A Geographical-Origin—Destination Model for Calculating the Cost of Multimodal Forest-Fuel Transportation

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ABSTRACT

As a consequence of increasing demand for wood fuels, the management of forest-fuel production chains has become an important logistics issue in Finland and Sweden. Truck-based transportation has been the dominant method in fuel supply from the areas around power plants. However, increasing demand has led to enlargement of supply areas and greater variety in supply methods, including also railway and waterway transportation. This study presents a GIS-based calculation model suitable for cost calculations for power plants’ forest-fuel supply chains. The model has multimodal properties—i.e., it provides transfer of forest-fuel loads between transportation modes—and enables case-specific adjustment of transportation and material-handling cost parameters. The functionality of the model is examined with a case study focusing on a region of intense forest-fuel use. The results indicate that truck transportation is competitive with railway transportation also for long transport distances. However, increasing the proportion of multimodal transportation for other than economic reasons (e.g., for supply security) could be reasonable, since the impact on total supply costs is marginal. In addition to honing of the parameters related to biomass availability and transport costs, the model should be developed through inclusion of other means of transportation, such as roundwood carriers.

Keywords: Transportation; Forest Fuels; Railway; Waterway; GIS

1. Introduction

The EU has set a target of increasing the share of renewable energy sources (RES) in final energy consumption to 20% by 2020 [1]. In the most heavily forested EU countries, Finland and Sweden, wood fuels have an important role in meeting the national targets, which are 38% for Finland and 49% for Sweden. Since the by-products of wood industries are already used mainly for energy production purposes, the greatest wood-energy potential is found in forest fuels [2,3]. The term “forest fuels” refers to all technically and economically exploitable parts of trees that are unsuitable for timber or pulp and paper production. In Nordic forestry, these are branches and treetops as logging residues, stumps from clear-cuttings, and small-diameter wood from young and dense forest stands.

Forest fuels’ supply can be divided into three parts: 1) forest operations; 2) transport operations; 3) material-handling operations. In the first, the energy wood is harvested and forwarded to roadside storage, principally with machines similar to those used in roundwood harvesting. Transport operations include all transportation taking place via the road network and optionally also by rail and waterway. Besides moving of biomass from one carrier to another, material-handling operations include comminution of biomass. In addition to costs from these operations, the stumpage price, costs of storing the fuel at the roadside or terminals (e.g., interest costs), and costs created by supply management are usually included in supply-cost figures.

From a geographical point of view, Finland and Sweden show similarities in their regional imbalances of forest-fuel supply and demand. While the heat and power plants in industrialized and densely populated areas represent the greatest demand, the most extensive forest reserves are found in rural areas. In these Nordic countries, this generally means that the balance of supply and demand is positive in the north and negative in the south. In comparison with, for example, fossil-fuel transportation, loads of wood chips tend to have low energy density, usually rendering their road transportation unprofitable over long distances. Compared with the main transportation method, by road on truck-trailers (Figure 1), the railway and waterway options are cost-efficient for tran-
2. Material and Methods

2.1. Source Data and Geographical Extent

The source data consisted of municipal estimates of forest-fuel availability, several studies of transport and material-handling costs, and geographical datasets for transport networks and land-use data. Despite the model being applicable in theory also for other countries (e.g., Sweden) or even for transnational analyses, the geographical extent was confined to continental Finland, because of the limited availability of source data. The datasets were imported to a GIS environment, which was handled by ArcGIS® software.

2.2. The Geographical Grid and Origin Points

The origin points of forest-fuel supply were generated through a 2 × 2 km grid. The midpoints in the grid were extracted for further use in transportation analysis. This raster-to-vector conversion was required for connecting the estimates of availability of biomass to the transport network in vector form. The origin points represented roadside storage locations as places where forest operations end and the transport and material-handling operations begin. In practice, there may be several roadside locations in a 4 km² area. From year to year, exact storage locations change as new cuttings appear. It was assumed that a precise geographical location is not necessary when the distance between an actual roadside location and the closest origin point in the model would be 0.0 - 1.4 km. Instead, describing the information on several roadside storage areas as attributes of one origin point reduces the load on route calculation processes. Another advantage of a network of fixed points is that it accepts source data in different formats. For example, the availability of small-sized energy-wood potential is typically assessed from growing stock, and geographical information is given as polygon features with harvestable volume and area as attribute values. Hence, the values of the polygon features whose center points are in the same grid cell are summed for the corresponding origin point. On the other hand, logging residues and stumps are usually estimated from logging data via biomass conversion functions and selection criteria for forest stands suitable for energy-wood harvesting. Instead of polygons, the locations of logging data are usually roadside storage points whose values can be summed for the grid points as well.

2.3. Biomass Availability Analysis

2.3.1. Biomass from Regeneration Fellings

In Finnish forestry, lots are harvested from regeneration fellings and also, to a lesser extent, from thinnings [11], while the feasible logging residue and stump extraction is related only to regeneration fellings [12,13]. On the other hand, regeneration fellings produce some pulpwood too. In terms of harvest volumes on a local scale, correlation can be found between the volumes of harvested logs...
from all kind of stands and the volumes of all roundwood harvested from regeneration fellings [11,14]. With this background, the biomass data were obtained from roundwood logging statistics reported by the Finnish Forest Research Institute [15]. Average roundwood cuttings from 2004 to 2008 were linked to municipal borders from 2008. There were 399 municipalities in continental Finland in 2008, with land area ranging from 6 km² to 17,333 km². One value for each tree species—i.e., the annual volume of logs harvested—represented each municipality. In practice, Finnish forests are dominated by three tree species: Scots pine (Picea sylvestris), Norway spruce (Picea abies), and birch (Betula pendula or Betula pubescens). Of these species, the least dominant, birch, was removed from this part of the analysis, because logging residues and stumps are obtained mostly from coniferous forests. The roundwood volumes of pine and spruce were converted to logging residue and stump volumes by means of biomass conversion factors based on earlier assessments [12,16-18] (Table 1). The volumes were then cropped by a 70% recovery rate given in guidelines for sustainable energy-wood harvests for regeneration fellings [19].

The analysis produced two theoretical estimate values for each municipality: 1) harvest potential of logging residues; 2) harvest potential of stumps. Since the technically and economically viable harvest potential is less than the theoretical potential, a conversion factor of 0.40 for logging residues and 0.37 for stumps was used for gauging techno-economic potential [20]. The factors were principally based on the experience that some remote stands do not interest harvest operators, mainly because of high costs of harvesting or forwarding (i.e., off-road transport to roadside storage).

2.3.2. Biomass from Young Forest Stands

The availability analysis for harvestable biomass from young stands was based on the National Forest Inventory data collected by the Finnish Forest Research Institute. The availability analysis has been reported upon in terms of techno-economic harvest potential by municipality in 2008 [22,23].

2.4. Land-Use Data

Municipality-level estimates of biomass availability were assigned to origin points via a method utilizing land-use data in raster format [24]. First, the value for a municipality was divided evenly over the origin points such that the sum of the values equaled the municipal estimate. Then, proportional values for forest area in grid cells were calculated by means of raster analysis. GRASS GIS software was used in the raster analysis. The analysis exported a proportional value that was used for distribution of the values within the municipality. The average proportion of forest area in the municipality was used as the reference value. As a result of this method, the origin points in the most heavily forested areas of the municipality got higher estimates than those with less forest land. In the land-use data, the forest area stated represents all forest areas where the average annual capability of producing solid-stem volume increment was more than 1 m³·ha⁻¹ [21]. In addition to all urban and agricultural areas, stunted peatlands were counted as areas with no potential for harvests.

2.5. Transport-Network Analysis

2.5.1. The Multimodal Transport Network

The purpose of the transport-network analysis was to: 1) create a geographical layer of demand points that consisted of existing and planned demand points in Finland with expected annual forest fuel use of at least 360 TJ·a⁻¹; 2) build a transport network with connectivity to the demand points. A multimodal network dataset was built from three vector layers, representing road, railway, and waterway networks. The source for the road-network layer’s data was Digiroad, a national road and street database maintained and kept updated by the Finnish Transport Agency [25]. Railway and waterway networks were extracted from the Topographic Database of the National Land Survey of Finland. The railway network included as an attribute value the status of electrification. Road-network data included, for example, speed limits and one-way traffic restrictions. Waterway data covered inland waterways with a draft of 4.2 m. The waterway data had no additional attribute values.

To enable multimodal functions of the network dataset, places for transfers from one network to another were defined. The forest-fuel demand points with rail or water connection were automatically transfer sites for unloading purposes. The selection of other transfer sites—i.e., loading points for trains and vessels—was based on recommendations as to the most suitable loading locations and terminals for railway transportation of roundwood [26] and a development study of navigation on inland waterways [27].

2.5.2. Costs of Truck-Based Transport

The economy of transportation is a sum of route-length-
The cost functions were added to the calculation model in two parts. In the first part, two attribute-value fields were created in the road-network database, and these new fields received their values from the shape length multiplied by the corresponding coefficient for truck type—i.e., 0.0075 or 0.0097. Accumulation of these shape values was a crucial part of the route calculation. The second part involved adding the constant cost value (0.37 or 0.54) to the accumulation. This was done through definition of an added-cost-point barrier [32] for the demand point. The barrier allowed traffic to the end point only by adding of the constant cost value to the route properties (Figure 2).

2.5.3. Material-Handling Costs

Chip-truck transportation is the usual method of forest fuels’ transportation in Finland [31,33]. In this method, biomass is chipped at the roadside. The method is viable for logging residues and small-diameter wood but not for stumps. For comminuting the thick rootstock, operations require heavy crushers, which usually are unable to work at the roadside. The cost of roadside chipping depends slightly on the type of fuel [34]. In this model, an average value of €0.83 GJ⁻¹ [35] was used as a default. This cost parameter was included in the route calculation, but, instead of origin point (i.e., the roadside), the action was determined for the point barrier that was already set as

Figure 2. Example of unit costs’ calculation for two supply methods: roadside chipping (left) and crushing at the power plant (right). Costs that do not depend on the transport distance are added to the route at the point barrier at the demand point.

By default, payloads for stump transportation as given by Kärhä et al. [31] were used as the reference for all fuel types.
the constant in truck transportation costs.

Whenever crushing is used as the only option (for stumps) or the most convenient one (other forest fuels) for comminution, energy-wood trucks are needed for transportation. Crushing usually takes place at demand points, at least if they are equipped with stationary crushers. In other cases, a mobile crusher is used. This applies also for more complex systems wherein a terminal is used for storing, comminuting, and blending purposes. The unit costs of crushing depend greatly on the utilization rate [35]. Besides forest fuels, power plants commonly use other biomass to be crushed, such as waste wood, which keeps the crusher’s utilization rate high. In addition to annual operating time, mobile crushers’ operation costs depend on, for example, the distances between the terminals where they operate. According to Rinne et al. [35], €0.42 GJ⁻¹ is the approximate crushing cost for a power plant with a stationary crusher when the annual crushing volume is 1.3 PJ. This was used as a default value for demand-point barriers whenever roadside chipping was not used. A mobile crushing cost of €0.92 GJ⁻¹ was applied as the default for all supply methods involving terminal handling. This cost value represented a terminal cost savings in the route layer, the model enables changes to the service areas. In this case, the aim was to determine the size of the forest-fuel supply area for a given volume of forest-fuel demand.

2.5.4. Waterway and Railway Transport Costs
Waterway and railway transport costs were added to the model similarly to the costs of road transportation. It was assumed that the transportation by water would be conducted by vessel units consisting of barges and tugboats. This was based on a study reporting the economy of this transport method [36]. The cost function was

\[ C_{ww} = 0.0019d_{ww} + 0.30 \]  

where \( C_{ww} \) is the cost of waterway transportation in € GJ⁻¹ and \( d_{ww} \) is the shortest waterway distance in kilometers from the loading point to the demand point. The expected carrying capacity of the vessel unit was 1500 m³ solid, equating to 11.3 TJ².

In Finland, availability of public reports about railway transportation costs is poor, and costs of railway transport services are difficult to predict. From a technical standpoint, transfers from diesel to electric power and vice versa are usual in Finland because the railway network is only partially electrified. A particularly large share of operation is that of yarding-in-transit, in which unit costs depend on the overall output of each rail yard. Furthermore, Finland’s rail freight traffic is open for competition, but the state-owned company, VR Transport, is still the only operator. The monopoly position means that, instead of distance, the pricing of freight services is based on competition with other modes of transportation, such as truck freight services [38]. The pricing is therefore very case-specific. The calculation model was unable to take into account complex price-fixing. A linear cost function was formed from sample data, which were collected from various transport cases. The cost function was

\[ C_{rw} = 0.0033d_{rw} + 0.30 \]  

where \( C_{rw} \) is the cost for train transportation in € GJ⁻¹ and \( d_{rw} \) is the shortest railway distance in kilometers from loading point to demand point. Accordingly, the train transportation costs given in this paper represent more the pricing itself than the operation costs for the service provider. It was assumed that the optimal train length would be 10 wagons, each carrying three chip containers [39]. The total carrying capacity of a train was assumed to be 500 m³ solids which corresponds to 3.8 TJ.

2.6. Steps in the Calculation
2.6.1. Service-Area Queries
The first part of the calculation procedure was a service-area query for the selected demand point. Service-area analysis is typically used for assessing the coverage areas of commercial services. In this case, the aim was to determine the size of the forest-fuel supply area for a given volume of forest-fuel demand.

This step included calculation of several service areas, starting with an area in which all parts of the network are within a 2 km driving distance. This was repeated with the range increased by 2 km until the maximum distance set¹ was reached. Each service-area query took the sum

²The ratio between the energy content and solid cubic volume is different for each fuel source, with the exact values depending on such factors as which wood density or moisture values are applied as defaults (e.g., [18,37]). In this study, it was assumed that the ratio is 7.56 GJ m⁻³ for logging residues and small-diameter trees and 10% higher (i.e., 8.32 GJ m⁻³) for stumps. The carrying capacity is here converted to energy content with a 7.56 GJ m⁻³ ratio.

¹This was to be manually defined. The user of the calculation model was expected to have a sense of the geographical extent of large-scale supply of forest fuels.
of forest-fuel availability from the origin points that were no more than a kilometer from the roads shown in the road layer of the service area. Other points were rejected because of the assumption of poor economy of forest operations far from roads. The output was a table of service areas, with driving ranges and forest-fuel availability volumes as attributes. With this table, appropriate calculation distance for the next step in the calculations could be obtained.

2.6.2. Origin-Destination Route Matrix with Route Optimization

When the correct extent for the supply area was found, a test of origin points to the demand point. Route calculation was carried out by finding the shortest routes from the origin points to the demand point. Because truck-transport costs were determined by route length (e.g., Figure 2), these routes were also the most profitable ones for supply methods based completely on direct transport by road to the power plant. In addition to the costs of these methods, the model calculated the costs of the most suitable multimodal transport options by adding up the costs of energy-wood-truck transportation to a loading point, costs defined for the point barrier at the loading point, costs derived from train or waterway transportation, and costs determined for the demand point. Examples of cost calculation for multimodal transport routes are presented in Figure 3.

The added-cost-point barriers were created for both loading and demand points, with the demand point displaying the same attributes as if the energy wood were transported directly to the plant. The loading points represented additional distance-independent costs of using train or waterway systems. By proceeding thus, the model was to select whether it was more economical to use a train or waterway option or transport the uncommitted biomass directly to the plant. The output was a route matrix (Matrix B in Figure 4) that could include both direct and indirect routes for transportation of uncommitted biomass. For the comparison with chip-truck transportation, a more complex method was needed, be-

![Figure 3](https://example.com/f3.png)

**Figure 3.** An example of unit cost calculation for multimodal supply methods: a method including waterway transportation (left) and a method including railway transportation (right). Costs that do not depend on the transport distance are added to the route at point barriers at loading and demand points.

*Distance-independent costs could be understood also as fixed costs and distance-dependent costs as variable costs. The terms “fixed costs” and “variable costs” also encompass business operations with no geographical sense, whereas the authors wanted to express the costs’ dependency on geographical properties explicitly.*

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cause of the differences in cost functions between truck types. This calculation step had two parts: The first part was calculation of the route matrix for energy-wood trucks, as explained above. In the second part, a route matrix allowing only chip-truck transport was calculated for the same area (Matrix A in Figure 4). These matrices were then compared record by record, and the best route for each fuel from each origin point was then saved to the final route matrix. For calculation of total transportation distances and costs, the distances for the individual routes were finally multiplied by the biomass volume available at the origin point and divided by the solid-content-carrying capacity of the respective carrier.

2.7. Case Study in the Selection of Alternative Transport Methods

2.7.1. The Case Study
The calculation model was used for choosing the optimal combination of supply methods for two CHP plants in Jyväskylä, Central Finland (62°13'59"N, 25°43'59"E). Total forest-fuel use at these facilities is 2.2 - 2.5 PJ·a\(^{-1}\) at present. The power plants’ energy production potential indicates that the demand for forest fuels could more than double from the current figures.

The main objectives in the case study were to: 1) determine the economic basis for railway transportation in an area of intense competition of forest fuels; 2) clarify the railway system’s influence on average supply costs in different demand conditions. Jyväskylä is an important logistics point on four railway lines, and the power plants in the study have a rail connection, in both cases about 5 km from the main railway station. The case study focused only on transportation and material handling between the origin and demand points, which means that, for example, shunting and unloading phases at the demand point were excluded.

The power plants were treated as a single demand point because they are near each other and owned by the same company. Based on the current and potential forest fuel use, three demand scenarios were used: 1) 2.5 PJ·a\(^{-1}\); 2) 4.3 PJ·a\(^{-1}\); 3) 5.4 PJ·a\(^{-1}\). To include train transportation as a supply option, we selected one loading location in the multimodal transport network for the case. The Haapajärvi rail yard (63°45'00"N, 25°19'59"E), 211 kilometers north of Jyväskylä by rail, was chosen because of the low local demand for forest biomass and spacious facilities for loading operations. Another advantage with this selection was that the railway route from Haapajärvi to Jyväskylä did not involve any additional yarding-in-transit or locomotive exchange.

2.7.2. Biomass Availability for the Power Plant
The biomass availability analysis was carried out as described in Subsection 2.3 but with additional limitations to the estimated availability volumes. The first limitation was related to the availability of small-diameter wood. In addition to transport and material-handling costs, supply costs include roadside price, which is composed of the given fuel’s stumpage price and costs of harvest operations\(^5\). The roadside prices of the three fuel types focused upon differ from each other, because of factors such as

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\(^5\)The spatial variation in roadside prices of all forest fuels is so great that the fuel types’ price ranges overlap each other [10]. Because of the uncertainty in the prediction of price differences between locations, roadside prices were excluded from the study. Given the study’s objectives and the finding that there were no great differences in small-diameter wood’s availability across the study area, ignoring the roadside price differences was not expected to have significant impact on the selection of supply method or on the sizes of supply areas in the case study.
differences in harvest techniques and costs. On average, the roadside price is lowest for logging residues and at its highest for small-diameter wood. Production of fuel from small-diameter energy wood is partially supported by the government, with subsidies of €1.11 GJ⁻¹ [10,18]. However, the national budget sets a ceiling for subsidy totals. Thus, subsidizing harvest for the full techno-economic potential would not be possible. Because of the restriction in the financial support from the government, a 50% limitation was set to the techno-economic availability of small-diameter wood (see Section 2.3.2).

Secondly, it was assumed that the power plants in the case together have a roughly 25% market share in biomass trade in the region around Jyväskylä, while the existing local forest-fuel demand around Haapajärvi is mainly from small-scale use. The techno-economic availability at the origin points was reduced by 75%, with the exception of those points within a 60 km driving distance of Haapajärvi, where the limitation based on the market situation was defined as 25%.

Figures 5 and 6 present the availability of forest fuels in the areas under study as theoretical potentials and potentials after techno-economic and market-position-based reductions. The supply analysis in the case study was based on availability volumes presented as “potential after market-share cuttings”.

2.7.3. Supply Analysis

Of the three forest-fuel types, logging residues and small-diameter wood were combined into one category for analysis because of the similarity in their various transport and material-handling methods. Stumps were treated as a separate category, because roadside chipping was not an option for stumps; in other words, stumps were loaded on an energy-wood truck unchipped, whether the truck was heading to a train terminal or straight to the power plant. Logging residues and small-diameter wood were transported directly to power plants by chip truck, but, because a mobile crusher at the train terminal could be used also for logging residues and small-diameter wood, short-range transport from roadside to terminal was determined to be best done by energy-wood trucks. According to the route optimization model, logging residues and small-diameter wood could also be transported in unchipped form to a plant equipped with a stationary crusher. This option was, however, ignored, because a power plant’s crusher with an expected processing capacity of 1.3 PJ·a⁻¹ might be overloaded if all forest fuels were crushed thus. Since waterway transportation was not an option in this case and logging residues and small-diameter wood were handled as a single category, three supply methods were included in the model: 1) roadside chipping and direct chip-truck transportation to power plants (hereafter referred to as the direct chip-truck method); 2) direct stump transportation and crushing at the power plants (direct energy-wood truck method); 3) energy-wood truck transportation to loading terminals combined with crushing at terminals and train transportation (train method).

The optimal supply method from each origin point was selected through comparison of the costs arising from material handling and transportation. While the train transport cost for a 216 km route was €1.00 GJ⁻¹ and the difference between terminal and crushing costs at a
power plant was €0.50 GJ$^{-1}$, the train method was chosen for stump transportation if transport to loading terminals was at least €1.50 GJ$^{-1}$ less costly than a direct truck route to the demand point. The selection procedure was not, however, applied for points over 200 km by road from Jyväskylä. From the origin points ruled out by this definition, the points in the Haapajärvi supply area within a 60 km radius were still included in the study, with the train method as the only supply option.

3. Results

All transportation between the origin points and the demand point was done by trucks when the annual demand of the power plants was 2.5 PJ. The average transport distance was 91 km, corresponding to a transport cost of €1.05 GJ$^{-1}$ for chips and €1.42 GJ$^{-1}$ for stumps. Of the total fuel supply, 27% was stumps and 73% chips created from logging residues and small-diameter wood. Nevertheless, the energy-wood truck represented 30% of the distance driven. Because of the lower load density, it had to make more trips than a chip truck if it was to transport the same amount of biomass. The most remote origin point in the supply area was 138 km by road from Jyväskylä, with a supply cost of €2.24 GJ$^{-1}$. In this scenario, train transportation was not a profitable option at all.

When the annual demand was increased to 4.3 PJ, the marginal transport cost, €2.56 G·J$^{-1}$, became so high that the train method was the most economical supply method from some origin points near the Haapajärvi loading point. Annual supply through the terminal was 29 TJ, corresponding to eight train deliveries per year. The average distance in road transportation was 117 km and the maximum distance 182 km. Chip-truck deliveries’ share of the total supply volume increased from the aforementioned 73% to 75%, reflecting the more advantageous cost function for the roadside chipping method with longer transport distances.

In the scenario with the highest fuel demand, 5.4 PJ·a$^{-1}$, 74% of the volume was transported by chip trucks. The lower number of chip-truck loads was principally a consequence of the increased volume transported by train. The train method represented a 151 TJ supply volume, even though this was much less than the mobile crusher’s potential capacity (360 TJ·a$^{-1}$) at the loading terminal. Also contributing to chip transportation’s slightly lower share was that the limiting transport distance of 200 km with the direct chip-truck method was reached when the supply exceeded 5.3 PJ. Therefore, all deliveries whose total supply costs were more than the marginal cost of the direct chip-truck method at 200 km (i.e., €2.70 GJ$^{-1}$) were transportation by either the direct energy-wood truck method or the train method. The most expensive deliveries resulted in a supply cost of €2.72 GJ$^{-1}$, which equates to a 181 km driving distance in direct energy-wood truck transportation or a 26 km distance to the loading terminal.

The main results of the case study are presented in Table 2. The average costs given for material handling include all costs of chipping, crushing, and terminal operations. Train transportation’s share of the total costs for a total supply of 4.3 PJ and 5.4 PJ was 0.3% and 1.3%, respectively.

Because only 151 TJ was allocated to train transportation, additional analysis was carried out in order to find the economic influence of increasing the biomass flow through the terminal to 360 TJ·a$^{-1}$, which was the mobile crusher’s projected annual processing capacity. Therefore, the most expensive direct truck loads, corresponding to 209 TJ of energy in total, were either redirected to a loading terminal or replaced with the most profitable transport beyond the 26 km driving range from the terminal. As a result, the average supply cost for the whole

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<th>Table 2. Results in the case study.</th>
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<td>Supply per transport methods, TJ</td>
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supply scenario was increased by €2.70 TJ\(^{-1}\) (i.e., €0.0027 GJ\(^{-1}\)). The enlargement of the supply area around Haapajärvi is shown in Figure 7, which also includes the geographical extent for the results presented in Table 2.

4. Discussion

4.1. The Case Study

The results of the case study indicate that railway transportation of forest fuels could be a viable alternative to direct truck-transport methods. Nonetheless, even in regions with intense competition of forest fuels, this conclusion holds only when very substantial amounts of forest fuels are to be transported. Direct chip-truck transportation is very competitive even with longer transport distances if the supply method is selected solely on the cost bases used in the study. In the additional scenario, 209 TJ of biomass was redirected from direct truck methods to the train method. Such redirection would be reasonable for, at least, the following reasons:
- The unit cost used for mobile crushing was initially intended for 360 TJ·a\(^{-1}\) productivity.
- Train transportation is probably unprofitable with low transport volumes, such as 151 TJ·a\(^{-1}\), unless concurrent use exists for the wagons utilized.
- It is sensible to use terminals for storing the biomass as a buffer against sudden disruptions in the supply system. The train method automatically includes terminal storage. The more biomass is stored at the terminal, the better the supply security is.

Usually, terminals are not accorded any concrete financial value for enhancing supply security. In the calculation model, this function should be compensated for by a negative cost attribute, but judging a suitable amount is difficult and case-specific. What is the likelihood of a fuel shortage for a large-scale power plant using biofuels if there are no buffer terminals for backup, and how costly would it be to shut down the plant or use more expensive fuels, for example, in the middle of the

![Figure 7. Forest-fuel supply areas in the scenarios used for annual demand.](image-url)
heating season? In relation to the additional scenario of the share of the train method being increased to 360 TJ·a⁻¹, the difference of €2.70 TJ⁻¹ in average supply costs may be considered a low cost for increased supply security.

4.2. The Calculation Model

Despite the fact that waterway transportation was excluded, the case study showed that a geographical calculation model including multimodal properties is suitable for forest-fuel transportation analyses insofar as transport alternatives are evaluated solely in economic terms. The cheapest means of transportation is found, and for most cases this is direct road transportation to the demand point. The case study also revealed that some distance-independent costs in the model should not be considered to be completely fixed costs, because the utilization rates and the actual unit costs of crushers at terminals and power plants depend on the amounts of biomass that have been allocated to these points in the route calculation. The same applies to trains, whose cost functions should be unequal for different amounts of transported biomass, and even for different rail lines. Now, the basis for the train transportation cost function was a set of samples from other transportation cases, for which the annual number of train deliveries and transport volumes were unknown and the costs were more like supplier-set prices than dependent costs. In a comparable case study from Eastern Finland, Tahvanainen and Anttila [40] found that train transportation could be profitable even when the transport distance is 135 km or greater. That finding can be questioned because the costs used for chip trains were based on wagons used for roundwood transportation and the number of train-loading points was most likely exaggerated in view of the investment and maintenance costs of forest-fuel terminals [35].

In the biomass availability analysis, the method applied for weighting the municipality-level availability estimates with proportional forest-land area attributes was important because of the multimodal character of transport analysis. If truck transportation alone were employed for large-scale supply, the differences in forest-fuel potential between individual origin points would probably even out in the final results. However, the supply areas around the loading points are so small that geographical differences within the municipalities matter. For example, if a train-loading point were surrounded by residential or agricultural land while the majority of the forests were further from the municipal center, which is usually the case, and if the origin points in the model had similar estimates of biomass availability, the calculation would result in excessively short average distances between the origin points and the loading point.

The source data for the availability analysis were based on roundwood logging statistics and results from forest inventory and were reprocessed such that the values for the origin points corresponded to the techno-economic harvest potentials for each fuel. Techno-economic potentials should still be reduced in consideration of the competition of forest fuels. This was done in the case study via reduction of the potential with coefficients that were based on local knowledge of competition conditions. Adding an advanced calculation module to predict the conditions of competing demand points could probably give more reliability to the harvest potential figures. In Finland, studies of forest-fuel supply for multiple demand points (e.g., [10,41]) have generally used simple demarcation between power plants, but the supply areas of competing demand points actually overlap with each other in free competition. In case-specific supply-area analysis, the competition should be modeled through definition of geographical rules that allow for overlap in the competition.

The analysis for multimodal transport networks focused on the supply methods most commonly used in Finland. Additional fleet alternatives for long-distance transportation were a bulk-load barge and a train carrying standard twenty-foot containers. Both of these methods necessitate the biomass being chipped before loading. However, since the energy use of small-diameter wood has recently increased [42], there would be a need also to include roundwood carriers in the model. In this study, all small-diameter trees were assumed to be harvested whole, which is the most profitable harvest method when chipping is done at the roadside [43]. This fuel source can also be harvested as delimbed stemwood, which results in higher harvest costs. On the other hand, delimbed wood can be transported from the roadside at a lower transportation cost via trucks and wagons as used in pulpwood transportation. Given the better cargo density and, especially, easier operations in trains’ loading and unloading, it can be assumed that transportation of delimbed small-diameter wood will increase as a consequence of the growth in forest-fuel demand nationwide and the increasing transport distances.

5. Conclusion

This paper presented a calculation model for selecting the most cost-efficient way of transporting forest fuels in different cases. The main focus of the paper was in presentation of the methodology, but a case study was also included to demonstrate how the model operates in GIS environment. Increasing demand for biofuels in the EU calls for more advanced planning and analyzing tools for logistics. This calculation model could be developed to include also other feedstocks, such as agro-biomass, and
additional means of transportation. The model is also applicable for analysing supply-chain based emissions.

REFERENCES


[27] T. Sikiö and I. Salanne, “Saimaan Sisävesiliikenteen Ke-
hitämiiselvitys (Development Study of Inland Navigation
on Lake Saimaa Area),” Publications of the Finnish

[28] Finland, “Decree on the Use of Vehicles on the Road,”

25 July 1996 Laying Down for Certain Road Vehicles
Circulating within the Community the Maximum Au-
thorized Dimensions in National and International Traffic
and the Maximum Authorized Weights in International Traffic,”
European Commission, Brussels, 1996.


[31] K. Kärhäm, A. Mutikainen and A. Hautala, “Saalasti Murs-
ka 1224 HF Käyttööppikamurskauksessa (Saalasti Murs-
ka 1224 HF at Power Plant Crushing),” Metsäteho Tulo-
skalvosarja, Helsinki, 2011.

ml#/004700000056000000.htm

[33] K. Kärhäm, “Metsähakkeen Tuotantoketjut Suomessa vu
onna 2010 (Industrial Supply Chains of Forest Chip Pro-
duction in Finland in 2010),” Metsäteho Tulos-
skalvosarja, Helsinki, 2011.

[34] T. Ihalainen and A. Niskanen, “Kustannustekijöiden Vai-
ikutukset Bioenergian Tuotannon Arvoketjuissa,” Working
Papers of the Finnish Forest Research Institute, Hel-
sinki, 2010.

Handelberg, “Terminaali Liiketoimintana,” In: K. Karttu-
nen, J. Föhr and T. Ranta, Eds., *Energiaputa Etelä-Sa-
vosta (Energywood from South-Savo)*, Lappeenranta Uni-

[36] K. Karttunen, E. Jäppinen, K. Väätäinen and T. Ranta,
“Metsäpoltonaineiden Vesitiekuljetus Proomukalustolla (In-
land Waterway Transport of Forest Fuels),” Research
Report ENTE B-177, Lappeenranta University of Tech-
logy, Lappeenranta, 2008.

[37] E. Alakangas, “Suomessa Käytettävien Polttoaineiden Omi-
naisuuksia (Properties of Fuels Used in Finland),” VTT
Research Notes 2045, Technical Research Centre of Fin-

[38] M. Mäkitalo, “Market Entry and the Change in Rail Trans-
port Market when Domestic Freight Transport Opens to
Competition in Finland,” Ph.D. Thesis, Tampere Uni-

[39] O.-J. Korpinen, J. Saranen, E. Jäppinen and T. Ranta,
“Evaluating the Suitability of Long-Distance Railway
Transportation of Forest Fuels in Finnish Circumstances,” 18th
European Biomass Conference and Exhibition, 3-7
May 2010, Lyon, pp.156-162.

[40] T. Tahvanainen and P. Anttila, “Supply Chain Cost Ana-
lysis of Long-Distance Transportation of Energy wood in
Finland,” *Biomass and Bioenergy*, Vol. 35, No. 8, 2011,
pp. 3360-3375. doi:10.1016/j.biombioe.2010.11.014

[41] T. Ranta and O.-J. Korpinen, “How to Analyse and Maxi-
mise the Forest Fuel Supply Availability to Power Plants
doi:10.1016/j.biombioe.2011.01.029

[42] E. Ylitalo, “Puun Energiakäyttö 2010, Metsätilastotiedote
16,” 2011.
upolttouaine2010.pdf

tives, Accumulation and Procurement Cost of Small-Dia-
meter Thinning Wood for Fuel in Central Finland,” *Silva