4). In addition, in Eq. (5), the use of purchased chips is limited to the residual amount that is available to the firm from the total chip quantity rX_s^E after the rivals' use of chips. Let us denote the Lagrange multipliers for constraints (3)–(5) by μ_s^i , μ_m^i and μ_h^i respectively. In an equilibrium x_s^i , x_m^i and x_h^i satisfy the following Karush-Kuhn-Tucker optimality conditions, which employ the slack variables δ_s^i , δ_m^i and δ_h^i :

$$\pi_s^i + r\pi_m^i - w_s - w_s'\gamma_s^i x_s^i - \mu_s^i - r\mu_m^i + \delta_s^i = 0 \quad (6)$$

$$\delta_s^i x_s^i = 0 \quad (7)$$

$$\pi_m^i - w_m - w_m'\gamma_m^i(x_m^i + x_h^i) - d - \mu_m^i + \delta_m^i = 0 \quad (8)$$

$$\delta_m^i x_m^i = 0 \quad (9)$$

$$\pi_h^i - w_m - d + b - \mu_h^i - \mu_m^i + \delta_h^i = 0 \quad (10)$$

$$\delta_h^i x_h^i = 0 \quad (11)$$

$$K_s^i - x_s^i \geq 0 \quad (12)$$

$$(K_s^i - x_s^i)\mu_s^i = 0 \quad (13)$$

$$K_m^i - x_m^i - x_h^i - rx_s^i \geq 0 \quad (14)$$

$$(K_m^i - x_m^i - x_h^i - rx_s^i)\mu_m^i = 0 \quad (15)$$

$$rX_s^E - \sum_{j \neq i} x_j^i - x_h^i \geq 0 \quad (16)$$

$$(rX_s^E - \sum_{j \neq i} x_j^i - x_h^i)\mu_h^i = 0 \quad (17)$$

$$x_s^i, x_m^i, x_h^i, \mu_s^i, \mu_m^i, \mu_h^i, \delta_s^i, \delta_m^i, \text{ and } \delta_h^i \geq 0.$$

Before going to the problem of independent sawmills, let us consider an example. If firm i does not buy any chips, i.e., $x_h^i = 0$, even when there is a positive residual supply of chips for the firm, it follows from Eq. (17) that $\mu_h^i = 0$. Consequently, if the pulpwood market is non-competitive so that $\gamma_m^i > 0$, Eqs. (8) and (10) imply that $\delta_m^i > 0$, if $x_m^i > 0$. Therefore, from Eq. (9) we must have $x_m^i = 0$. A Cournot firm buys all the chips available to it from the market at a price $w_m + d - b$ before it starts buying pulpwood from the stumpage market. Since this conclusion holds for all firms, the clearance of the chips market is guaranteed, if $x_m^i > 0$, for any i .

Independent sawmill $e \in E$, maximises its profit V^e as:

$$\text{max}_{x_s^e} V^e = \pi_s^e x_s^e + (w_m + d - b - l)rx_s^e - w_s x_s^e \quad (18)$$

s.t.

$$x_s^e \leq K_s^e, \quad (19)$$

$$x_s^e \geq 0.$$

Denoting the Lagrange multiplier for constraint (19) by μ_s^e and introducing a slack variable δ_s^e , the Karush-Kuhn-Tucker conditions for an optimal solution are:

$$\begin{aligned} \pi_s^e + r(w_m + d - l - b) \\ - w_s - w_s'\gamma_s^e x_s^e - \mu_s^e + \delta_s^e \leq 0 \end{aligned} \quad (20)$$

$$\delta_s^e x_s^e = 0 \quad (21)$$

$$K_s^e - x_s^e \geq 0 \quad (22)$$

$$(K_s^e - x_s^e)\mu_s^e = 0 \quad (23)$$

$$x_s^e \geq 0, \mu_s^e, \delta_s^e \geq 0.$$

From now on, while examining market equilibria, we limit our consideration to an industry where all the firms are active in the market equilibrium, i.e., we assume that all the firms $i \in I$ and $e \in E$ are producing sawnwood and that all the firms

$i \in I$ are producing pulp as well. Hence we are interested in the cases where the slack variables δ_s^i and δ_m^i of constraints (6) and (8) are zero for integrated firms $i \in I$, and where slack variable δ_s^e is zero for non-integrated firms $e \in E$. We also assume that all the firms hold the same wood market conjecture. I.e., $\gamma_s^i = \gamma_s$ for all integrated and independent sawmills and $\gamma_m^i = \gamma_m$ for all pulp producers. Hence $\gamma_s = 1$ and $\gamma_m = 1$ refer to Cournot markets, whereas $\gamma_s = 0$ and $\gamma_m = 0$ refer to perfect competition. Constraints (6), (8) and (20) become:

$$\begin{aligned} \pi_s^i + r\pi_m^i - w_s - w_s' \gamma_s x_s^i \\ - \mu_s^i - r\mu_m^i = 0, \quad \forall i \in I \end{aligned} \tag{6}$$

$$\begin{aligned} \pi_m^i - w_m - w_m' \gamma_m (x_m^i + x_h^i) \\ - d - \mu_m^i = 0, \quad \forall i \in I \end{aligned} \tag{8'}$$

$$\begin{aligned} \pi_s^e + r w_m + rd - rb - rl - w_s \\ - w_s' \gamma_s x_s^e - \mu_s^e = 0, \quad \forall e \in E. \end{aligned} \tag{20'}$$

Let us denote by $\bar{x}_m^I, \bar{x}_s^I, \bar{x}_h^I, \bar{\pi}_m^I, \bar{\pi}_s^I, \bar{\mu}_m^I$ and $\bar{\mu}_s^I$ the averages of the integrated firms $i \in I$ for variables x_m^i, x_s^i, x_h^i , parameters π_m^i, π_s^i and shadow prices μ_m^i and μ_s^i respectively. In a similar manner, we denote the averages of the active independent sawmills $e \in E$ by $\bar{x}_s^E, \bar{\pi}_s^E$ and $\bar{\mu}_s^E$. With some rearranging, aggregating across firms $i \in I$ in Eqs. (6') and Eqs. (8'), and aggregating across firms $e \in E$ in Eqs. (20') we obtain:

$$w_m = \bar{\pi}_m^I - \gamma_m w_m' (\bar{x}_m^I + \bar{x}_h^I) - d - \bar{\mu}_m^I \tag{24}$$

$$w_s = \bar{\pi}_s^I + r \bar{\pi}_m^I - \gamma_s w_s' \bar{x}_s^I - \bar{\mu}_s^I - r \bar{\mu}_m^I \tag{25}$$

$$w_s = \bar{\pi}_s^E + r w_m + rd - rb - rl - \gamma_s w_s' \bar{x}_s^E - \bar{\mu}_s^E \tag{26}$$

The value of the option to use sawmill chips in pulp production enters the sawlog price equations (25) and (26) and increases the sawlog price. In an unconstrained competitive equilibrium $\bar{\mu}_m^I = \bar{\mu}_s^I = \bar{\mu}_s^E = 0$ and $\gamma_m = \gamma_s = 0$. (For no firm to have a positive shadow price for its production capacities, the active firms must have identical marginal revenues π_s^i and π_m^i of wood use.) Then for Eqs. (25) and (26) to hold simultaneously, substitution of the pulpwood price from Eq. (24) to

Eq. (26) implies that the independent sawmills only produce if $\bar{\pi}_s^E - \bar{\pi}_s^I \geq rb + rl$. Consequently, if $b > 0$ or $l > 0$, the independent sawmills have to be more cost-effective or they have to price differentiate to obtain a better price for their product than the integrated sawmills to successfully compete with them.

Consider now an unconstrained oligopsony in the sawlogs market. Substituting the pulpwood price from Eq. (24) to Eq. (26), we obtain the result that the integrated and independent sawmills are of the same size in the sawlog market if $\bar{\pi}_s^E = \bar{\pi}_s^I + rb + rl$, when the pulpwood market is competitive. Imperfect competition in the pulpwood market increases the size of the integrated sawmills with respect to independent sawmills. In the Cournot market for sawlogs, the long-run difference between the average size of integrated and independent sawmills in terms of sawlog use is²⁾:

$$\begin{aligned} \bar{x}_s^I - \bar{x}_s^E = \\ \frac{(\bar{\pi}_s^I - \bar{\pi}_s^E + \gamma_m r w_m' (\bar{x}_m^I + \bar{x}_h^I) + rb + rl)}{w_s'} \end{aligned} \tag{27}$$

We now demonstrate that depending on the output market conditions, the sawlog price can decrease or increase due to non-competitive behaviour of the integrated firms in the pulpwood market. We also propose that non-competitive behaviour in the sawlog market may increase the pulpwood price.

An Example with a Sawlog Price That Is Decreasing Due to a Non-Competitive Pulpwood Market

Consider first the case with perfect competition in all markets, so that $\gamma_s = \gamma_m = b = 0$. Assume all firms to be active with idle capacity, so that $\bar{\mu}_m^I = \bar{\mu}_s^I = \bar{\mu}_s^E = 0$. The competitive sawlog price w_s^P is obtained by substituting competitive pulpwood price w_m^P to Eq. (26) as:

²⁾ Due to scale economies in the pulp and paper industry, the wood consumption in pulp production by a single firm may be substantial. In Finland, for instance, the average pulpwood input by a producer is close to 10 mill. m³ annually, while the proportion of wood chips r can be taken to be between 0.3-0.4. Hence the impact of the non-competitive wood market behaviour on the relative sizes of the sawmills can be non-negligible.

$$w_s^P = \bar{\pi}_s^E + rw_m^P + rd - rl \tag{28}$$

If the pulp industry now shifts to Cournot behaviour, pulpwood price w_m^C becomes

$$w_m^C = w_m^P - w_m'(\bar{x}_m^I + \bar{x}_h^I) - \bar{\mu}_m^I \tag{29}$$

If the pulpwood price decreases sufficiently because some large firms cut output substantially, some small pulp producers may increase their production and become capacity-constrained. That is why $\bar{\mu}_m^I$ enters Eq. (29). Nevertheless, because $w_m' > 0$ and $\bar{\mu}_m^I > 0$, the Cournot price cannot be higher than the competitive price. Therefore, since $w_m^C < w_m^P$, the sawlog price adjusts downwards as follows:

$$w_s^C = w_s^P + r(w_m^C - w_m^P) \tag{30}$$

An Example with a Sawlog Price That Is Increasing Due to a Non-Competitive Pulpwood Market

Consider now the case where the business cycle in the pulp market is favourable with a capacity-constrained pulp industry, but assume that each integrated sawmill has idle capacity. If there were more pulp capacity, integrated sawmills would be able to produce more. In other words, the pulp capacity also limits the sawnwood output. In this case, the competitive sawlog price is:

$$w_s^P = \bar{\pi}_s^I + r\bar{\pi}_m^I - r\bar{\mu}_m^I \tag{31}$$

If the pulp industry now shifts to Cournot competition in the wood market, and if this implies idle capacity both for sawnwood and pulp, it follows that $\bar{\mu}_m^I = 0$. Then the sawlog price increases to the unconstrained competitive level, where $w_s = \bar{\pi}_s^I + r\bar{\pi}_m^I$. Hence, it is possible that imperfect competition in the pulpwood market will increase the sawlog price.

Impact of Non-Competitive Behaviour in the Sawlog Market on Pulpwood Price

If we ignore the possibility of using sawlogs as a direct substitute for pulpwood, imperfect com-

petition in the sawlog market may not decrease pulpwood price. In the short run, the competitive pulpwood price depends solely on the marginal product value of pulpwood in pulp production and on the production capacity. Hence, the sawlog price level does not influence the pulpwood market directly. However, it can influence the pulpwood market via the chip market. If the oligopsony decreases sawnwood production, the supply of sawmill chips will be reduced in the same proportion. The cut in the input of chips may be replaced partly or entirely by pulpwood, which may increase the pulpwood price. This behaviour will be seen in the numerical application of the model to the Finnish wood market.

3 Numerical Application

Let us now describe the numerical application of the model to the Finnish softwood market. The market for the hardwood species was excluded because imports form such an important part of the industrial use of hardwood. In 1998, roughly 50% of the hardwood and 6% of the softwood used by the forest industry were imported (The Finnish Forest Research ... 1999).

To capture the production structure of the Finnish forest industry in a more detailed manner, the model in Section 2 was extended to include two pulp grades and two mechanical forest industry products. The products are sawnwood, plywood, chemical pulp and mechanical pulp and they are referred to with sub-indices s , v , m and y , respectively.

The inclusion of two more products means that additional decision variables are needed for each firm in the model formulation. In Section 2, x_m^i is the firm's pulpwood input in (chemical) pulp processing, x_h^i is the firm's input of purchased chips in (chemical) pulp processing, and x_s^i is the firm's input of sawlogs in sawnwood processing. To simplify calculations, we assume that all the sawmill chips are consumed in chemical pulp processing, although in Finland chips are used in mechanical pulping as well. In 1998, chemical pulping accounted for 76% of total chips use (The Finnish Forest Research... 1999). Then, the additional variables for firm i are the pulpwood

Table 1. Production in 1999 and assumed annual production capacities in 2000 (1000 t, 1000 m³) for softwood products in Finland by firm.

	Sawnwood		Plywood		Sulphate pulp		Mechanical pulp	
	Output	Capacity	Output	Capacity	Output	Capacity	Output	Capacity
UPM-Kymmene	1910	1980	365	375	1820	2040	1970	2250
Stora-Enso	1885	2120	0	0	1680	1780	1370	1430
Metsä-Serla	2243	2350	141	200	870	960	800	870
Vapo	689	730	0	0	0	0	0	0
Others	4973	5230	0	0	0	0	0	0
Total	11700	12410	506	575	4370	4780	4140	4550

input in mechanical pulp, x_y^i , and the sawlog input in plywood production, x_v^i . New parameters corresponding to extended product grouping are required respectively. The Appendix shows how the new variables and parameters enter the profit maximising problem of the integrated (Eqs. (A.1)–(A.5)) and non-integrated (Eqs. (A.6)–(A.8)) firms.

The Industry Data

The Finnish forest industry is concentrated in input markets. Three large forest industry firms buy practically all the pulpwood and sawmill chips and their share of the sawlog demand is over 50%. Table 1 presents the production in 1999 (based on the Finnish Forest Industry Federation, 2000c and 2000d) and assumed capacities of the firms for the softwood products in 2000. The figures account for holdings in any jointly owned mills. Myllykoski Paper has been included with Metsä-Serla, due to their alliance. Unless mentioned elsewhere, our source for capacity data was the www-pages of the Finnish Forest Industries Federation (2000a). The figures in Table 1 were used to define the wood processing capacities K_m^i , K_y^i , K_s^i and K_v^i of the chemical pulp, mechanical pulp, sawnwood and plywood producers, respectively.

Our data source aggregates softwood and hardwood sulphate pulp capacities. The capacity was allocated between the grades following their shares of the mill's production in 1999. Mechanical pulp is integrated with paper and paperboard production. The integrated paper and paperboard

capacity limits its demand and production. Its capacities were defined as follows. First, we calculated the mill capacity utilisation rates for paper and paperboard containing mechanical pulp. For this we used the production volumes for 1999 (The Finnish Forest Industry Federation, 2000c) and the production capacities for 2000 (The Finnish Forest Industry Federation, 2000a). This capacity utilisation rate was also assumed for the mechanical pulp capacities of the mills, which were then calculated from the mills' mechanical pulp production in 1999.

For large sawnwood producers (members of the Finnish Forest Industry Federation) we used the capacities for 1998, using the Finnish Forest Industry Federation (1998) as a basic source. These figures were updated using the data published by the web-sites of the individual companies in August 2000, whenever such data were available. For the rest of the producers, all of which are relatively small, we defined the aggregated production capacity assuming the average capacity utilisation rate to be same as that of the larger producers. This capacity block was divided to 200 smaller units in the model.

Plywood capacities are not of great significance with respect to wood use. Half of the wood used in plywood production was softwood in 1998 (The Finnish Forest Research...1999). Lacking the wood use data for 1999, we assumed that 50% of the plywood production was also softwood plywood in 1999. For Metsä-Serla, we obtained the softwood plywood capacity from a web-site of its subsidiary Finnforest in August 2000. For UPM-Kymmene, we used the 50% softwood assumption to disaggregate the soft-

wood production capacity from the total plywood capacity.

The wood input per one unit of output has been quite stable in the forest industry. Due to substitution between wood and the other production factors, and due to differences between the mills in their wood use efficiency and respective variation in the mills' activity levels, there can be slight annual variation. Based on the data by the Finnish Forest Industry Federation (2000a) we used the coefficients, $a_v=2.8\text{ m}^3/\text{t}$ and $a_m=5.6\text{ m}^3/\text{t}$ for pulpwood input in mechanical pulp and chemical pulp, respectively, and the coefficients $a_s=2.25\text{ m}^3/\text{m}^3$ and $a_v=3.0\text{ m}^3/\text{m}^3$ for sawlog input in sawnwood or plywood, respectively. The coefficient of $5.3\text{ m}^3/\text{t}$ was given for sulphate pulp by the source above, but that figure also includes the hardwood pulp with lower wood input. The pulp yield of wood in softwood chemical pulping is approximately half of that in mechanical pulping (e.g., Saarnio, 1999). For the chips output coefficients we employed the values $r_v=0.4$ and $r_s=0.36$ per one m^3 of sawlogs used in plywood and sawnwood production. These figures were calculated from the data by the Finnish Forest Industry Federation (in 1999a and 2000d).

Roundwood Supply

Econometric studies have established a positive correlation between wood stumpage price and supply from the private forests, which supply over three-quarters of the softwood in Finland. Toppinen and Kuuluvainen (1997) obtained price elasticity estimates for short-term pulpwood supply as follows: 0.4 during 1960–1992 but over 2.0 for the period from 1976 to 1992. For the sawlog supply, Kuuluvainen et al. (1988) obtained a price elasticity of 0.53, and Tikkanen and Vehkamäki (1990) obtained a price elasticity of 0.68. The studies using more recent time-series data have given mixed results. In Toppinen and Kuuluvainen (1997), the sawlog supply elasticity was found to be insignificant or very small and in Toppinen (1998) it was estimated to be of the order of 1.9.

We represent the wood supply with two inverse supply functions (i.e., functions for wood prices), one for the pulpwood price and one for the sawlog

price. The production data in Table 1 and the input coefficients above give the reference demands: 27.8 mill. m^3 for sawlogs and 26.1 mill. m^3 for pulpwood. These quantities were used together with reference market prices to form inverse wood supply functions of linear form: $w_s = M_s + \beta_s X_s$ for sawlogs, and $w_m = M_m + \beta_m X_m$ for pulpwood. The supply function parameters (M_s , M_m , β_s and β_m) were defined to equate the price elasticity of wood supply in the reference point with a given price elasticity estimate, for which we explored a range of values. The base case reference prices were weighted averages of pine and spruce stumpage prices from private forests in 1999: 250 FIM/ m^3 for sawlogs, and 109 FIM/ m^3 for pulpwood. The purchased quantities were used as weights. These data were based on the Finnish Forest Research Institute (2000). We tested the sensitivity of the results with respect to other reference price levels as well.

Product and Input Prices

From 1978 to 1998, the real prices of forest products in Finland obtained their peaks during the last ten years, sawnwood being an exception. The maximum and minimum values were obtained simultaneously for pulp and pulpwood. For sawlogs, the minimum and maximum prices were attained simultaneously with the lowest and highest pulpwood prices, respectively. To encompass market cycles and also uncertainty in cost data, we consider three alternative scenarios: high (HIGH), average (AVG) and low (LOW) output markets. Table 2 shows the data employed to define marginal revenue parameters for wood use, π_m^i , π_v^j , π_s^j , and π_v^i in chemical pulp, mechanical pulp, sawnwood and plywood, respectively, in the scenarios. The same parameters were used for both the integrated and non-integrated producers. Since pulp is an intermediary product, our procedure encompasses the assumption that the price of pulp entirely reflects the value of pulp in paper and paperboard production.

Solving the Model

We assume either perfect competition or Cournot

Table 2. Prices and variable production costs other than stumpage costs (FIM/m³ or FIM/t in 1998 money) employed in defining the marginal revenues of wood use in scenarios HIGH, LOW and AVG.

	Sawnwood			Plywood		
	HIGH	LOW	AVG	HIGH	LOW	AVG
Price	1169	954	1060	4665	3023	3750
Energy	36	36	36	225	225	225
Labor	120	120	120	957	957	957
Fixed wood	152	152	152	202	202	202
Other	8	8	8	41	41	41
Margin	853	638	744	3240	1598	2325

	Mechanical pulp			Sulphate pulp		
	HIGH	LOW	AVG	HIGH	LOW	AVG
Price	2976	1879	2280	3185	2049	2640
Energy	455	455	455	0	0	0
Labor	32	32	32	185	185	185
Fixed wood	260	260	260	520	520	520
Other	85	85	85	260	260	260
Margin	2144	1047	1448	2220	1084	1674

Source: Prices are minimum, maximum and average export unit values in 1988–1998 from the Statistical Yearbook of Forestry. For sawnwood and plywood, the cost data were obtained by dividing the total non-wood costs in the Industrial Statistics 1998 by the production quantity. For mechanical pulp, the non-wood costs are averages of thermo-mechanical pulp and groundwood pulp and they are calculated using the technology definitions in Saarnio (1999). For sulphate pulp the costs have been calculated on the basis of the technology definitions in Saarnio (1999) and Jaakko Pöyry Consulting (1992). Fixed wood costs include the harvesting and long-distance transportation costs of roundwood. The harvesting costs were obtained from Metsäteho Oy and the long-distance transportation costs are from the Finnish Statistical Yearbook of Forestry 1999. Margin refers to profit margin before the stumpage costs of wood and capital costs.

competition in the roundwood markets. The market for sawmill chips is competitive in the base case (parameter $b=0$), but to explore the influence of non-competitive pricing of sawmill chips we also investigate cases with $b > 0$. We use the figure $l=30$ FIM/m³ for the average transportation cost of chips from a sawmill to a pulp mill. This was roughly the average costs of long-distance transportation (FIM/m³) for roundwood in Finland in 1998 (the Finnish Forest Research... 1999).

To find the market equilibria for the alternative competition hypotheses, we first formed the Karush-Kuhn-Tucker optimality conditions of the problems of the individual firms. Then, using the GAMS software package (Brooke et al. 1992), we solved a mathematical programming problem, which consists of these conditions and the market clearing conditions for wood chips, sawlogs and pulpwood (Eqs. (A.9)–(A.11) in the Appendix).

Any feasible solution for this problem is a market equilibrium.

4 Simulation Results

This section describes and compares the simulated market outcomes in alternative competition patterns of the wood buyers. We let the output market cycle and the price elasticities of wood supply vary.

Results for Price Elasticities of Wood Supply of 1.0 or above

Facing unitary elastic or more elastic roundwood supply functions, the simulated forest industry produces at full capacity under all output market

conditions and competition patterns. Due to a rather elastic wood supply, no firm is able to gain from oligopsonistic behaviour in any market. Hence, if a firm cuts its wood demand in order to pay less for wood, the decrease in the wood costs cannot offset the decrease in variable profits caused by the decreased sales.

Results for Price Elasticities of Supply of 1.0 for Pulpwood and below 0.5 for Sawlogs

Let us look at a case where the price elasticity of the pulpwood supply is 1.0, and where the price elasticity of the sawlog supply varies from 0.3 to 0.5. With an elasticity of 0.5, the Cournot outcome differs from the competitive outcome only in scenario LOW. With an elasticity of 0.3, the oligopsony also contracts its sawlog demand under better market conditions. Fig. 1 graphs the impacts of the oligopsonistic behaviour on the roundwood demand in scenario LOW. Fig. 2 presents a comparison of the aggregated profits in the alternative competition patterns relative to perfect competition when the sawlog price elasticity is 0.3.

All the independent sawmills are well below the Cournot firm size of our experiments, which in terms of sawlog input is roughly 5 mill. m³ (4.5 mill. m³) in the average (low) market for a sawlog price elasticity of 0.3. Their behaviour is unaffected by the competition pattern. However, as is evident from Fig. 2, they are the biggest winners in relative terms if the larger companies behave non-competitively in the sawlog market.

While imperfect competition in the sawlog market reduces sawnwood and plywood output, it also decreases the supply of chips. As shown in Fig. 1, the demand for pulpwood increases. The resulting increase in pulpwood price dilutes some of the gains from imperfect competition in the sawlog market for the integrated firms. In Fig. 2 the forest owners' are slightly better off when there is Cournot competition in both markets than in the case of Cournot competition in the sawlogs market only. The two largest sawlog buyers cut their sawlog demand more under sawlog market oligopsony than under oligopsony in both roundwood markets. Aggregation of profits hides firm-level differences. Two of the three integrated

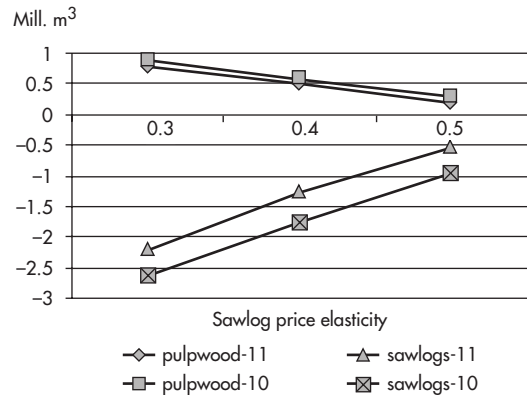


Fig. 1. Change (mill. m³) in the demand for pulpwood and sawlogs in scenario LOW, when the industry shifts from competitive behaviour to Cournot oligopsony in the sawlog market (10) or in the both sawlog and pulpwood markets (11). Pulpwood price elasticity is fixed at 1.0.

producers clearly have the largest profits when there is a Cournot oligopsony in the sawlog market only, while the largest pulp producer makes roughly the same profit in both the sawlog market oligopsony and in the entire roundwood market oligopsony.

Results for Price Elasticities of Supply of 1.0 for Sawlogs and below 1.0 for Pulpwood

Let us keep the sawlog price elasticity unitary and experiment with pulpwood price elasticity. In scenario AVG, the pulp companies produce at full capacity under the Cournot oligopsony when we employ the lowest econometric price elasticity estimate for the pulpwood supply in Finland, 0.4. In scenario LOW, however, the pulpwood consumption is then 5.6 mill. m³ (20%) lower in the Cournot pulpwood market than in the competitive market. In the low market, the largest pulp producer cuts its pulpwood input slightly with an elasticity of 0.9. The second largest pulpwood buyer contracts its production when we reduce the pulpwood price elasticity to 0.5. The sawlog price and demand remain unaffected in all the cases.

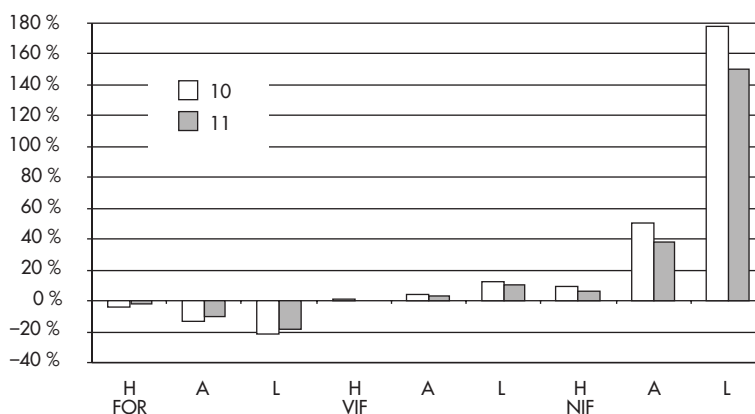


Fig. 2. Change (%) in the income of forest owners (FOR) and in the profits of integrated (VIF) and non-integrated (NIF) firms in the high (H), average (A) and low (L) output markets when the industry shifts from competitive behaviour to Cournot competition in the sawlog market only (10) or in the pulpwood and sawlog markets (11). Results for the supply elasticities of 1.0 for pulpwood and 0.3 for sawlogs

Collusion of Integrated Firms (Monopsony)

Now consider a case where all the integrated firms form a wood-buying cartel. In the pulpwood market, this means a monopsony.

Facing unitary elastic wood supply functions, the cartel would produce practically at full capacity in scenarios AVG and HIGH, while in scenario LOW the cartel would cut its roundwood demand. Then the Cournot behaviour in the sawlog market only is not sustainable. Due to the resulting increase in pulpwood price, the cartel makes less profit than under perfect competition. When both wood markets are oligopsonistic, the cartel contracts its pulpwood demand by 28% and its sawlog demand by 9% from the competitive levels.

Given the average output markets, the current pulp capacity in Finland roughly equals the optimal monopsonistic capacity when the price elasticity of the pulpwood supply is 0.8 (The capacity utilisation by the monopsony is then 99.8%). Given that the sawlog market is also oligopsonistic, the current integrated sawmill capacity is optimal to the monopsony pulp industry if the sawlog price elasticity is about 0.7. Hence, then the capacity is in full use. If the sawnwood capac-

ity of the pulp industry were disintegrated and used by an independent sawmill, sawnwood production would decrease by circa 17%.

Non-Competitive Pricing of Sawmill Chips

For non-competitive pricing of chips to have a short-run influence on the production and harvest levels, the mark-down in the chip price has to be considerable. In scenario LOW, the non-integrated sawmills are most vulnerable to non-competitive pricing of chips. Then, given a unitary elastic sawlog and pulpwood supply, the first impact on the sawnwood production quantities is seen for mark-down $b = FIM 200$. Then the largest independent sawmill cuts its sawnwood production under the Cournot competition, but not under the competitive market. It thus seems that the short-run impacts of the non-competitive chips market are mainly distributional. Integrated forest industry companies make more profit, independent sawmills make less profit, but forest owners' income is unaffected. While the impact on the forest owners is neutral in the short run, the small sawmills may be left to face this potential problem alone. Nevertheless, there can be long-

run effects, shown as a decrease in the size of the sawmilling sector.

Further Sensitivity Analysis

Let us finally test the sensitivity of the results with respect to some other pricing schemes. The wood input in 1999 is still used as a reference quantity.

When the wood supply functions are benchmarked to the average real prices in the period from 1988 to 1998, 109 FIM/m³ for softwood pulpwood and 218 FIM/m³ for sawlogs, the pulpwood supply function remains unchanged. Expectedly, the behaviour of the pulpwood buyers is unaffected. The sawlog prices are lower, and all the scenarios are more favourable to the sawmilling industry. Even less elastic sawlog supply functions than before are required to make the oligopsonistic behaviour attractive in the sawlog markets. In scenario LOW, the sawlog supply elasticity has to be decreased to 0.4 to make the largest buyer contract its sawlog input in Cournot.

When we keep the sawlog reference price at 250 FIM/m³ and choose a pulpwood reference price of 141 FIM/m³, the price spread between the two wood grades (FIM 109) equals the average spread during 1988-1998. The position of the pulpwood buyers is now weakened. Under a unitary elastic pulpwood supply, Cournot behaviour in the pulpwood market now decreases the pulpwood demand by 4.7 mill. m³ (16%) in LOW, but not at all in the other scenarios. In scenario AVG, the pulpwood price elasticity has to be 0.6 or less to make the Cournot outcome deviate from the competitive outcome.

5 Discussion

We presented and analysed a forest sector model that links the markets for sawlog and pulpwood via the market for sawmill chips. The model was used for a numerical analysis of the Finnish softwood market under alternative competition patterns. Both the analytical and numerical results suggest that due to the linkage of the sub-markets,

the impact of the alternative competition patterns on the performance of the market players is not ex ante predictable; it depends on the firm-capacity structure, the output market cycle and on the wood supply elasticities.

The analytical model suggests that the value of the option to use sawmill chips as an input in pulp production should be nested in the sawlog price. If there are transaction costs in the exchange of chips between the firms or if the pulp industry marks down the chip price, independent sawmills have to obtain a higher marginal revenue from wood use than the sawmills owned by pulp companies to compete with them. Oligopsonistic behaviour in the sawlog market allows the operation of sawmills with differing marginal product values for sawlogs in the market. However, if the pulpwood market is non-competitive, sawmills owned by the pulp producing companies tend to be larger than the independent sawmills, even in the absence of transactional economies of integration. This can increase the buyer-side concentration in the sawlog market. However, because a sawmill integrated with a pulp company may choose a considerably larger output than what is optimal for a respective independent oligopsonistic sawmill, the integration can also be welfare-enhancing in this case.

The principal purpose of the numerical analysis was to explore the phenomena that can emerge in the wood market due to the use of chips and due to integrated pulp and sawnwood production. Since the model was tailored to represent the Finnish softwood market with its most recent firm-capacity structure, some suggestions may be drawn regarding the Finnish timber market. Accounting for the sawlog market competition, the study also extends the work in Kallio (2001). When considering our results, their sensitivity with respect to the choice of wood supply elasticities and to the use of a linear approximation of the wood supply curve, should be borne in mind.

First, given the current structure of the Finnish roundwood market, it seems that one should be worried about the short-run welfare impacts of imperfect competition mainly during recessions. Under the average market conditions the industry is capacity-constrained for a rather plausible set of elasticities, which makes the demand for wood rather insensitive with respect to price. Then the

market power issues have mainly distributional impacts in the short-run. Since the pulpwood processing capacity equals the monopsony capacity in the average market conditions for a rather plausible pulpwood supply elasticity of 0.8, this result seems not to be very sensitive with respect to the assumed level of conjectural variation. Nevertheless, in order to enhance wood market stability during recessions, further mergers between pulp producers should not be encouraged.

The Finnish sawlog market is less concentrated on the buyer side than the pulpwood market, and the sawlog supply has to be very inelastic to render market power to the buyers. Independent sawmills are too small to influence wood price. Possibly, they face non-competitive pricing of sawmill chips, which might affect the size of the sawmilling sector and the structure of the roundwood demand in the long run. A wider array of market opportunities for sawmill chips would be a remedy to this potential problem.

There are some indications that the pulp production capacity has reached the limits of its growth potential in Finland. Rough estimates based on national forest resource accounting suggest that the domestic pulpwood resources were practically in full use during 1994–1996 (The Finnish Forest Research... 1997). An industry specialist, Diesen (1998, p.25) writes that “the accepted opinion in the forest industry is that significant expansion of [pulp] capacity based on additional wood removals will no longer be possible after the mid 1990s”. Provided that this picture of the situation is realistic, quantity-setting oligopsonistic competition should not have significant long-run welfare impacts in the pulpwood market. Regarding the outcome, it is not important, whether the growth in domestic pulpwood demand is constrained by the domestic wood resources or whether it is constrained by the reluctance of the oligopsonistic pulp industry to add further capacity.

We modelled the wood market at an aggregate national level. Also, while the volume of foreign trade in softwood timber has been relatively low, we assumed that the supply functions of pulpwood and sawlogs mainly represent domestic sources. There is, however, some evidence of the Finnish market for pine and spruce pulpwood being divisible into regional sub-markets with

differing price structures (Toppinen and Toivonen 1998, Tilli, Toivonen and Toppinen 2000). This can be the signal of a non-competitive wood market behaviour at the regional level. On the other hand, Thorsen (1998) proposes that the strong law of one price holds between spruce sawlogs markets in Finland and Sweden. While this can, for instance, be a reflection of the common export markets of sawnwood, it does not prove the existence of the spatially integrated sawlog market (See discussion in Tirole 1990, p.13). Nevertheless, the integrated markets are less likely to be inefficient than the non-integrated ones. Furthermore, our analysis leaves any questions influenced by the current and future developments in roundwood imports and exports subject to further studies.

Acknowledgements

The author thanks Markku Kallio and the two referees of this journal for their valuable comments on earlier versions of this paper.

References

- Bergman, M. & Brännlund, R. 1995. Measuring oligopsony power. An application to the Swedish pulp and paper industry. *Review of Industrial Organization* 10: 307–321.
- Brännlund, R. 1989. The social loss from imperfect competition – the case of the Swedish pulpwood market. *Scandinavian Journal of Economics* 91(4): 689–704.
- Brooke, A., Kendrick, D. & Meeraus, A. 1992. GAMS, a user's guide. The Scientific Press.
- Diesen, M. (ed.). 1998. Economics of the pulp and paper industry. Book 1. In *Papermaking science and technology*. Helsinki. Fapet. 186 p.
- The Finnish Forest Industries Federation. 1998. Key to the Finnish forest industry. Helsinki.
- 1999a. Environmental report. Sawmilling and panel products industry. Statistics for 1998. Espoo.
- 1999b. Environmental report. Paper and pulp industry. Statistics for 1998. Espoo.
- 2000a. Information on the www.forestindustries.fi.

- In August, 2000.
- 2000b. The Finnish forest industry facts and figures. Helsinki 6/2000. 47 p.
 - 2000c. Environmental report. Paper and pulp industry. Statistics for 1999. Espoo.
 - 2000d. Environmental report. Sawmilling and panel products industry. Statistics for 1999. Espoo.
- The Finnish Forest Research Institute. 1997. [Finnish forest sector economic outlook]. Metsäsektorin ajankohtaiskatsaus 1997. Helsinki Research Centre, Report 655. 62 p. (In Finnish).
- 1999. The Finnish Statistical Yearbook of Forestry 1999. Helsinki.
 - 2000. [Newsletter of forestry statistics 28.1.2000. Purchases and prices of wood, December 1999] Metsätalostatiedote 28.1.2000. Puun ostot ja hinnat, joulukuu 1999. Helsinki. (In Finnish).
- Jaakko Poyry Consulting. 1992. The data for the Finnish forest sector model. Unpublished document.
- Kallio, A.M.I. 2001. Analysing the Finnish pulpwood market under alternative hypotheses of competition. *Canadian Journal of Forest Research* 31: 236–245.
- Kuuluvainen, J., Hetemäki, L., Ollonqvist, P., Ovaskainen, V., Pajuoja, H., Salo, J., Seppälä, H. & Tervo, M. 1988. The Finnish roundwood market: an econometric analysis. *Finnish Economic Papers*. 1: 191–201.
- Murray, B.C. 1995a. Oligopsony, vertical integration, and output substitution: welfare effects in U.S. pulpwood market. *Land Economics* 71(2): 193–206.
- 1995b. Measuring the oligopsony power with shadow prices: U.S. Markets for pulpwood and sawlogs. *The Review of Economics and Statistics* 77: 486–498.
- Ronnila, M. & Toppinen, A. 2000. Testing for oligopsony power in the Finnish wood market. *Journal of Forest Economics* 6: 7–22.
- Saarnio, A. 1999. Choice of strategic technology investment – case of pulp production technology. *Acta Universitatis Lappeenrantaensis* 75. 225 p. + appendices.
- Skogsstatistisk årsbok 1999. Official statistics of Sweden. National Board of Forestry.
- Størdal, S. & Baardsen, S. 2000. Concentration and market power in the Norwegian sawlog market 1974–1991. Forthcoming in *Scandinavian Forest Economics* 38.
- Thorsen, B.J. 1998. Spatial integration in the Nordic timber market: long-run equilibria and short-run dynamics. *Scandinavian Journal of Forest Research* 13: 489–499
- Tikkanen, I. & Vehkamäki, S. 1990. The effects of economic and forest policy on roundwood supply. *Proceedings, IUFRO Working Group S4.08-01*. Montreal. p. 129–137.
- Tilli, P., Toivonen, R. & Toppinen, A. 2000. [Integration of the regional wood price changes in Finland]. *Puun hintavaihteluiden alueellinen yhtenevyys Suomessa*. *Metsätieteen aikakauskirja* 3/2000: 433–441. (In Finnish).
- Tirole, J. 1990. *The theory of industrial organization*. Fourth edition. Massachusetts Institute of Technology. 479 p.
- Toppinen, A. 1998. Incorporating co-integration relations in a short-run model of the Finnish sawlog market. *Canadian Journal of Forest Research* 28: 291–298.
- & Kuuluvainen, J. 1997. Structural changes in sawlog and pulpwood markets in Finland. *Scandinavian Journal of Forest Research* 12: 382–389.
 - & Toivonen, R. 1998. Roundwood market integration in Finland: a multivariate cointegration analysis. *Journal of Forest Economics* 4(3): 241–265.

Total of 30 references

Appendix

Extended firm models (Notation as in Sections 2 and 3)

The profit maximising problem of a vertically integrated firms $i \in I$ is:

$$\begin{aligned} \text{Max}_{x_s^i, x_v^i, x_m^i, x_y^i} \quad & V^i = \pi_s^i x_s^i + \pi_v^i x_v^i + \pi_m^i (x_m^i + x_h^i + r_s x_s^i + r_v x_v^i) + \pi_y^i x_y^i - \\ & w_s(X_s)(x_s^i + x_v^i) - (w_m(X_m) + d)(x_m^i + x_h^i) - (w_m(X_m) + d - b)x_h^i \end{aligned} \quad (\text{A.1})$$

s.t.

$$x_s^i \leq K_s^i \quad (\text{A.2})$$

$$x_v^i \leq K_v^i \quad (\text{A.3})$$

$$x_m^i + x_h^i + r_s x_s^i + r_v x_v^i \leq K_m^i \quad (\text{A.4})$$

$$x_y^i \leq K_y^i \quad (\text{A.5})$$

$$x_s^i, x_v^i, x_h^i, x_m^i, x_y^i \geq 0$$

The profit maximising problem of an independent sawnwood or plywood producer $e \in E$ is:

$$\max V^e = \pi_s^e x_s^e + \pi_v^e x_v^e + (w_m + d - b - l)(r_s x_s^e + r_v x_v^e) - w_s(X_s)(x_s^e + x_v^e) \quad (\text{A.6})$$

s.t.

$$x_s^e \leq K_s^e \quad (\text{A.7})$$

$$x_v^e \leq K_v^e \quad (\text{A.8})$$

Extended market clearing conditions

The market clearing conditions for sawmill chips, pulpwood and sawlogs, respectively, are:

$$\sum_{i \in I} x_h^i = \sum_{e \in E} (r_s x_s^e + r_v x_v^e) \quad (\text{A.9})$$

$$\sum_{i \in I} (x_m^i + x_y^i) = X_m \quad (\text{A.10})$$

and

$$\sum_{i \in I} (x_s^i + x_v^i) + \sum_{e \in E} (x_s^e + x_v^e) = X_s \quad (\text{A.11})$$