SILVA FENNICA

Silva Fennica 43(1) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Regional Energy Wood Logistics – Optimizing Local Fuel Supply

Christian Kanzian, Franz Holzleitner, Karl Stampfer and Sarah Ashton

Kanzian, C., Holzleitner, F., Stampfer, K. & Ashton, S. 2009. Regional energy wood logistics – optimizing local fuel supply. Silva Fennica 43(1): 113–128.

The promotion of electric energy production from solid biomass by the Austrian government has lead to a boom in the construction of new combined heat and power plants. The current total demand for wood chips in the research area for energy purposes is 70 400 m^3 of loose volume chips per year. The expected increase in demand due to these new plants is more than 4 times greater than current demand: up to 302 700 m^3 of loose volume per year. Even if the energy wood feedstock potential is satisfactory, the design of the supply chain is still unresolved. The aim of this study is to give decision-makers a base for further development. To accomplish this, we designed and tested four different supply scenarios: one for 9 plants and one for 16 plants. The scenarios were developed using a combination of geographic information systems (GIS) and linear programming methods. The results indicate that direct transport of solid fuel wood as round wood and chipping at the plant is the cheapest supply system with a resulting cost of 5.6–6.6 EUR/m^3 loose. Using harvesting residues can only be recommended for large plants because of poor fuel quality. In this case, residues would be chipped at or near the landing, piled and transported via self-loading trucks at a cost between 8.4 and 9.1 EUR/m^3 loose. In order to meet increasing demand and to ensure a continuous supply, especially during the winter and spring seasons it is necessary to optimize the supply chain by including storage terminals. However, using terminals and increased demand both lead to higher logistical costs. For example, if the total volume is handled via terminals, the average supply costs including storage will increase by 26%. Higher demand increases the costs by 24%.

Keywords energy wood, logistics, transport optimization, GIS
Addresses *Kanzian*, *Holzleitner* and *Stampfer*, University of Applied Life Sciences Vienna, Institute of Forest Engineering, Peter Jordan Straße 82, A-1190 Vienna, Austria; *Ashton*, Southern Regional Extension Forestry, Forestry Bldg. 4-420, University of Georgia, Athens, GA 30602, USA **E-mail** christian.kanzian@boku.ac.at
Received 5 October 2007 **Revised** 5 December 2008 **Accepted** 20 January 2009
Available at http://www.metla.fi/silvafennica/full/sf43/sf431113.pdf

1 Introduction

New regulations to promote bioenergy increase the demand for forest fuel in Austria. Wood chips are burned as fuel at combined heat and power plants (CHP), and subsidies from recent regulations have made it such that a lot of new CHPs have cropped up throughout Austria. This increase in the number of plants will raise the forest fuel demand from 2.1 up to 5.0 million m^3 solid through 2010 (Katzensteiner and Nemestothy 2006). Use of wood for fuel is a long-standing tradition in Austria. However during the last two decades, a number of new municipal and home heating systems have been installed, most of which require relatively small amounts of fuel. Thus, short transport distances with a maximum of 30 km are typical. Most of the chips burned in municipal heating plants are purchased as sawmill by-products.

Historically, forest derived wood chips have not been competitive because of high supply costs and varying quality (Stockinger and Obernberger 1998). In addition to cost and quality issues, a constant supply is required throughout the year, and winter weather conditions often make mountainous regions inaccessible. Wood terminals, however, would allow fuel storage and a secure supply, especially during the winter months. Additionally, because CHP plants are mostly located close to more urban areas, chipping or crushing at the plant is sometimes a problem because of noise and dust emissions. Thus, these terminals can also be seen as a process management tool providing a more acceptable place for chipping or crushing. Besides providing supply flexibility in the winter season, they can also stabilize changes in transport vehicle capacity and balance seasonal variations in supply (Gunnarsson et al. 2004). At present, the physical supply networks necessary to meet Austria's growing needs do not exist, thus creating an opportunity to design such networks from scratch.

Constructing supply networks is a difficult task, as several fundamental questions must be considered, questions like transport modes, storage locations, economically justifiable transport distances, preferred areas of supply and much more. A particular problem, spatial in nature, is the location of storage points (terminals) within the supply chain. Several authors have tried to answer these questions, all with different approaches.

Eriksson and Björheden (1989) for example evaluated five theoretical production flows of fuel from the forest to a single plant or from the forest via storage terminals to a single plant, respectively. Using linear programming methods, the computed results showed that direct supply of fuel to the plant was the most economic because the added cost of improved fuel quality and secure supply does not pay off. In general, it can be expected that the integration of terminals in the supply chain results in higher overall costs (Eriksson and Björheden 1989, Vartiamäki et al. 2006). Eriksson and Björheden (1989) pointed out, "optimizing forest-fuel production essentially means minimizing transport costs". To determine terminal locations, Gronalt and Rauch (2007) presented a simple approach based on iso-cost curves, but also mentioned that for a near optimal supply network, total cost of transport and terminal must be considered. Freppaz et al. (2004) developed a decision support system (DSS) for forest biomass in an effort to find suitable plant locations and sizes as well as optimal supply areas within a region. Supply options using terminals were not considered. The DSS integrates geographic information system (GIS) and linear programming (LP) techniques for problem solving. Nord-Larsen and Talbot (2004) used similar methods to allocate fuel wood potential to specific plants. Additionally, the economic potential of fuel wood was assessed using marginal cost-of-supply curves in Denmark. The availability of logging residues (harvesting residues) was investigated by Ranta (2005) using a similar combination of GIS and LP.

Besides Eriksson and Björheden (1989) and Gunnarsson et al. (2004), none of the cited studies dealt with supply networks using storage terminals, so the aim of this study is to develop a regional fuel wood supply network for forest derived wood chips that includes the optional use of terminals by testing a number of different possible scenarios.

2 Material and Methods

To accomplish this study, a simple procedural method was set up. This method was applied to a sample region to calculate optimal material flows and expected costs at plant level for different demand scenarios and supply options and to demonstrate the differences between direct flow and flow via a terminal. Additionally, this study ran a scenario based analysis and sensitivity analysis, which are common ways of dealing with uncertainty (Beaudoin et al. 2007). Input data from the region was collected during a survey that measured demand and existing infrastructure for terminals (Kanzian et al. 2006). In addition, an estimation of the fuel wood potential taking forestry inventory data was performed.

The 2006 survey showed that in 2005, approximately 670 000 m^3 loose of wood biomass was consumed by 25 conversion plants. The survey also showed that most of the plants operate close to urban areas in the southeast (Fig. 1), and wood waste (45%), bark (29%), sawmill by-products (13%) and forest chips (13%) made up the wood biomass consumed.

Focusing on plants with a forest chips demand of ≥ 1000 m³/a, four demand scenarios were setup. Scenario I assumes a current demand level of 73 400 m^3 loose/a of forest chips and no new installation or upgrading of existing plants (base 2005). Scenario II includes upgrading and installation of small and medium sized plants, with an additional demand of less than 50 000 m^3 loose/a (2006 onwards). The number of plants using forest chips rises from 10 to 15, but the demand increases only by 26% to 92 700 m^3 loose/a. Scenario III includes the upgrading and installation of larger plants, which will increase the demand up to 302 700 m^3 loose/a (Table 1). Scenario IV deals with forest chips made of harvesting residuals, which have the disadvantage of poor quality. Based on questionnaires and interviews with plant operators, wood chips from harvesting residues were recommended for larger plants with a demand above 15 000 m^3 loose/a only. Therefore only large plants (p_3, p_{22}, p_{26}, p_{27}) within the region are supplied with wood chips from harvesting residues. As will be shown later on, only approximately 23% of the selected plants demand can be covered by this resource (Table 1–IV).

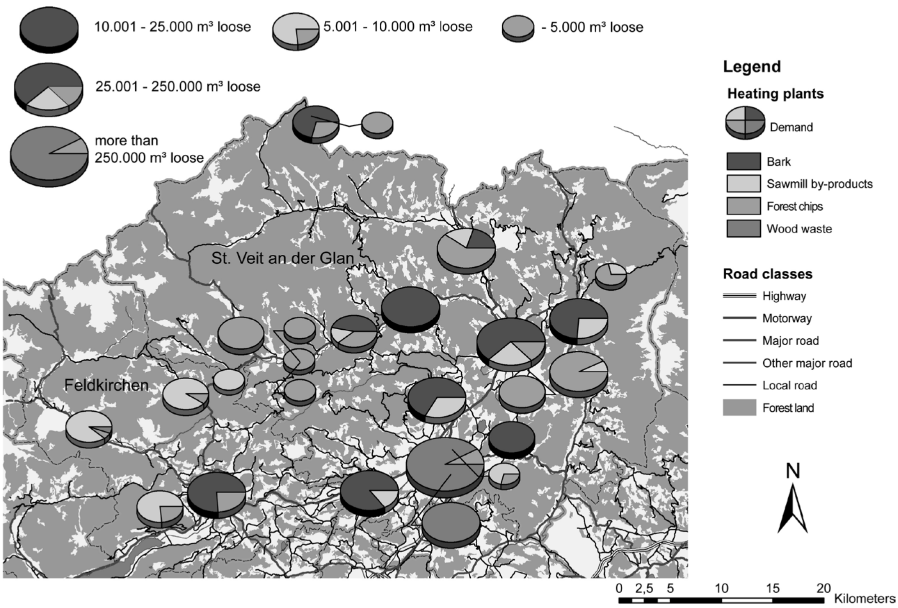

Fig. 1. Geographical position, demand level and share of fuel types of heating plants within the study area in 2005.

Table 1. Defined demand scenarios I–IV of forest fuel by heating plants with respect to the survey 2005 (Kanzian et al. 2006).

Plant	Demand scenario [m^3 loose/a] I	II	III	IV
p_1	2500	2500	2500	-
p_3	16800	16800	16800	3900
p_5	2800	2800	2800	-
p_8	-	1900	1900	-
p_9	2500	2500	2500	-
p_{10}	1800	1800	1800	-
p_{14}	1500	1500	1500	-
p_{15}	3000	3000	3000	-
p_{20}	1000	1000	1000	-
p_{21}	-	9600	9600	-
p_{22}	25000	25000	25000	5900
p_{26}	16500	16500	16500	3900
p_{27}	-	-	210000	49300
p_{28}	-	4400	4400	-
p_{29}	-	2200	2200	-
p_{31}	-	1200	1200	-
	73400	92700	302700	63000

Table 2. Area and calculated storage capacities of terminals.

Terminal	Area [m^2]	Capacity [m^3 loose]	Turnover [m^3 loose/a]
t_1	4020	20100	20100
t_2	1210	-	-
t_3	680	3400	3400
t_4	1800	9000	9000
t_5	2500	12500	12500
t_6	1350	6750	6750
t_7	11500	57500	57500
t_8	5000	25000	25000
t_9	8800	44000	44000
	35650	178250	178250

The potential of fuel wood is determined in a separate study (Kanzian and Kindermann 2007), and because general forest management plans do not exist on a regional level, the estimation and prediction is based on the raw data of 375 sample plots located in the research area from the Austrian National Forest Inventory. Using taper curves and biomass functions (Kennel 1972, Pellinen 1986, Pöytäniemi 1981), the volume of compartments like "non-merchantable" wood, tops and branches were calculated stemwise and summed up. At sensitive sites, where nutrient removal causes degradation, the use of branches was excluded. To predict the development of usable fuel wood for the next 20 years, the tree growth model 'Prognaus' (Ledermann 2004) was applied. Different utilization periods for reducing the backlog of thinnings were assumed and the respective theoretically usable volume of energy wood was estimated. The theoretical ecologically available amount of all defined fuel wood assortments (e.g. poor quality wood, tops and branches) is in the range of 330 000 m^3 solid per year for the whole area or 2.3 m^3 solid/ha/a, respectively. Harvesting of the thinning backlog within the next 10 years will increase the amount of energy wood by 30% within this time period. A time period of 20 years will not gain any additional energy wood (Kanzian and Kindermann 2007).

The distributable fuel wood potential is reduced further to 85 000 m^3 solid/a because of reduced use of branches and tops at the plant, losses during harvesting, and low market prices. Converting the solid mass into loose cubic meters is done by the factor 2.5 (ÖNORM 1998), giving us approximately 212 500 m^3 loose/a. In terms of demand, this amount would be sufficient for scenario I and II, but not for scenario III. It is assumed that a rising demand will gain higher sales prices and thereafter a sufficient distributable fuel wood potential will be available. So for scenario III, the fuel wood potential is set to 342 000 m^3 loose/a. The yearly potential of harvesting residues in the region is set to 25 000 m^3 solid, which are 0.18 m^3 solid/ha/a. This amount is distributed to four plants in proportion to their total demand (Table 1).

Nine different locations where proposed as possible terminal locations by the regional forest ownership association. Terminal no. 2 was near a settlement and because traffic and chipping operations at terminals can cause high dust and noise emissions, it is excluded. It should be noted that we only gathered the size and position of terminals during the survey (Fig. 2), so we had to estimate storage capacities for each terminal. To determine the maximum capacity and the yearly turnover respectively, a storage time of 12 months and an area usage of 200 m^2/1000 m^3 loose is considered.

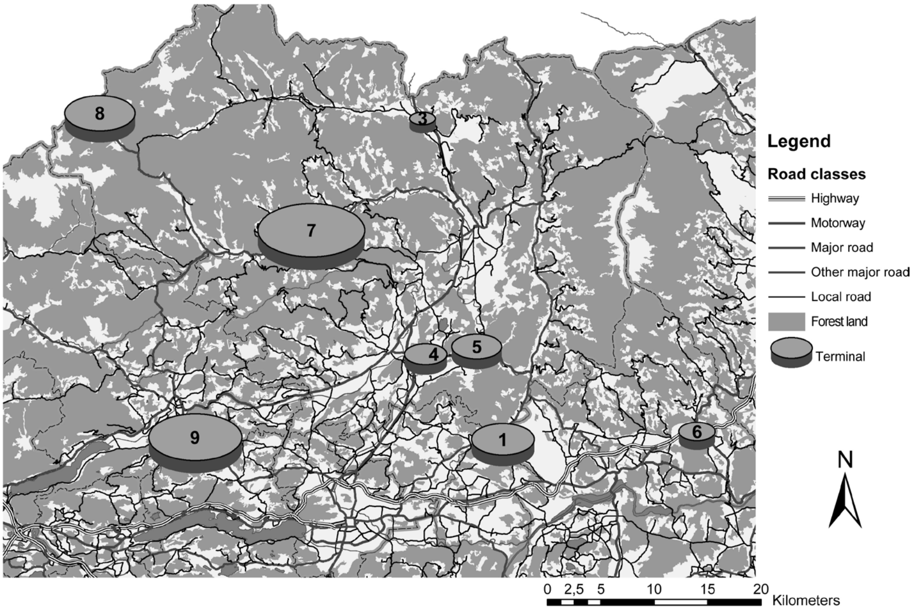

Fig. 2. Map of optional terminal locations with storage capacities in the region.

Table 3. Overview of investigated supply scenarios and options.

Demand senarios	Options – Share via Terminals		
	1 0%	2 50%	3 100%
I	I – 1	I – 2	I – 3
II	II – 1	II – 2	II – 3
III	III – 1	III – 2	-
IV	IV	-	-

There are a variety of supply chain options available for supplying feedstock to combined heat and power plants, including having a place to chip as well as the option of using interim terminals. So, several scenarios were set up and tested.

The three supply options assume different uses of the terminals in the supply chain. The first option is based on transport of round wood directly to the plant, chipping at the plant and no storage terminal use. In option two and three, 50% and 100% of the demand are handled via terminals, respectively. Only chipped material is transported from terminal to plant because this is the cheapest transport mode and no additional trans-loading is required. The high demand associated with scenario III and insufficient terminal capacities make option three impossible (Table 3).

The supply chain for harvesting residues includes a combination chipper and self-loading chip truck. Chipping is done at or close to the landing, where the chips are blown on to a pile. Nevertheless, practical findings recommend some accumulation of the residuals to larger piles. This can be done by a timber truck for example, but in terms of costs only over a very short distance (1–3 km pre-transport). The truck, equipped with a boom and a clamshell bucket, loads the chips and transports them to the plant immediately afterwards (Fig. 3). With this system, the chipper can work independent from transport, therefore avoiding operational delays (Asikainen 1998, Ganz et al. 2005, Kanzian and Holzleitner 2006). Furthermore typical landings under mountainous conditions are narrow and do not allow direct chipping into trucks.

Fig. 3. Self-loading chip truck during loading of forest chips close to landing.

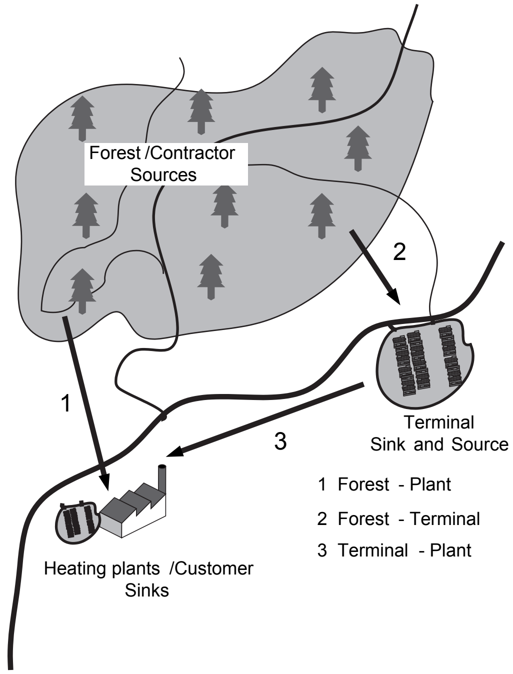

Fig. 4. Flow of material from forest to terminal or conversion plant, respectively.

2.1 Model Description

Eriksson and Björheden (1989) optimized the supply for only one consumer with linear programming methods (LP). The number and size of decision variables within LP-models determine the size of the problem and the memory requirements to solve it. As the model should be simple and solvable for a network of 8 terminals and 16 plants with standard software, the number of material flows were reduced. The following three flows are considered: (1) direct transport of solid fuel or harvesting residues as chips from forest to plant, (2) transport of solid fuel from forest to terminal and (3) transport of chipped fuel from terminal to plant (Fig. 4). The network analysis assumes that all sinks and sources are available in the form of locations, therefore terminals and heating plants are geo-referenced. A square grid of 1 kilometer by 1 kilometer represents fuel wood sources. So each source point will represent 100 ha of forest land.

The calculation of different scenarios and options is done in several steps. Geographic information and data based on time studies for the static simulation have to be pre-linked (Fig. 5). Data concerning real supply areas of the plants are not considered. During routing and linear programming, theoretical supply areas are calculated. The model for optimizing contains a list of assumptions and simplifications:

– The fuel wood potential is uniformly distributed over the forest area.
– Transport costs consist of a variable part and a fixed part based on the capacity. The variable part is calculated with network analysis in combination with routing. Fixed part contain loading and unloading.
– The costs of chipping are constant and dependent on the location. Chipping at the plant or terminal is considered lower cost than at the landing.
– The period under consideration is one year.
– Considering time for drying is four to six months during the spring and summer seasons and peaks in demand in the winter season allow for no more than one turnover, the maximum storage capacity at terminals will be turned over once a year.
– There are no limits for storage capacities at heating plants. It is assumed that the yearly turn over can be handled at plant.
– Every source delivers to the nearest sink. Regional in- or outflows of fuel wood are not considered.
– The model contains only plants with a yearly demand of 1000 m^3 loose.

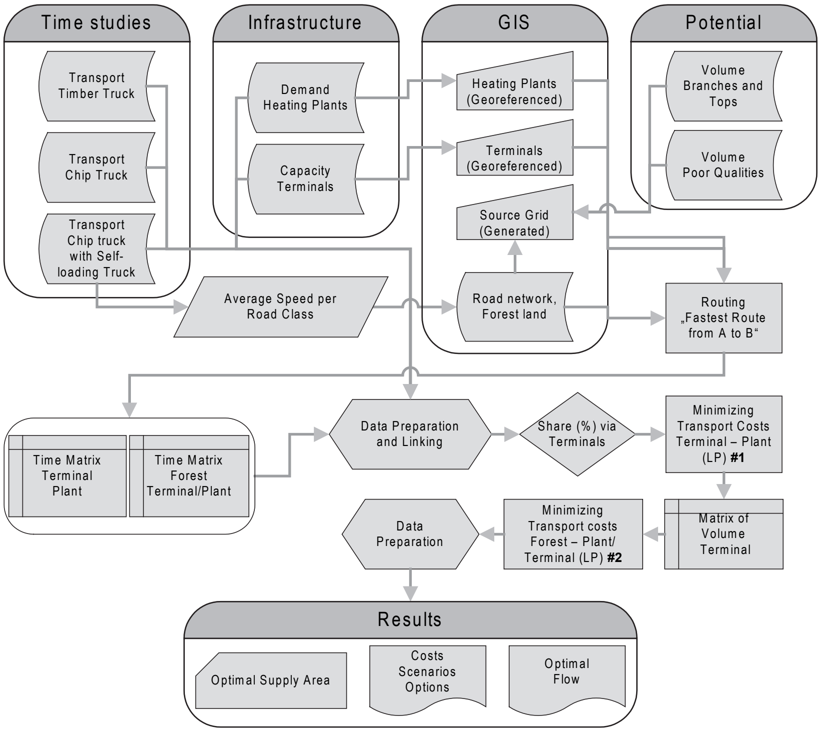

Fig. 5. Database, Dataflow and used methods for the static simulation and optimization.

– Only costs for transport and chipping are included without any harvesting or raw material costs.
– The terminal cost calculation uses a period of 15 years and two interest rates (5% for the construction costs and 4% for the tied-up capital of the fuel wood stock). No other interest rates were applied, as the view period is one year.

The costs, which have to be minimized during optimization, are the transport costs. This can be done in two steps, where two slightly different optimization models (labeled as sub model 1 and 2) are applied consecutively. The sub models are derived from the well described, classical LP transport model (Domschke and Drexl 2005, Vahrenkamp and Mattfeld 2007). The classic formulation contains an objective function, which computes the minimum transportation costs for a set of sources and sinks and two constraints. The constraints ensure that supply and demand is balanced.

In the first step (sub model 1), the transport from terminal to plant is optimized considering that the proportional demand of each plant has to be satisfied (2). As we want the optimization to decide how much volume should be taken from a terminal, constraint (3) has to be modified in contrast to the classical LP model. Therefore constraint (3) ensures that the maximum capacities of the terminals have not to be exceeded. Quantities which have to be transported from source to sink are described with x_{tp}. The maximum capacity of terminals is fixed with $v_t^{\text{max.capacity}}$ (3). The amount of material handled via terminals (p^{share}) depends on the chosen option and is 0, 50 and 100% respectively.

Sub model 1:

$$\min(z) = \sum_{t \in T} \sum_{j \in J} c_{tj} x_{tp} \tag{1}$$

$$\sum_{t \in T} x_{tp} = d_p^{\text{plant}} p^{\text{share}} \qquad \forall p \in P \tag{2}$$

$$\sum_{p \in P} x_{tp} \leq v_t^{\max.\text{capacity}} \qquad \forall t \in T \tag{3}$$

$$x_{tp} \geq 0 \qquad \forall t \in T, \forall p \in P \tag{4}$$

P = Set of plants, $\{p_1, p_2, \ldots p_n\}$
T = Set of terminals, $\{t_1, t_2, \ldots t_n\}$
x_{tp} = Decision variable – volume of chips transported from terminal (t) to plant (p) [m^3 loose/year]
c_{tp} = Transport costs from terminal (t) to plant (p) [EUR/m^3 loose]
d_p^{plant} = Demand of plant (p) [m^3 loose/year]
p^{share} = Percentage of demand supplied via terminal [%]
$v_t^{\text{maxcapacity}}$ = Maximum yearly trurnover of terminal (t) [m^3 loose/year]

In the second step (sub model 2), a cost optimal flow from forest to plant or terminal is computed. In this case, terminals act as sinks too, where the optimal turnover calculated by step 1 is now treated as demand. To ensure that every source point will be assigned to one sink, the objective function has to be extended by a binary decision variable f_{ik} (5), leading to a similar objective function as presented by Ranta (2002). Constraint (6) satisfies demand ($d_k^{\text{termplant}}$). Because of the binary assignment of sources, this must be modeled with greater than or equal. Otherwise the model will be infeasible, where demand and supply do not meet exactly. This will be true for most cases and result in oversupply. The limits of fuel wood potential or that each source is assigned only once ensures constraint (7), respectively.

Sub model 2:

$$\min(z) = \sum_{i \in I} \sum_{j \in J} c_{ik} y_i f_{ik} \qquad f_{ik} = \{0,1\} \tag{5}$$

$$\sum_{i \in I} f_{ik} y_i \geq d_k^{\text{termplant}} \qquad \forall k \in K \tag{6}$$

$$\sum_{k \in K} f_{ik} \leq 1 \qquad \forall i \in I \tag{7}$$

K = Set of plants and terminals, $\{k_1, k_2, \ldots k_n\}$
I = Set of sources, $\{i_1, i_2, \ldots i_n\}$
f_{ik} = Binary decision variable – supply plant or terminal (k) from source (i): yes (1), no (0)
y_i = Fuel wood potential of source (i) [m^3 loose/year]
c_{ik} = Supply costs from source point (i) to plant or terminal (k), respectively [EUR/m^3 loose]
$d_k^{\text{termplant}}$ = Demand of plant or terminal (k) which must supplied directly from forest [m^3 loose/year]

Supply costs per entity of potential from source to sink (c_{tj}, c_{ik}) are calculated with formula (8), which includes time associated with transport, loading, unloading and operational delays. This total transport time is multiplied by the hourly costs and finally divided by the load volume to achieve the costs per entity. Defined flow costs per entity for chipping (c^{chip}), storing (c^{store}) and otheres (c^{other}) are added.

$$c_{tj}, c_{ik} = \frac{(2 * t_{tj,ik}{}^{T} + t^{L} + t^{U} + t^{D}) / 60 * c^{\text{truck}}}{l} + c^{\text{chip}} + c^{\text{store}} + c^{\text{other}} \tag{8}$$

c_{tj} = Supply costs from terminal (t) to plant (j) [EUR/m^3 loose]
c_{ik} = Supply costs from source (i) to plant or terminal (k) [EUR/m^3 loose]
$t_{tj,ik}{}^{T}$ = Drive time from terminal (t), source (i) to plant (j), plant or terminal (k) [min]
t^L = Loading time [min]
t^U = Unloading time [min]
t^D = Operational delay time [min]
l = Load volume [m^3 loose]
c^{truck} = Cost of truck per hour [EUR/h]
c^{chip} = Chipping costs [EUR/m^3 loose]
c^{store} = Variable terminal costs [EUR/m^3 loose]
c^{other} = Other costs e.g. shifting costs for trucks, preconcentration of raw material [EUR/m^3 loose]

2.2 Data Preparation and Processing

Demand for different fuel types of each plant, which was collected during the survey, was digitized and georeferenced (Fig. 1) using the geographic information system ArcGIS® from ESRI. The

Table 4. Input data for the supply cost calculations for each node to node connection. The according variables are given in parenthesis, whereas units are enclosed in brackets (Kanzian et al. 2006)

Means of transportation: Origin – destination:	Self-loading truck Forest – plant	Timber truck Forest – plant	Timber truck Forest – terminal	Chip truck Terminal – plant
Cost rate (c^{truck}) [€/h]	57.00	65.00	65.00	55.00
Load volume (l) [m^3 loose]	60.00	62.50	62.50	70.00
Process times [min]				
Driving ($t_{tj,ik}{}^{T}$)	*GIS*	*GIS*	*GIS*	*GIS*
Loading (t^L)	72.00	84.00	84.00	42.00
Operational delays (t^D)	10.00	10.00	10.00	10.00
Unloading (t^U)	10.00	30.00	30.00	10.00
Additional costs [€/m^3 loose]				
Preconcentration (c^{other})	2.84	0.00	0.00	0.00
Terminal costs (c^{store})	0.00	0.24	0.00	0.24
Chipping (c^{chip})	2.50	2.50	2.50	0.00
Shifting (c^{other})	0.00	0.07	0.07	0.12

same was done with the possible terminal locations and their maximum capacities. Because we do not have any information on harvesting sites or site data, we created a one by one kilometer square grid. Clipping the grid by the layer of forest land results in 1409 of theoretical landings or source points, respectively. An equal yearly amount of fuel was set up based on the estimated fuel wood potential for the study area for each source. So for scenario I and II, each point represents 150 m^3 loose /a and at scenario III 242.5 m^3 loose /a and at scenario IV 45 m^3 loose/a fuel wood.

Using Formula (8), two matrices, including supply costs, are setup. The first one contains the cost information for each sink source combination landing to plant or terminal; the second one contains the combination terminal plant. The parameters depend on the chosen supply option and are provided in Table 4. A chip truck costs 55 EUR per hour, whereas a timber truck, the more costly, costs 65 EUR/h. Transport time was derived using GIS for each source-sink connection. Via network analysis, the quickest route for each sink-source connection was derived using the extension 'Network analyst' of ArcGIS. As impedance for the built-in search algorithm, the drive time was set to find the quickest and not the shortest network path. A network analysis requires a specific road network dataset, which is digitized and attributed properly. More precisely, each road is split in sections connected via nodes. All sections include information about distance, travel time, average speed, restrictions and so on. The state database contains no drive time for trucks as it is normally used by car navigations systems, thus time of transport for trucks must be computed for each section of the road using distance and average speed. Average speeds of trucks on different functional road classes are taken from Ganz et al. (2005). Times for loading, unloading and operational delays originate from various time studies (Ganz et al. 2005, Kanzian and Holzleitner 2006, Kanzian et al. 2006). Additional costs, like terminal, preconcentration or shifting costs for trucks are added. There are no shifting costs for the chipper added because the chipping costs 2.5 EUR/m^3 includes shifting (Table 4).

If fuel wood goes from forest to plant via terminal, terminal cost must be added. In this study, only variable costs, which were calculated for a simple terminal, are accounted for in the supply costs. Considering direct transport also, variable terminal costs are added to the supply costs, to make the results comparable. Both terminal costs are set to 0.24 EUR/m^3 loose (Table 4).

The implementation of the LP and Mixed Integer Programming (MIP) model were carried out in two different environments to check out their practicality and their runtime for the given problem. Premium Solver® using the "Large Scale

LP-Solver" package for MS-Excel was used. After the tables and solver engine were setup, a small Visual Basic Script was written to call the submodels consecutively and to track the runtime. For the second environment, the solver platform Xpress-MP was chosen, which provides the algebraic programming language Xpress-Mosel for model formulation. Because of its high level language, it is possible to separate model and data. Using indexed variables and data arrays, generic models independent of the problem size can be written (Guéret et al. 2006). In this case, one main program calls two sub programs containing the submodels and all data were saved in databases.

The processing of geographical information, the routing and building maps are done with ArcGIS 9.x®. Data preparation and linking is carried out in a spreadsheet using MS-Excel® or in database using MS-Access, respectively.

2.3 Sensitivity Analysis

In addition to the scenario-based analysis, a sensitivity analysis was conducted on the four main data variables: demand, fuel wood potential, transport costs and terminal utilization. Demand scenario I was used as the base. These input variables were modified by applying factors. For example, the demand was varied in range from 50 to 150% in 10% of the steps, which means the model runs on 50, 60,… 150% of the original demand. The objective value of every run is compared to the base scenario I and expressed as percentage of it. This was repeated for the data variables fuel wood potential and transport costs in range from 50 to 150% and supply via terminal in range from 0 to 100%.

3 Results

3.1 Scenario and Sensitivity Analysis

Both implementations of the submodels deliver the same objective value, but the runtimes are much higher using the PREMIUM Solver in comparison to Xpress-MP (Table 5). Nevertheless the spreadsheet based implementation is applicable for every day use regarding the runtime on the given problem size, which never lasts more than 2.5 minutes. The computed costs (supply costs at plant level) include chipping, transport and variable terminal costs. The supply costs reflect the viewpoint of forest owners and suppliers respectively, so there are no fixed terminal costs calculated at the plant, as they are paid by the plant owner. At a yearly demand level of 73 000 m^3 forest chips, the optimal supply cost will be on average 5.8 EUR/m^3 loose, if the material is delivered directly to plant. Fuel flow via terminal creates additional need for transport. Therefore the costs increase to 6.4 and 7.4 EUR/m^3 loose, respectively. Another effect appears when demand rises as is the case of scenarios II and III. Supply costs of direct transport will increase from 5.8 to 6.6 EUR/m^3 loose (Table 5).

Table 5. Computed supply costs and objective values for the defined scenarios and options are achieved by two different model implementations (Xpress-MP, PREMIUM Solver).

Demand scenario	Supply option	Demand [m^3 loose/a]	Objective value [€]	Delivery [m^3 loose]	Costs [€/m^3 loose]	Runtime [s] XPRESS	Runtime [s] PREMIUM
I	1	73400	423978	73650	5.80	1.39	139.34
	2		474023	74250	6.40	1.53	144.89
	3		538211	73650	7.30	1.31	137.61
II	1	92700	542261	93150	5.80	1.61	144.09
	2		608851	93900	6.50	1.81	151.70
	3		691160	93000	7.40	1.44	137.70
III	1	302700	2 014825	305065	6.60	2.03	145.19
	2		2 198001	306035	7.20	2.28	156.83
IV	1	63000	540516	63090	8.60	1.52	137.19

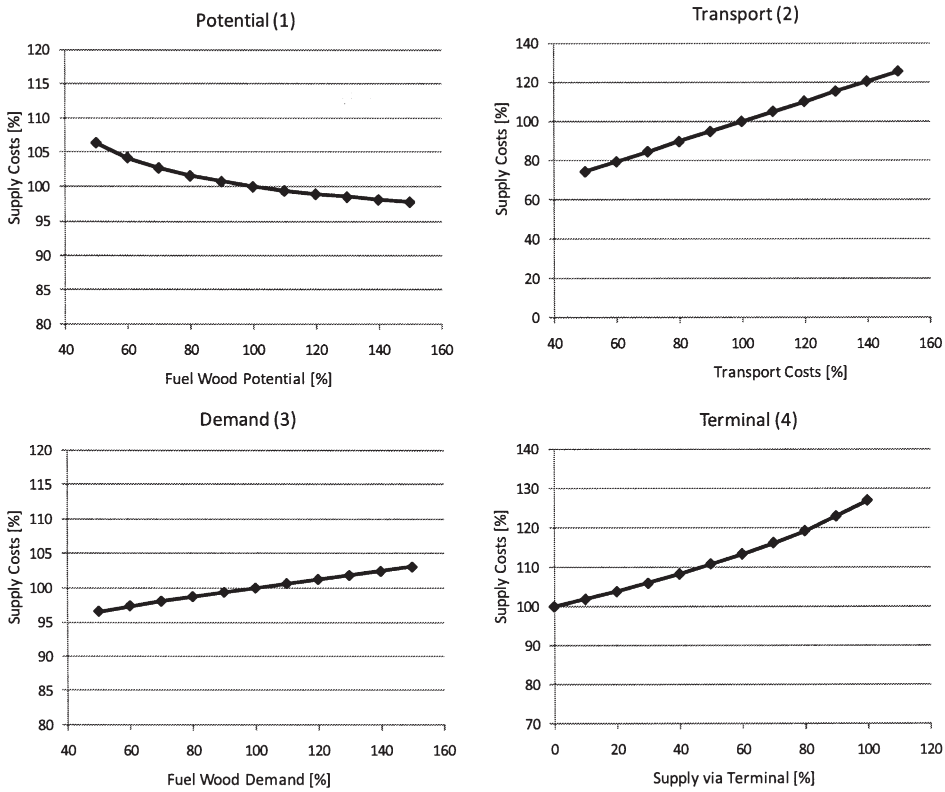

Fig. 6. Results of the sensitivity analyses of the supply costs for the main input data at scenario I. The x-axis represents data variation for fuel wood potential (1), transport costs (2), demand (3) and supply via terminals (4).

In the research area only, plants p_3, p_{22}, p_{26} and p_{27} consume more than 15 000 m^3 loose per year, which means that harvesting residuals can be used as fuel without concerns. The assumed potential of harvesting residuals covers 24% of the selected plants' demand. Based on the given parameters, supply costs at plant level are expected to be between 8.4 and 9.1 EUR/m^3 loose and 8.6 EUR/m^3 loose on average, respectively. Be aware, the results of scenario IV cannot be compared to scenarios I, II, and III as there are different resources being transported by the self-loading truck system. Also a cost of 2.0 EUR/m^3 loose is included for the accumulation of the harvesting residuals in the average supply costs (Table 4).

For the sensitivity analysis, the Xpress implementation was used, largely because of its flexibility and the fast runtime. On the base scenario I, the model is not sensitive to variation of the fuel wood potential. Reducing the estimated amount by half results in 6% higher supply costs, whereas a higher amount will decrease the costs marginally (Fig. 6). On the demand side, the supply costs are also not very sensitive. Unlike potential and demand, supply costs react directly on variation in transport costs, because transport costs make up most of these costs. If transport costs rise by 20%, the supply costs increase by 15%. As already shown, an integration of terminals in the material flow also has an impact on supply costs. Twenty percent flow via terminals creates 4% higher costs, and supplying all fuel wood via terminals means 27% higher costs compared to direct supply to the plant (Fig. 6).

Table 6. Optimized fuel flow from terminals to plants at scenario III option 2 in cubic meter loose per year.

Plant	Terminal								Σ plant
	t_1	t_3	t_4	t_5	t_6	t_7	t_8	t_9	
p_1	0	0	0	0	0	1250	0	0	1250
p_3	0	3400	0	0	0	5000	0	0	8400
p_5	0	0	0	0	0	0	1400	0	1400
p_8	950	0	0	0	0	0	0	0	950
p_9	1250	0	0	0	0	0	0	0	1250
p_{10}	0	0	0	900	0	0	0	0	900
p_{14}	0	0	0	0	0	750	0	0	750
p_{15}	0	0	0	0	0	1500	0	0	1500
p_{20}	0	0	0	0	0	500	0	0	500
p_{21}	0	0	0	4800	0	0	0	0	4800
p_{22}	0	0	6800	5700	0	0	0	0	12500
p_{26}	0	0	0	0	0	8250	0	0	8250
p_{27}	15100	0	2200	0	3450	40250	0	44000	105000
p_{28}	2200	0	0	0	0	0	0	0	2200
p_{29}	0	0	0	1100	0	0	0	0	1100
p_{31}	600	0	0	0	0	0	0	0	600
Σ terminal	20100	3400	9000	12500	3450	57500	1400	44000	
Utilization of terminal	100 %	100 %	100 %	100 %	51 %	100 %	6 %	100 %	

3.2 Terminal Locations and Procurement Areas

In addition to the optimal cost allocation of sources, the material flow from terminals to plant is optimized. To answer the question of which terminals should be used, scenario III option 2 is taken as an example. The optimization assigns a high yearly turnover to terminal 7, which is located at the center of the study area. A total volume of 57 500 m^3 loose should distribute to plants p_1, p_3, p_{14}, p_{15}, p_{20}, p_{26} and p_{27} with optimal flows of 1250; 5000; 750; 1500; 500; 8250 and 40 250 m^3 loose per year (Table 6). All terminals except number 8 operate in full capacity, which implies that this location is less competitive with respect to the others. There are high transport costs because this terminal position is close to the border of the research area. Comparing all other scenarios and options, terminals 5, 7 and 9 are located at the most promising locations.

Each source point was allocated to one sink, so optimal trading areas can be displayed. The areas are more or less located around the plants along major roads. Only small procurement areas appear because of the given potential and the low demand (Fig. 7). If the demand rises, like in scenario III where a new CHP will consume most of the forest fuel, the supply areas of existing plants will move. It would take nearly all the resources in the research area to meet the demand of plant 27, if fuel delivered to plant 22 is only coming from the East (Fig. 8).

4 Discussion and Conclusions

With the presented approach, fuel wood flows from landing to plant (chipping and transport) and optional terminal use can be optimized based on traceable calculations of different scenarios. Supply options for a network of sources, terminals and plants can also be evaluated quite quickly. The outcomes can be seen as a benchmark of supply costs for the region. Furthermore, different terminal locations can be evaluated in terms of competitiveness.

Eriksson and Björheden (1989) figured out that supply via terminals does not pay of, and our results do not refute this in general. The study findings indicate that supply costs will increase

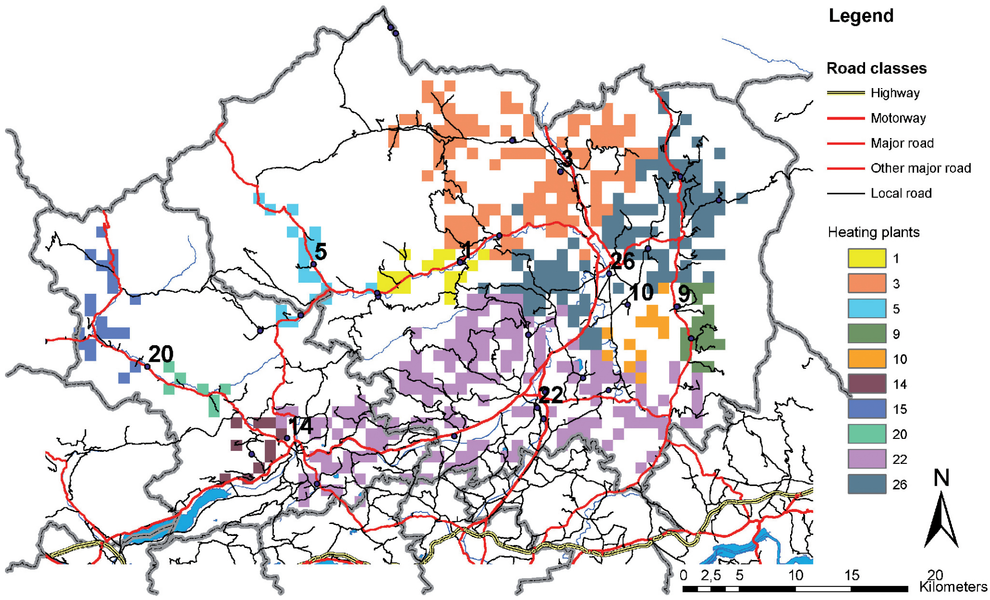

Fig. 7. Optimal supply areas at scenario I variant 1 and cost optimal allocation of potential respectively.

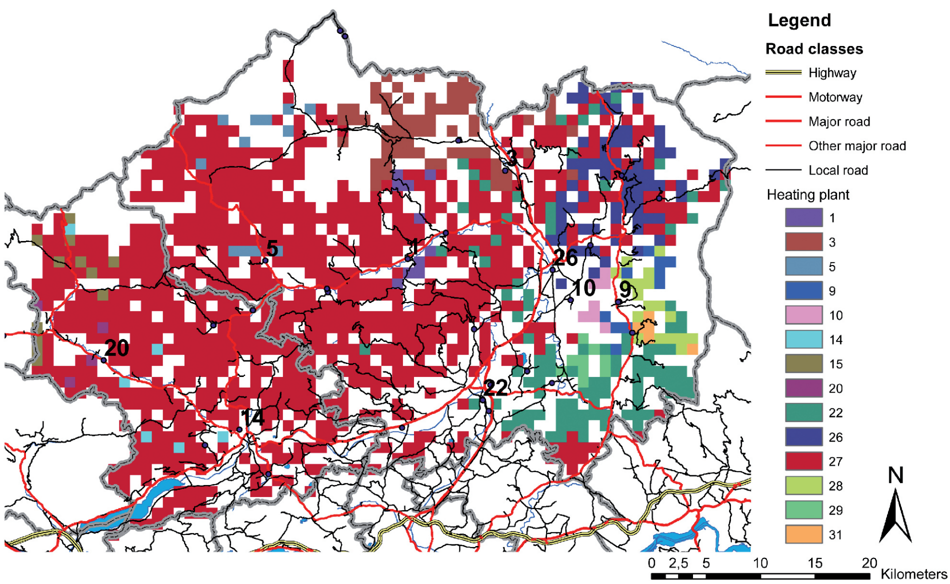

Fig. 8. Optimal supply areas at scenario III variant shows that most of the potential will be allocated to heating plant 27.

by 10% if half the fuel and 26% if all the fuel goes through terminals. On the other hand, the additional costs can be designated as expenses necessary to ensure constant supply throughout the year. The sensitivity analysis of supply via terminals shows that with up to 50% supply via terminals, the cost increase is moderate, below 10%. Thereafter the cost increase is steeper. Mountainous regions, as is the case in the study area, are partially inaccessible during the winter, but this depends on the severity of the winter weather conditions. Independent of weather conditions, terminals could act as buffer storage and supply fuel on demand, maybe even at a higher sales price. Another aspect, not considered here, is the feedstock at the plant. Dividing the feedstock capacity by the peak load of each plant shows that some plants only could operate a view days, whereas others would have fuel for more than one year (Kanzian et al. 2006).

In the last few years, many studies concerning supply chains for forest fuel have been published, especially from the Nordic countries. However, a comparison between study results has to be done carefully, as aims and frameworks are different. Often they are investigating aspects of a single supply chain like productivities, or they try to identify bottlenecks with the aim of improving productivity and lowering costs (Asikainen 1998, Spinelli and Hartsough 2001, Johansson et al. 2006, Kärhä and Vartiamäki 2006, Stampfer and Kanzian 2006, Laitila 2008). The approach here builds upon these experiences and makes an attempt to this for an entire supply network, rather than a single customer.

Calculating different supply chains, taking terminals into account, Vartiamäki et al. (2006) present costs at plant from 10.5 to 12.5 EUR/MWh including harvesting costs of approximately 4.0 EUR/MWh. This would lead to supply costs, as defined in this study, of 6.5 to 8.5 EUR/MWh, which are comparable to the study results with 6.7 to 8.6 EUR/MWh when water content is set to 40%.

Asikainen (1998) simulated a chipping terminal with a discrete-event-based simulator to figure out the best loading and transport technologies. Depending on the transport distance, total costs of 10.0 to 20.2 EUR/m^3 were found. The study results are in a similar range with 14.5 EUR/m^3 to 18.5 EUR/m^3, but not comparable as hourly costs for the equipment differs. Nevertheless the outlined interactions between chipper and trucks could result in a cost bias of 20% because of operational delays, if not considered. In case of this study, the operational delays were set to be constant with 10 minutes per turn of a truck. For the chipper it is assumed that this cost already include in the chipping costs. Further investigations have to be done to prove and enhance this model component.

Scenario and sensitivity analyses indicate that increasing demand also causes higher supply costs. If demand is more than four times larger in the study area and it is presumed that the fuel wood potential is sufficient, supply cost will increase by 24% because of larger supply areas. This ‘scale of operation’ effect has been described by Asikainen et al. (2001) and is somewhat contrary to economies of scale. Clearly, this directly influences the economy of plants, and the supply or logistics costs become a key factor, respectively (Caputo et al. 2005).

An attempt to quantify the optimal feedstock at terminals was not carried out with this study. One way to track down the needed and also optimal feedstock at terminal or plant will be to extend the objective function by a time factor. This can be done in such a way that demand and resource availability on a monthly basis are incorporated into the model (Eriksson and Björheden 1989, Gunnarsson and Rönnqvist 2008).

The study results, her, do ignore market behavior, however. Simulation of market behavior in biomass supply has been carried out by Gronalt and Rauch (2006) through different approaches demonstrating possible savings using optimization models on an inter-regional level. Findings are only computed using models; a comparison to the real world is still missing because plant owners do not want to share sensitive data they think might be of use to their potential competitors.

This model provides only local optimums due to the chosen stepwise procedure. A global optimal solution must take into account all cost factors along the supply chain. Considering how our models were constructed, if the model is expanded, the limits of spreadsheet calculations will be reached quite quickly. This is also true, if this study is to be carried out on a larger scale. In these cases, the tested professional solver environment would be the way to go. Furthermore, data exchange between a GIS system and spreadsheet calculations will need improvement and so on. Professional solver platforms can overcome these barriers and offer a wide range of interfaces. Additionally, they can be tailored to solve mathematical problems, scripting, and programming language, respectively.

In general, the given problem can be formulated as a Warehouse Location Problem (WLP), where the sum of variable transport, variable and fixed storage costs has to be minimized (Domschke and Drexel 1996, Vahrenkamp and Mattfeld 1997). The presented approach takes this only partially into account. So further development of the approach is being carried out, whereby global optimums for material flows and terminal locations can be achieved. Nevertheless, the initial results remain very promising.

References

Asikainen, A. 1998. Chipping terminal logistics. Scandinavian Journal of Forest Research 13(3): 386–391.

— , Ranta, T. & Laitila, J. 2001. Large-scale forest fuel procurement. In: Pelkonen, P., Hakkila, P., Karjalainen, T. & Schlamadinger, B. (eds.). Woody biomass as an energy source – challenges in Europe. European Forest Institute (EFI). p. 73–78.

Beaudoin, D., LeBel, L. & Frayret, J.-M. 2007. Tactical supply chain planning in the forest products industry through optimization and scenario-based analysis. Canadian Journal of Forest Research 37(1): 128–140.

Caputo, A., Palumbo, M., Pelagagge, P. & Scacchia, F. 2005. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass and Bioenergy 28(1): 35–51.

Domschke, W. & Drexl, A. 1996. Logistik: Standorte. Oldenbourg, München & Wien. 276 p. (In German).

— & Drexl, A. 2005. Einführung in Operations Research. Springer, Berlin [u.a.]. 264 p. (In German).

Eriksson, L.O. & Bjoerheden, R. 1989. Optimal storing, transport and processing for a forest-fuel supplier. European Journal of Operational Research 43(1): 26–33.

Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R. & Taramasso, A. 2004. Optimizing forest biomass exploitation for energy supply at a regional level. Biomass and Bioenergy 26(1): 15–25.

Ganz, M., Holzleitner, F. & Kanzian, C. 2005. Energieholzlogistik Kärnten – Transport von Energieholz. Technical Report, Institut für Forsttechnik, Universität für Bodenkultur, Wien. 89 p. (In German).

Gronalt, M. & Rauch, P. 2006. Alternative Strategien für die Landwirtschaft. Facultas, chapter: Kostenvorteile einer Kooperation und die Bestimmung der Systemkosten im Versorgungsnetzwerk Holz-Biomasse. p. 173–187. (In German).

— & Rauch, P. 2007. Designing a regional forest fuel supply network. Biomass and Bioenergy 31(6): 393–402.

Guéret, C., Prins, C. & Sevaux, M. 2006. Applications of optimization with Xpress-MP. Dash Optimization Ltd., Blisworth. 256 p.

Gunnarsson, H. & Rönnqvist, M. 2008. Solving a multi-period supply chain problem for a pulp company using heuristics – an application to Södra Cell AB. International Journal of Production Economics 116(1): 75–94.

— , Rönnqvist, M. & Lundgren, J. 2004. Supply chain modelling of forest fuel. European Journal of Operational Research 158(1): 103–123.

Johansson, J., Liss, J.-E., Gullberg, T. & Björheden, R. 2006. Transport and handling of forest energy bundles – advantages and problems. Biomass and Bioenergy 30(4): 334–341.

Kanzian, C. & Holzleitner, F. 2006. A new approach in the fuel wood supply chain using a self-loading truck for hauling. In: FORMEC 2006, 39th International symposium on Forestry Mechanization. p. 34–44. (In German).

Kanzian, C. & Kindermann, G. 2007. Estimation of Energy Wood Resources Based on Inventory Data. Draft paper. 13 p.

— , Holzleitner, F., Kindermann, G. & Stampfer, K. 2006. Regionale Energieholzlogistik Mittelkärnten. Technical report, Institut für Forsttechnik, Department für Wald- und Bodenwissenschaften, Universität für Bodenkultur. 133 p. (In German).

Kärhä, K. & Vartiamäki, T. 2006. Productivity and costs of slash bundling in Nordic conditions. Biomass and Bioenergy 30(12): 1043–1052.

Katzensteiner, K. & Nemestothy, K.P. 2006. Energetische Nutzung von Biomasse aus dem Wald und Bodenschutz – ein Widerspruch? Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft 74: 1–10. (In German).

Kennel, R. 1972. Die Buchendurchforstungsversuche in Bayern von 1810–1910 mit dem Modell einer Strukturertragstafel für die Buche. Technical report, Institut für Ertragskunde, Forstliche Forschungsanstalt, München. (In German).

Laitila, J. 2008. Harvesting technology and the cost of fuel chips from early thinnings. Silva Fennica 42(2): 267–283.

Ledermann, T. 2004. Programmdokumentation Waldwachstumssimulator Prognaus for Windows Version 2.3. Manual, Universität für Bodenkultur in Wien. (In German).

Nord-Larsen, T. & Talbot, B. 2004. Assessment of forest-fuel resources in Denmark: Technical and economic availability. Biomass and Bioenergy 27(2): 97–109.

ÖNORM M-7132. 1998. Energiewirtschaftliche Nutzung von Holz und Rinde als Brennstoff Begriffsbestimmungen und Merkmale. Österreichisches Normungsinstitut, Wien. 9 p. (In German).

Pellinen, P. 1986. Biomasseuntersuchungen im Kalkbuchenwald. PhD thesis. Georg-Augustus-Universität Göttingen. 145 p. (In German).

Pöytäniemi, A.-M. 1981. Schaftkurvensystem für die Fichte zur Anwendung bei der Österreichischen Forstinventur. PhD thesis. Universität für Bodenkultur in Wien. 121 p. (In German).

Ranta, T. 2002. Logging residues from regeneration fellings for biofuel production – a GIS-based availability and supply cost analysis. PhD thesis. Lappeenranta University of Technology. 180 p.

— 2005. Logging residues from regeneration fellings for biofuel production – a GIS-based availability analysis in Finland. Biomass and Bioenergy 28(2): 171–182.

Spinelli, R. & Hartsough, B. 2001. A survey of Italian chipping operations. Biomass and Bioenergy 21(6): 433–444.

Stampfer, K. & Kanzian, C. 2006. Current state and development possibilities of wood chip supply chains in Austria. Croatian Journal of Forest Engineering 27(2): 135–145.

Stockinger, H. & Obernberger, I. 1998. Life Cycle Analysis of District Heating with Biomass. In: 10. European Bioenergy Conference. p. 1–4.

Vahrenkamp, R. & Mattfeld, D.C. 2007. Logistiknetzwerke: Modelle für Standortwahl und Tourenplanung, Gabler. 337 p. (In German).

Vartiamäki, T., Ranta, T. & Jäppinen, E. 2006. Large-scale forest fuel supply solution through a regional terminal network in Finland. In: World Bioenergy 2006. Conference & Exhibition on Biomass for Energy. 30 May – 1 June 2006. Jönköping, Sweden. p. 1–6.

Total of 34 references