The Terminal Location Problem in the Forest Fuels Supply Network

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Abstract

Being sustainably available and CO_2-neutral, woody biomass is becoming increasingly more important as an alternative energy source on a worldwide basis. However, despite broad acceptance of bioenergy plants in Austria, more and more neighboring residents are lodging a protest because of the noise and dust burden during wood-chipping operations. These circumstances force plant operators to utilize separate terminals for storing and chipping forest wood, in turn resulting in a redesigning of the forest fuel supply chains. The present paper focuses on the choice of spatial arrangement and the type of terminals used. For redesigning the forest fuels supply network, a Mixed Integer Linear Programming (MILP) model was developed and subsequently implemented for a study region. The network consists of direct supplies from the forest for combined heat and power facilities (CHP) and indirect supply lines via terminals. The MILP model provides a cost-optimal spatial arrangement of terminals by considering different terminal types with respect to spatial context, chipping technology, and the volume processed. Different scenarios are used to test the robustness of the network design. A simulation of a transportation cost increase shows that the optimal network design is stable within an increase of 20 to 50% and between 70 and 110%. At other levels of increase, the number of terminals used decreases. Furthermore, the number of terminals decreases as the domestic forest timber utilization rate increases. It was possible to demonstrate that industrial terminals offer considerable saving potentials. Therefore, the cooperation of CHP operators with a forest-based industry partner as a terminal provider is one of main management implications of the study results.

Keywords: CHP, forest fuels, MILP, procurement, terminal, bioenergy.

Introduction

Being sustainably available and CO_2-neutral, woody biomass is becoming increasingly more important as an alternative energy source on a worldwide basis. By garnering support from government grants, several combined heat and power facilities (CHP) firing woody biomass have recently been built in Austria. As CHPs have a high fuel demand and are mainly located in or near residential areas, their storage capacity is rather low. Despite the broad acceptance of bioenergy plants, increasingly more of CHP's neighboring residents are lodging protests because of the noise and dust burden during chipping operations. These circumstances are forcing CHP operators to store and chip forest wood in separate terminals, in turn resulting in a total redesigning of their fuel supply chains. Whether a terminal can contribute to decreasing supply costs depends on the entire supply chain of the CHPs. On the one hand, using a terminal means additional investment costs and material handling but, on the other hand, scale effects decrease the chipping and transportation costs (Asikainen et al. 2001). The main challenge is deciding how to spatially arrange and combine different terminal types. At least in Central Europe, planners allocate forest fuels harvested in specific forest districts to CHPs using common sense and basic cost calculations focusing on transportation distances. As most planners have to provide several CHPs with feedstock, the supply networks are too complex to be optimized based on an experienced guess. The task is to design a forest fuels supply network where procurement areas, different terminal types, and plants are connected via various kinds of fuel supply chains in a cost-effective manner.

The terminal location problem addressed here is related

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to the well-known warehouse or plant location problem. A comprehensive survey of model formulations, solution approaches, and applications ranging across numerous industries is provided by Krarup and Pruzan (1983) as well as Owen and Daskin (1998). Erikson and Björheden (1989) described a forest fuels supply network with several supply regions, one central terminal as a processing site, and a single energy supply system as the demander. For several years the problem was solved with Linear Programming, and it was shown that the transportation cost constituted the most essential part of the total forest fuels supply cost. Noon and Daly (1996) developed a geographic information system-based model for estimating total purchase and transportation costs for supplying woody fuel from the forest directly to coal-fired power plants in Tennessee, Alabama, and Kentucky. The results stressed the importance of a plant-based approach for assessing biomass resources and procurement costs in order to determine the profitability of co-firing woody fuels.

A recently developed model combines GIS-based fuel potential and cost estimates with a Linear Programming model to allocate forest fuels from regeneration fellings to CHPs, but no terminals are considered in the potential supply chains (Ranta 2002). A Mixed Integer Linear Programming model (Gunnarsson et al. 2004) supported supply chain planning for heating plants firing both forest and sawmill residues. The decisions that were to be made included the kind of fuels (e.g., forest residues, sawmill by-products, or decay-damaged wood), the harvest area and sawmills to be contracted, as well as transportation modes. A heuristic solution was developed in order to more quickly solve the problem with a planning horizon of one year, considering monthly periods. At a regional level, Freppaz et al. (2004) proposed a Linear Programming Model to locate and size CHPs by considering fuel harvest and transportation costs, as well as regulatory and social restrictions. Gronalt and Rauch (2007) show an evaluation method of a forest fuels supply network design that comprised inventory management policies to buffer seasonal fluctuations in fuel demand and supply. When implementing it in an Austrian province, the supply chain using a central forest industry-based terminal outperformed all the regional terminals that were located within a radius of 100 km. Frombo et al. (2009) developed a decision support system including the costs for biomass transportation and collection, as well as the choice of energy conversion technology (grate-firing combustion, fluid-bed combustion, fluid-bed gasification, and fast pyrolysis) for a woody biomass-based plant. Daily variations in the moisture content of the delivered woodchips as well as weather conditions that slow logging operations have been included in a more recently developed operational forest fuel logistics model (Mahmoudi et al. 2009).

Forest fuel is a relatively new commodity and the market is immature and unstable (Junginger et al. 2008). Therefore, the main function of a terminal is to balance the seasonal fluctuation of the plant's demand and the respective variability of supply from the forests (Gunnarsson et al. 2004). Both non-chipped and chipped forest fuels can be stored at terminals, and the chipping of energy wood can also be executed. Terminals can be served by a mobile chipper on a demand basis, or by a stationary chipper. The cost analyses of different supply chains for forest fuels showed that the terminals at heating plants required a large storage area, a high annual volume to be processed, and a stationary chipper to be competitive (Asikainen 2001). Furthermore, the vicinity to settlements was recognized as a negative factor excluding the location of a terminal with chipping operations because of the noise and dust produced.

However, in the same context of the forest fuels supply network, the problem of the optimal spatial arrangement of different terminal types has not yet been satisfactorily addressed. Therefore, the present paper focuses on the aforementioned problem, and a MILP model is developed and subsequently implemented for a study region for the optimal spatial arrangement of terminals. The remainder of the paper is organized as follows: In Section 3, a comprehensive problem description is presented, followed by the mathematical model formulation. Section 4 shows the derived computational results for the basic case and provides sensitivity analyses of transportation costs and domestic forest timber utilization rates. A discussion of the results and concluding remarks summarize the paper in Section 5.

Materials and Methods

Supply of forest fuels

Under Central European conditions, forest fuels are mainly harvested as a byproduct of sawlogs or pulp logs, and these higher-priced assortments bear the main part of the logging costs. The most important cost drivers for forest fuels are transportation, storage, and chipping, which are considered as supply costs in this paper. For 38 domestic supply districts the net supply potential of forest fuels has been estimated according to the calculation scheme devised by Gronalt and Rauch (2007). Furthermore, four foreign districts in the vicinity provide for import capacities, so that the demand in the study region can be fulfilled by 42 supply districts in total. Forest fuels can be supplied directly from a district to a CHP in chipped or non-chipped form. In the forest, chipping operations can be executed at landings, so that a chipper and a truck can stand on the forest road side-by-side. Furthermore, different types of terminals are used as intermediate feedstock storage and chipping points. When woody biomass is chipped, the coefficient used to turn m^3_{solid} to m^3_{loose} includes material losses based on practical experience. Material losses due to temporary storage are neglected because of the usually rather dry material and short-term storage.

Terminals

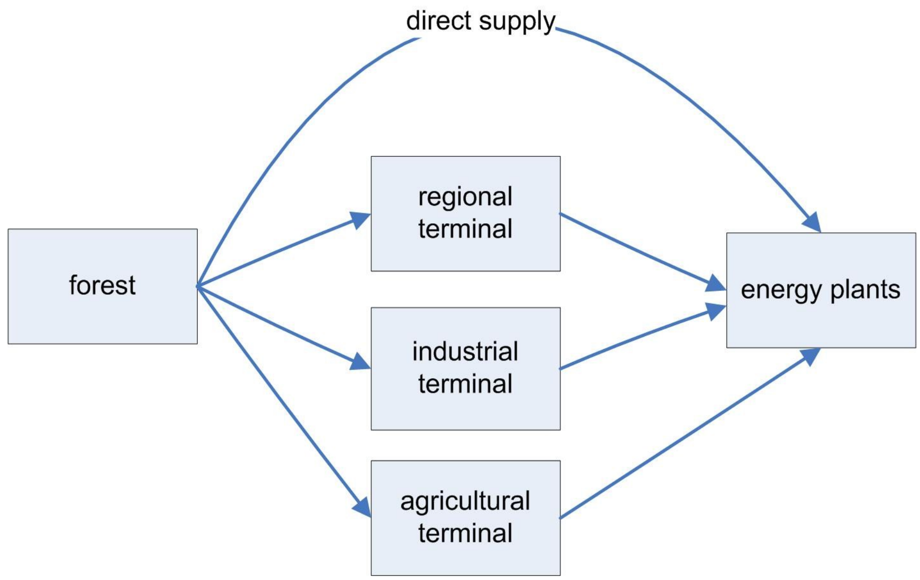
Terminals serve as transshipment points where chipping is carried out. However, they differ with respect to the chipper technology and transshipment volume. Three different types of terminals are considered, beginning with the regional terminal storing of forest wood and supplying chips for one or several CHPs. A regional terminal is located near or in the forest, where access is ensured throughout the year. A mobile truck-mounted chipper, visiting the regional terminal on demand, converts forest wood into chips. The area of the regional terminal has to be determined according to the maximum amount of forest fuels stored at a certain time of the year. This amount depends on the seasonality of both the fuel supply from the forest and the fuel demand (Gronalt and Rauch 2007). Regional terminals need part-time employees to receive forest fuels shipments and to organize chipping and transportation operations. One benefit of a regional terminal is that investment costs are low. However, on the other hand, storing coniferous wood for several months is forbidden in order to prevent bark beetle infestations. The average storage capacity of a regional terminal is relatively low compared with the feedstock amount of a CHP, and the same applies to scale effects on chipping and transportation.

The second type of terminal is an industrial terminal, where a stationary chipper is available. At forest-based industry sites, the chipper is mainly used for chipping pulp wood or wood for fiberboard production. Fuel chipping in connection with paper or fiberboard production leads to high capacity utilization resulting in extraordinarily low chipping costs. Furthermore, using the existing infrastructure and personnel resources makes the industrial terminal a very efficient fuel distributor. The available capacities of the proposed industrial terminals have been evaluated in a previous study (Gronalt and Rauch 2008). As timber storage and processing is already part of the ongoing business, no additional legal approval process is needed for setting up such a system. The dry weight and moisture content of the received feedstock is estimated according to the procedure for production wood. Precise information on the net calorific value of feedstock is thus calculated in addition to the cost advantages. In the study region, one industrial terminal is presumably available for each province, four are part of a forest-based industry plant, and one is the fuel terminal of Austria’s largest CHP.

The third terminal type considered is an agricultural terminal, which is usually used for sugar beet harvesting and is, therefore, equipped with a weighbridge. Agricultural terminals can accept forest fuels supplies based on weight and moisture content. Some of the agricultural terminals are not used anymore, so they are available year-round. Others cannot be used during sugar beet harvest from the middle of September until the end of December. Agricultural terminals can be used on a hire basis, and the investment cost for adapting moisture content estimation for timber is very low. The major drawback of agricultural terminals is that the forest cover of such agriculturally favored regions, as well as the feedstock potential of the regions, is rather low.

Except for the industrial terminals, the potential sites are actually not used as processing and transshipment points for forest fuels. Figure 1 shows the different supply lines of forest fuels, including the above-described terminal types.

Figure 1. Forest fuels supply network.



Procurement of demolition wood, sawmill, or particleboard residues is excluded, because Austrian law (Green Electricity Act) restricts their co-firing in CHPs.

Combined Heat and Power Facilities

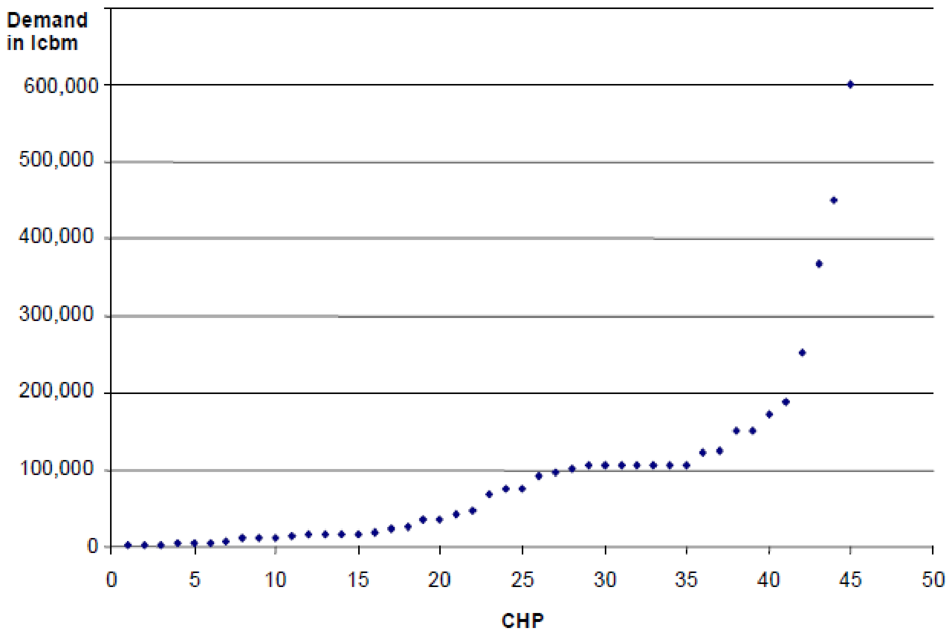
Whereas wood-fired heating plants in Austria have an average annual fuel demand of 1,000 loose cubic meters (lcbm), an average CHP built between 2005 and 2007 requires 50,000 to 60,000 lcbm (Nemestohty 2005). The largest CHP of the study region has a yearly demand of 600,000 lcbm and is one of the largest bio-energy plants in Central Europe. Figure 2 shows the cumulative distribution of the annual demand of the CHPs in the study region. Every second CHP needs less than 50,000 lcbm per year, and only 10% of the CHPs have an annual demand of more than 200,000 lcbm.

Some CHPs are a part of a forest-based industry, which can use heat from the combustion process, e.g., for kilning chambers or drying chips. Other CHPs supply households with heat during the cold time of the year and raise their electricity output in the warmer period. The 42 CHPs built in the study region have a total annual forest fuels demand of approx. 4.4 M lcbm. Some of the larger CHPs are using strategic alliances with forest enterprises or with forest-based industries to ensure an efficient forest fuels supply. For those of the 42 newly built CHPs that are able to fulfill their forest fuels demand in their own district, a local supply chain is estimated and they are set apart from the network problem. This results in 28 CHPs that require at least part of their supply from other districts.

Transportation

The study includes the truck transportation of non-chipped and chipped forest fuels. The truck transportation cost is set in accordance with the past experience of Austrian forest -based industries (Table 1, next page). The transportation cost model adds the loading and unloading costs, costs for trans-

Figure 2. Annual demand distribution of the study region's CHPs.



portation, and toll costs. Where the forest road network is accessible from the public road network, entry points were set in each supply district. Transportation distances were measured between the entry points, terminals, and CHPs with the utilization of a geographic information system (GIS), and the average transport distance from the supply district to the terminal or CHP was calculated. For the study region, the portion of forest fuels transported by agricultural tractors and trailers was estimated at less than two percent of the total volume and, therefore, this transportation mode is not included in the decision model.

Table 2 (next page) shows the calculated supply and demand figures for a selected region. Highlighting the regional demand and supply of forest fuels shows the free potential available for other regions or feedstock lacking in the region (Table 3, next page).

A MILP Model of the forest fuels supply network

The forest fuels supply network defines the supply channels and volumes for each CHP and is designed for a study region including five Austrian provinces using a MILP model. The proposed terminals are spread out over the total study area, but because of the low system costs and the huge capacity of industrial terminals, few terminals were located in their nearer surroundings. The 19 proposed regional terminals were mainly located in districts with both a high forest fuels potential and a low internal demand in the district. In each of the five Austrian provinces, one appropriate industrial terminal site was spotted, four are a part of an existing forest-based industry plant, and one is located at Austria's largest CHP. The prospective agricultural terminals are only available in sugar beet regions, and 14 of them were selected. Five agricultural terminals are available year-round, whereas nine others are not available during the sugar beet harvest season. The terminal map (Figure 3, next page) shows the prospective locations of the terminal sites in the study area.

The forest fuels supply network is designed for 28 CHPs (P_1, …, P_{28}) and 42 supply districts, consisting of 38 domestic districts and four foreign import regions (D_1, …, D_{38}; I_1, …, I_4). The possible network consists of five industrial terminals (IT_1, …, IT_5), 19 regional terminals (RT_1, …, RT_{19}), five agricultural terminals available year-round (AT_1, , AT_5), and nine agricultural terminals that are not available during the sugar beet harvest season (ATg_1, , ATg_9). Furthermore, forest fuels can be delivered directly to the CHP from the forest. Figure 4 (page 37) provides an overview of the potential supplies in the network. The solid lines show the chip transportation and the dotted lines display the transportation of the non-chipped forest fuels. The MILP model covers a time

Table 1. Cost estimates (lcbm, loose cubic meters; h, hours; a, annum). Original model was run in Euros (US$1.3446 = 1 Euro).

Parameter	Value	Unit
terminal		
recovery period	20	years
infrastructure	0.43	USD / lcbm
rent (agricultural terminal)	8,605	USD / a
personnel costs (regional/agricultural terminal)	0.67	USD / lcbm
chipper		
chipping costs mobile chipper	3.36	USD / lcbm
chipping costs stationary chipper	1.61	USD / lcbm
transportation expenses		
toll cost	0.36	USD / km
system costs truck and driver	52.72	USD / h
un-/loading time energy wood	2	h
un-/loading time chips on truck	1	h
average truck load: non-chipped wood	26	m^3 / truck
average truck load: chipped wood	80	lcbm / truck
transportation expenses	1.17	USD / km

Table 2. Expected demand and supply of forest fuels in 2006 in the regions of Upper Austria (lcbm, loose cubic meters).

Region	New demand [lcbm]	Available forest fuel [lcbm]	Free Potential [lcbm]
Braunau am Inn	9,100	58,000	48,900
Freistadt	0	50,000	50,000
Gmunden	0	63,000	63,000
Grieskirchen	0	6,000	6,000
Kirchdorf/ Krems	0	66,000	66,000
Linz	401,800	5,000	-396,800
Perg	0	26,000	26,000
Ried im Innkreis	0	15,000	15,000
Rohrbach	0	35,000	35,000
Schärding	4,200	25,000	20,800
Steyr	3,300	54,000	50,700
Urfahr	0	23,000	23,000
Vöcklabruck	17,500	71,000	53,500
Wels	92,680	14,000	78,680
Upper Austria	**528,580**	**511,000**	**-17,580**

horizon of one year. Dynamic changes in important economic parameters that are supposed to occur during a longer time span are modeled with the scenario method.

The mathematical model of the forest fuels supply network problem is presented in this section. The set of variables is described first, which is followed by the objective function and constraints. The set of supply sources (supply districts) is *K*; *I* is the set of terminals and *J* the set of CHPs. Index *k* is used for sources, *i* for terminals and *j* for CHPs. The following notation is used in the formulation of the MILP model.

Table 3. Expected demand and supply of forest fuels in 2006 in the Austrian provinces in the study area (lcbm, loose cubic meters).

Province	New demand [lcbm]	Available forest fuel [lcbm]	Free Potential [lcbm]
Salzburg	502,620	486,000	-16,620
Lower Austria	1,762,368	704,000	-1,058,368
Upper Austria	528,580	511,000	-17,580
Vienna	600,000	5,000	-594,000
Burgenland	1,009,000	143,000	-866,000
total	**4,402,568**	**1,850,000**	**-2,552,568**

Decision variables:

Variables representing the transportation flow of forest fuels from supply districts to plants; from districts to terminals; and from terminals to plants are defined as follows:

$x1_{kj}$ volume of chipped fuel transported from district *k* to CHP *j*

$x2_{ki}$ volume of non-chipped fuel transported from district *k* to terminal *I*

$x3_{ij}$ volume of chipped fuel transported from terminal *i* to CHP *j*

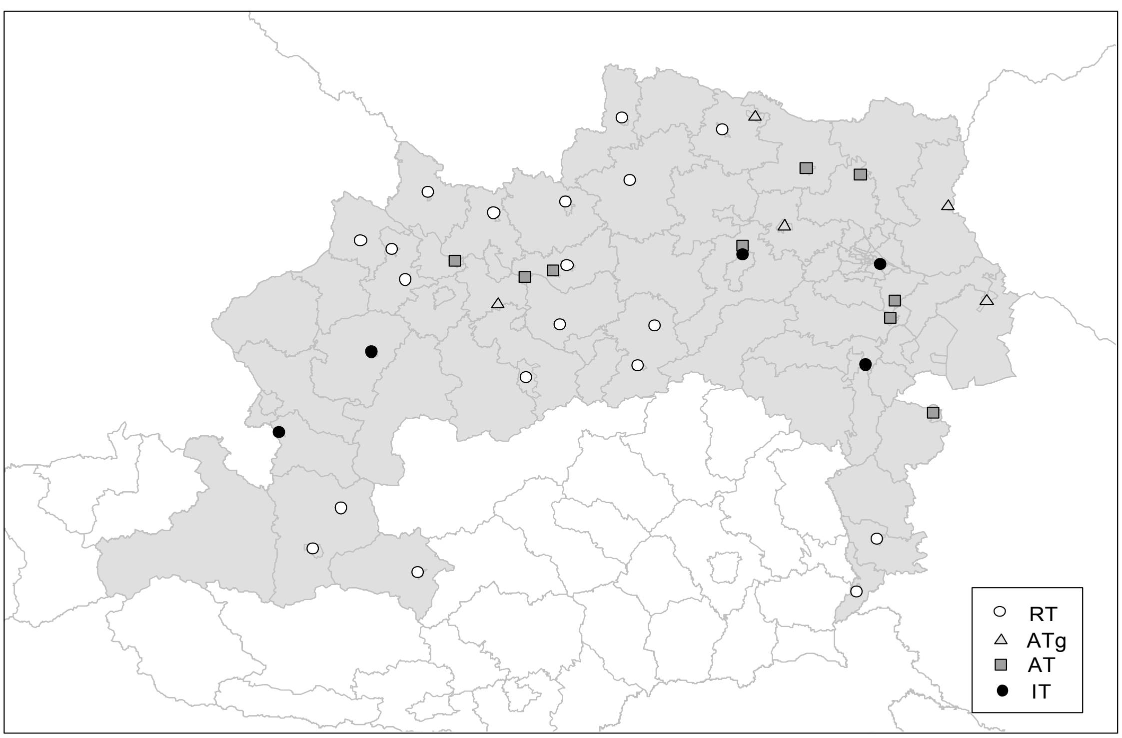
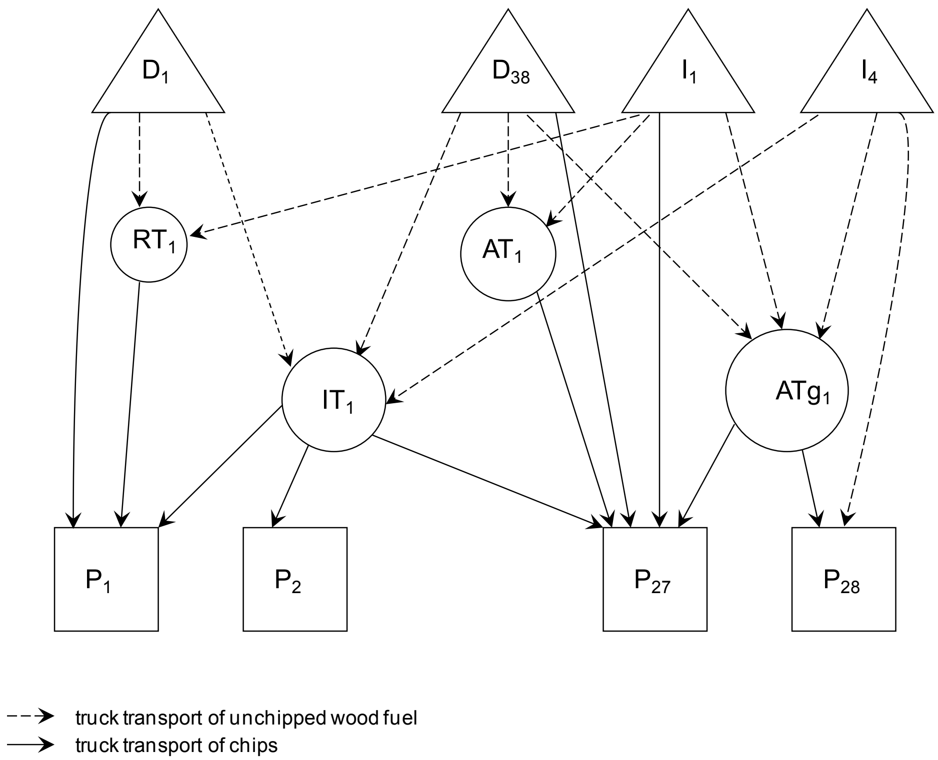


Figure 3. Map of prospective terminal locations (RT = regional terminal, ATg = agricultural terminal open all year round, AT = agricultural terminal temporally limited, IT = industrial terminal) and study area (grey shaded).

Figure 4. Possible transportation flows and network design in the model.



The variables defined so far are continuous variables. The set of variables related to the use of a terminal are binary ones and are defined as follows:

y_i {1 if terminal i is opened; 0 otherwise}.

Data:

$c1_{kj}$ cost for the direct fuel supply from district k to CHP j *(USD/m^3_{solid} resp. USD/m^3_{loose})*

$c2_{ki}$ cost for the fuel transport from district k to terminal i *(USD/m^3_{solid})*

$c3_{ij}$ cost for the fuel supply from terminal i to CHP j *(USD/m^3_{loose})*

$c4_i$ personnel cost per unit of forest fuels handled at a terminal i *(USD/m^3_{loose})*

s_k supply volume of forest fuels available in district k *(m^3_{solid}/a)*

CU_i maximum storage capacity at terminal i *(m^3_{solid}/a)*

d_j the demand of forest fuels in CHP j *(m^3_{loose}/a)*

cth cost of truck and driver per hour (USD/h)

ctkm cost of truck and driver per driven km (USD/km)

tlulc time to load and unload chips (h)

tluln time to load and unload non-chipped fuel (h)

e_{ki} distance between supply district k and terminal i (km)

e_{kj} distance between supply district k and CHP j (km)

e_{ij} distance between terminal i and CHP j (km)

eh transportation distances using a highway (km)

cto toll cost per highway km (USD/km)

cct_i chipping cost in terminal i *(USD/m^3_{loose})*

ccf_k chipping cost in the forest in supply district k *(USD/m^3_{loose})*

ctf_k transportation cost to accumulate energy wood in the forest in supply district k *(USD/km)*

f_i cost to open a prospective regional/agricultural terminal i *(USD/ storage area in m^3_{loose} resp. USD/a.)*

Cost c1 includes the transportation costs from district k to CHP j plus chipping costs in the forest, plus the cost of prehauling forest fuels to the chipping place in the forest. Cost c2 includes transportation costs from district k to terminal i. Cost c3 includes the transportation costs from terminal i to CHP j, plus chipping costs in terminal i. The different cost values were calculated according to the following equations:

(1a) $c1_{kj} = cth*tlulc + ctkm*e_{kj} + cto*eh + ccf_k + ctf_k$

(1b) $c2_{ki} = cth*tluln + ctkm*e_{ki} + cto*eh$

(1c) $c3_{ij} = cth*tlulc + ctkm*e_{ij} + cto*eh + cct_i$

In terms of the above notation, the model of the forest fuels supply network can be formulated as follows:

(1) Minimize $\sum_k\sum_j c1_{kj}\, x1_{kj} + \sum_k\sum_i c2_{ki}\, x2_{ki} + \sum_i\sum_j c3_{ij}\, x3_{ij} + \sum_i \sum_k c4_i\, x2_{ki} + \sum_i f_i\, y_i$

Subject to:

(2) $\sum_i x3_{ij} + \sum_k x1_{kj} = d_j \quad \forall\, j\in J$

(3) $\sum_i x2_{ki} + \sum_j x1_{kj} = s_k \quad \forall\, k\in K$

(4) $\sum_k x2_{ki} = \sum_j x3_{ij} \quad \forall\, i\in I$

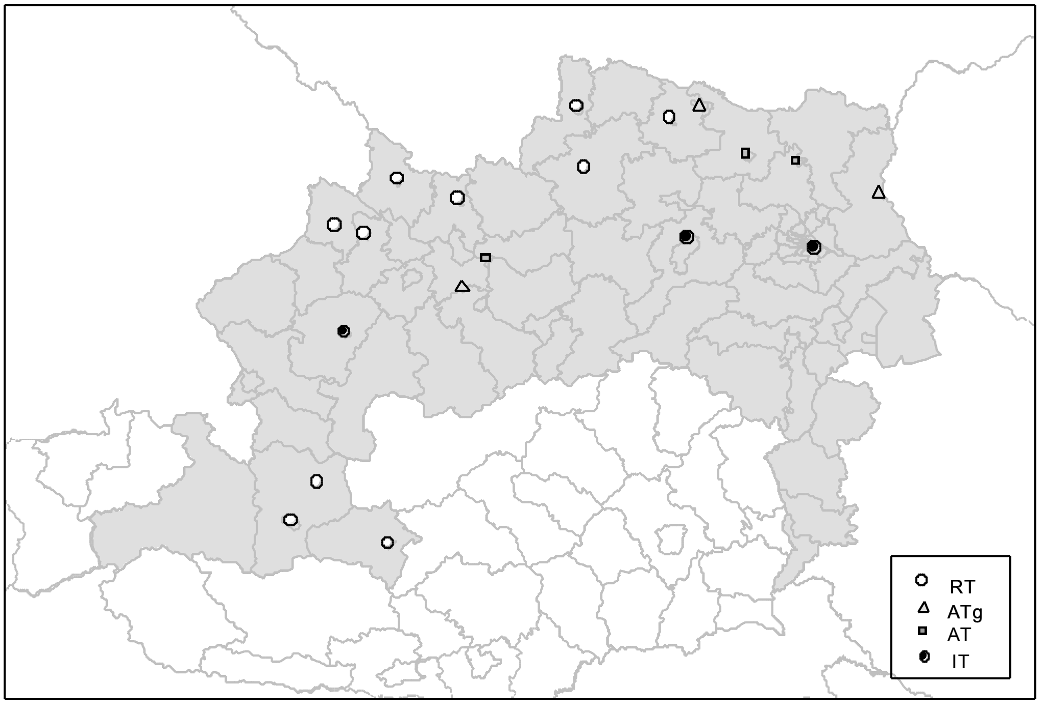
(5) $CU_i\, y_i \geq \sum_j x3_{ij} \quad \forall\, i\in I$

(6) $x3_{ij}, x2_{ki}, x1_{kj} \geq 0 \quad \forall\, i\in I, k\in K \text{ and } \forall\, j\in J$

(7) $y_i \in \{0,1\} \quad \forall\, i\in I$

The model minimizes the total costs (1), which are the sum of transportation and chipping costs, as well as the costs associated with opening and operating terminals. The constraint set (2) ensures that the demand of all the CHPs is fulfilled by direct supply from the forest and/or by supply via the terminals. Forest fuels supplies from the forest to the CHPs and the terminals are restricted to the forest fuels potential of the districts (EQ (3)). In Constraints (4) the flow constraint at each terminal is modeled. The fuel volume that goes into a terminal must equal the terminal output. The storage capacity of the terminals is limited according to space restrictions. This constraint also ensures that a flow from a terminal is only feasible if this terminal is opened (EQ (5)). The model was encoded using the Mosel algebraic modeling language with the Xpress Optimizer Ver.16.10.02, professional optimization software supporting the model formulation and solution of LP -models.

Figure 5. Terminal map of the optimal solution (RT = regional terminal, ATg = agricultural terminal open year-round, AT = agricultural terminal temporally limited, IT = industrial terminal).



Parametric Sensitivity Analyses

The calculations start with the configuration of a basic scenario. Furthermore, various changes in important parameters of the business environment are defined in order to test the sensitivity of the optimal network design. Opening a terminal is connected with high fixed costs. Therefore, the scenario method is used to investigate whether a terminal site is competitive under varying conditions. Reflecting prospective energy price rises, scenario 1 assumes an increase in transportation costs from 10 to 120%. The second scenario modifies the domestic forest timber utilization rate within a range of 10 to 50% more or less from the actual rate, as domestic forest timber utilization is rather unstable due to the high proportion of small-scale forest owners in Austria. With the above-mentioned changes, the input parameters are newly calculated and the MILP model is resolved again.

Results

Basic Scenario Results

The optimal solution requires 19 terminals out of the 38 prospective sites. The network uses ten regional and six agricultural terminals in addition to three industrial terminals. The direct fuel flow from the forest to the CHPs is approximately 60% of the total annual feedstock demand, and another 27% is supplied by the three industrial terminals. The supply volume of the ten regional terminals is 8%, whereas the agricultural terminals supply is only 5%.

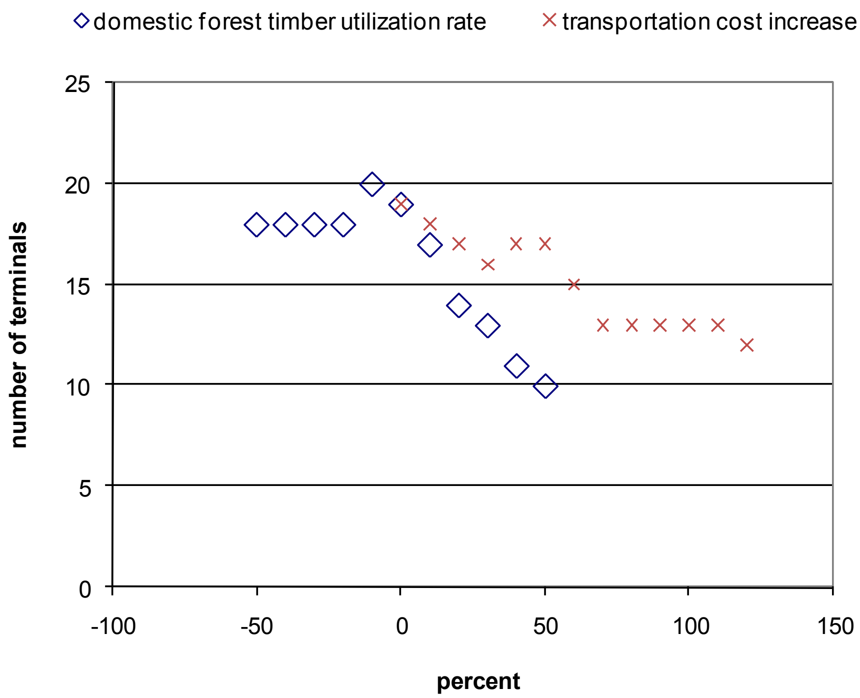
Results of the parametric sensitivity analyses

The simulation of rising transportation costs shows that the optimal network design is almost stable within an increase of 20 to 50%, as well as between 70 and 110%. For an increase of between 20 to 50%, the network always uses the same seventeen terminals. Only the optimal solution for an increase of 30% requires one less terminal. The second stable interval constantly requires thirteen terminals, yet from one solution to the next only a single terminal site changes. Solutions for the other increased rates show that the number of terminals decreases when the transportation costs rise. The number of terminals needed to optimally supply the study area decreases when the domestic forest timber utilization rate increases. At the same time, the volume of direct supplies from the forest to the CHPs rises. However, if the mobilization rate decreases 20% or more, a stable set of 18 terminals is used for the forest fuels supply network. For a decrease of 10% in the domestic forest timber utilization rate, 20 terminals would be needed.

Discussion and Conclusion

Analyzing the robustness of the solution, i.e. which terminals are a part of the solution in different scenarios, was first to be addressed. Figure 7 shows terminals that are a stable part of the optimal solution even under changing conditions. When domestic forest timber utilization rates are increasing, ten terminals are constantly part of the optimal network design. Under decreasing rates, 18 terminals are always open, and for all mobilization rate scenarios, seven terminals are always found in the optimal terminal set. A group of ten terminals is part of the optimal solution under all transportation cost scenarios, and three further terminals are included for increased rates of up to 70%. In the scenario of increasing transportation costs, the number of terminals needed is constant over small ranges of parameter changes, but increases by steps as the level of change increases further. Under all the scenarios of both parameters, five terminals are a part of the optimal network design (iT1, aTg2, rT6, rT13, and rT14). In total, four of them import fuel and three are located close to the border terminals (aTg2, rT13 and rT14) serving exclusively as import transshipment points. The fuel import rate of the industrial terminal iT1 reaches 56% in the basic scenario. Ris-

Figure 6. Sensitivity of the optimal solution to changes in transport costs or changes in the domestic forest timber utilization rate.



ing transportation costs and higher domestic forest timber utilization rates decreases it considerably or marginally. The next five terminals (rT16, aTg1, aT2, iT2, and rT8) are a part of the supply network under all the parameter settings in at least one of the scenarios. The industrial terminal, (iT2) as well as the most southerly located regional terminal, is supplied with domestic forest fuel only. The other three terminals are again close to the border and are exclusively supplied by imported sources. Their business is threatened by an increase of the domestic forest timber utilization rate, as their supply costs would thus become uncompetitive. Prospective regional or agricultural terminal sites in the close proximity of an industrial terminal are not used. In regions with a high demand, forest fuel is supplied directly, and no terminals are opened in such regions.

The presented MILP models assume cooperation in the forest fuel procurement of all CHPs and, due to competition between CHPs, procurement costs are certainly lower than in reality. Rauch et al. (2010) simulated the actual forest fuel procurement costs for Austria with heuristics and found that they are at least 20% higher. Cooperation will result in higher procurement costs only for a few CHPs (Rauch 2010). Therefore, the result of the optimization provides valuable information for managers supplying forest fuel to CHPs regarding the spatial arrangement of terminals and which type of terminal to use under the given conditions. To begin with, the direct fuel supply from forests to a CHP has been proven to be the preferable option for transportation from local and

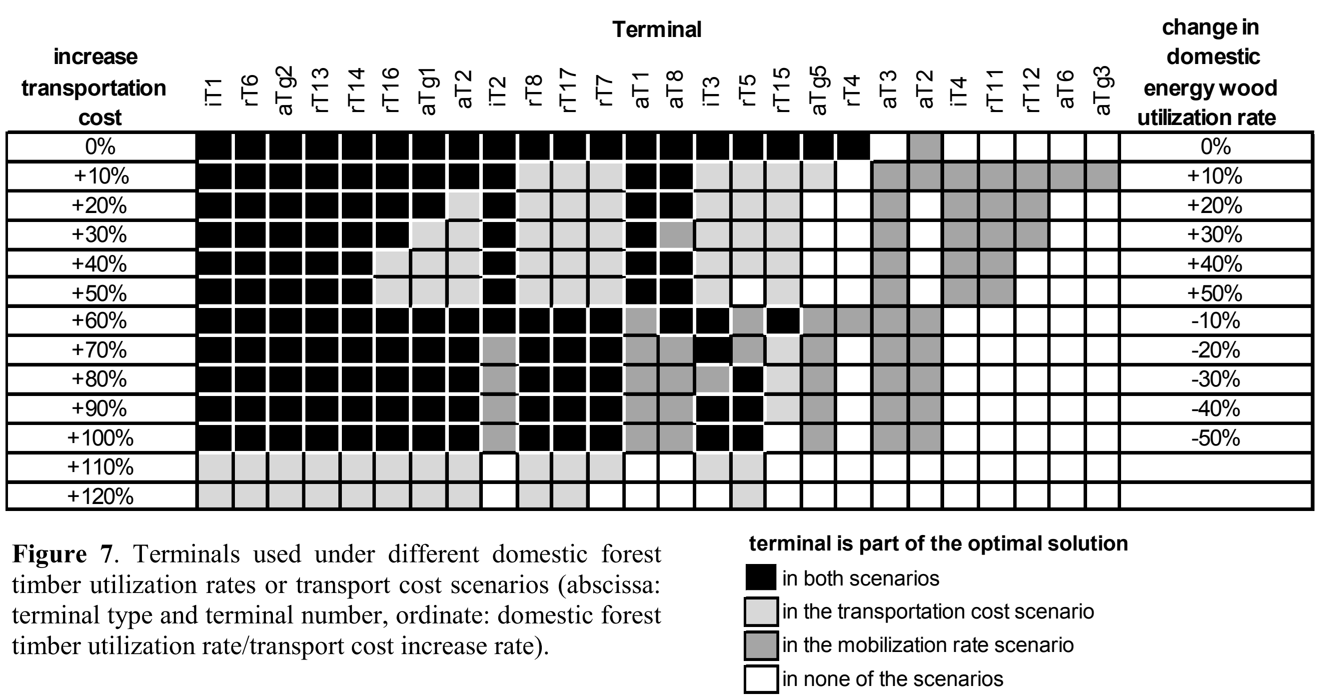


Figure 7. Terminals used under different domestic forest timber utilization rates or transport cost scenarios (abscissa: terminal type and terminal number, ordinate: domestic forest timber utilization rate/transport cost increase rate).

neighboring regions. For these direct supply flows, chipping is primarily performed at the forest roadside or even under favorable conditions in the forest. For longer transportation distances, terminals proved to be valuable forest fuel transshipment points. Next to cost considerations, a terminal also has an important function as a safety inventory because most Austrian CHPs lack fuel storage capacities to buffer supply uncertainties. In particular, the direct fuel supply substantially contributes to supply uncertainty, as most Austrian forest roads cannot be used year-round, e.g., after rainy periods or heavy snowfall.

It was demonstrated that industrial terminals offer high transshipment capacities at low forest fuel supply costs. Therefore, the cooperation of several CHPs with a forest-based industry partner as a terminal provider is one of the main resulting management implications of this study. The forest-based industry partner benefits from the higher capacity utilization of its stationary chipper, as well as from synergies in wood procurement organization. Furthermore, robust terminal sites have been estimated by testing competitiveness under different transportation costs and domestic forest timber utilization rate scenarios.

The shortcoming of the presented network model is the exclusion of the long-distance transportation modes of rail and barge, which could expand the import possibilities. In addition, the planning horizon of the MILP model is only one year because the decision to build a terminal was assumed to primarily depend on the economic conditions in the first period. However, even when considering a longer planning horizon, the terminal set utilized in the first period predetermines the supply network of the following periods due to high terminal investment costs. Although the planning horizon is only one year, the performance of a certain terminal can be observed for years with different parameter settings. The sensitivity of the supply network to natural hazards is also not estimated by the presented model. However, the resulting delays of terminals or direct supplies can have a considerable impact on the supply network design, e.g., if additional terminals are needed for fuel buffer stocks.

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