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Assessment of Energy Wood Resources in the Leningrad Region

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Abstract
Possibilities for energy wood procurement in the Leningrad region are assessed in this report. As sources for energy production, wood from thinnings, logging residues, non-industrial round wood and residues from sawmilling are considered. The costs for energy wood procurement are also calculated.

Available energy wood, based on the 2004 actual cut, if collected, is approximately 4 million m^3. Nearly 86% of it is non-industrial round wood and felling residues in cutting areas (56%) and central processing yards (30%), the rest (14%) are by-products from sawmilling. The deciduous tree species (birch and aspen) dominate and are valued at 65% of the total amount of felling residiues and non-industrial wood. It is possible to intensify utilisation of forest resources and thereby also to increase the use of wood in energy production. The total amount could be 54% higher if the allowable cut could be utilised completely and 124% higher if thinnings could also be utilised completely. There are, however, big differences within the region, as the current rate of utilisation of forest resources varies in the region.

Currently, pre-commercial thinning is an economically unfeasible source of energy wood. Despite well developed technologies, the high costs of the pre-commercial thinning make supply of energy wood unprofitable. Commercial thinnings are economically more attractive as sources of energy wood. However, a choice of energy wood procurement chain for the 1st commercial thinning is limited by cost factors. There are more possibilities for energy wood supply from the 2nd commercial thinning. The most cost-efficient supply chain based on a harvester and a forwarder allows a profitable energy wood supply from a distance of up to 150 km. Currently, at final felling areas non-industrial wood is an economically feasible resource for energy production. The same applies to the availability of process residues at central processing yards and sawmills, where lump wood and slabs are the most cost-efficient resources for wood chip production and at present these sources of energy wood look very attractive.

The issue of how much energy wood may enter the market depends almost entirely on the market situation, i.e. supply and demand, which is influenced by the price of energy wood and competing energy sources.

Keywords
Energy wood, logging residues, non-industrial round wood, wood procurement, cost calculation

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Other information

Contents

Preface

Biomass and in particular wood biomass is becoming an increasingly important source of energy. In many cases, it is a local source whose availability is not influenced by international crisis, it benefits local and regional economies and its use also helps to improve the structure of forest resources. Biomass can substitute non-renewable energy sources and thus help in the reduction of greenhouse gas emissions and mitigation of climate change. In many parts of Europe, over the decades use of conventional fuel wood has decreased, while use of residues from wood processing industries, recovered wood and demolition waste for energy purposes has increased. Collection of felling residues for energy production purposes is becoming common. In addition to the EU, individual countries have also set targets to increase the use of renewable energy sources. In this respect, it is important to estimate energy wood sources, supply methods, technologies and costs. This would be particularly important in Russia, where the role of wood in energy production is currently marginal compared to other energy sources.

This report has been prepared as part of the project “Possibilities for Energy Wood Procurement and Use in Northwest Russia” at the Finnish Forest Research Institute. The aim of the project is to estimate the availability of different energy wood sources, their technical and economic availability in the Leningrad region, to design cost effective energy wood procurement systems and to assess needs for technology development. This project is part of a larger research consortium “Reduction of Greenhouse Gas Emissions in Russia – Finnish Business Opportunities” coordinated by the Lappeenranta Technical University, belonging to the technology program CLIMBUS of the National Technology Agency TEKES. This project at the Finnish Forest Research Institute has received funding from TEKES, Komatsu Forest, Stora Enso and UPM Kymmene. The authors would like to thank Dr. Greg Watson for having checked the English language of this report.

In Joensuu,

Yuri Gerasimov, Vadim Goltsecv, Ján Ilavský, Timo Tahvanainen, Timo Karjalainen

1 Introduction

Energy production in Northwest Russia is based on the use of fossil fuels (oil and gas) and nuclear energy, although in remote areas, and in single family houses in particular, the use of traditional firewood is common. For example, in the Leningrad region, the share of natural gas is 62%, coal 11%, biofuels 3% and other sources 24% (Anon 2003). The share of natural gas and biofuels will grow, while that of coal and other sources will decrease in the future.

There is a long tradition of using wood for energy purposes in Finland, currently about 19% of the produced energy is wood based (Statistics Finland 2005). Technology is advanced and barriers against using wood energy are smaller compared to Russia, where the environment for wood based energy production is different. Barriers in Russia are related to administrative and legal aspects, traditions, and most importantly to the dominant role of cheap oil and gas for energy production. On the other hand, district heating systems in towns and villages in Northwest Russia could also allow utilisation of wood in centralized heat production.

The area of forests and growing stock in Northwest Russia is approximately 4 times larger than that in Finland, but the intensity of forest resources utilisation is lower than in Finland. Fellings in Northwest Russia are about 0.4% of the standing volume and approximately 32% of the increment, while in Finland they are 2.9% and 70%, respectively (Karvinen et al. 2005, FFRI 2005). In Finland, already nearly 90% of the maximum sustainable removal is used, while in Northwest Russia only 40% of the annual allowable cut is utilised. Domestic forest industry in Russia is largely based on utilisation of coniferous tree species, whereby domestic demand for deciduous tree species is lower. Thinnings, which represent nearly 60% of the area treated with fellings in Finland, are far less applied in Northwest Russia, as they represent only 12% of the felled area. Therefore, from a forest resources point of view it would be possible to expand the use of deciduous tree species and of wood from thinnings in Northwest Russia for modern energy production, for heat and electricity. There are, however, regional differences in the intensity of utilisation and availability of forest resources.

Another source for energy production from forests is felling residues. In Russia, current forest management norms require collection of felling residues after wood harvesting from the site. Traditionally, these felling residues have not been used for energy production purposes. How felling residues are collected varies between different wood harvesting methods. If traditional full tree or tree length felling methods and technologies are applied, no additional work in the forest is required to collect felling residues, as branches and tops are cut at central processing yards (low landings), in Russian - *nizhniy sklad*, a place where wood transported from different cutting areas are delimbed and bucked to the desired length and sometimes debarked. If the cut-to-length method is applied then collection of felling residues from the felling site requires additional work, thus causing additional costs. This indicates how felling methods influence not only the availability of felling residues but also the costs of felling residues.

The total growing stock of the Leningrad region is estimated to be 825 mill m^3, of which more than 600 mill m^3 are available for wood supply. Approximately 35% of the growing stock is pine, 30% spruce, 25% birch, 9% aspen and 1% other tree species. The annual allowable cut is 9.4 mill m^3 under bark (u. b.), of which 3.9 mill m^3 are coniferous and 5.5 mill m^3 deciduous tree species (Ministry of Natural Resources, 2003). The tree species distribution of the growing stock and the annual allowable cut differ markedly due to specific approach for the annual allowable cut calculation in Russia.

The actual cut in 2004 was below the allowable cut, 7.9 million m^3 u.b., including 5.1 million m^3 from final felling, 1.5 million m^3 from thinnings (in Russian – *rubki promezhutochnogo pol'zovania*), and 1.3 million m^3 from other fellings. The region produces 4% of the industrial round wood in Russia, 10% of its pulp and paper, and 3% of its sawn timber. Forest industry is an important branch of the Leningrad region's economy, as it produces 16% of the volume of industrial production and employs 16% of the industrial workforce in the Leningrad region (Goskomstat, 2004).

The Leningrad region has good potential for energy wood, because a large share of wood resources currently has no use in industry, especially deciduous tree species. Local authorities estimate this potential to be 5 million m^3 (Guseva 2005). Every year several small-scale boilers are changed from oil or coal to wood-based fuel, but further large-scale investments will depend on reliable information about energy wood supply. Public opinion is that logging companies in the Leningrad region would be able to supply wood-based fuels for a reasonable price. Logging companies would be ready to invest in energy wood harvesting technology if there would be enough demand and large customers for energy wood. Enhancement of investments requires information about potentials for energy wood resources, technology, costs and identification of suitable cases for larger scale utilisation of energy wood.

The aim of this report is to provide a comprehensive picture of the energy wood resources in the Leningrad region and an estimation of costs for energy wood production. Logging residues, non-industrial round wood and residues from sawmilling are considered as sources of energy wood. Different energy wood sources, and potential harvesting methods and machinery have been taken into account when estimating costs for energy wood supply.

2 Energy wood resources

2.1 Classification

In order to estimate annual wood fuel supplies in the Leningrad region, we evaluated the availability of wood residues and non-industrial round wood (hereafter *energy wood*) from the following sources:

- logging
    - at cutting areas
        - branches
        - tree tops
        - log tops
        - non-industrial round wood
    - at central processing yards of logging companies using the traditional tree-length method
        - non-industrial round wood
        - lump stems
        - cross-cut ends
- sawmilling
    - slabs
    - strips of wood
    - cross-cut ends
    - sawdust
    - shavings
    - bark

The following sections provide a procedure for estimating energy wood resources and the results of such an estimation for the Leningrad region.

2.2 Methodology for the estimation of energy wood resources

2.2.1 Logging

Logging is defined as an operation that fells and extracts timber from forests (Dykstra and Heinrich 1996). *Energy wood* from logging includes *logging residues* and *non-industrial round wood*.

Logging residues here mean:

- branches and tops of trees after delimbing. Volume of branches and tops of trees after delimbing is equal to 8% of the felled stem volume. These biomass components are partly used for strip roads improvement (estimated to equal 3% of felled stem volume) and rest (equal to 5% of the felled stem volume) can be used for energy wood supply (Korobov at al. 1991);
- lump stems due to improper cutting, skidding or forwarding, loading into truck, and tops of logs before transporting to central processing yard. This is equal to about 5% of felled stem volume.

Non-industrial round wood means round wood not suitable for forest industries because of its quality, size or tree species. It is also often regarded as round wood of firewood quality. An average output of non-industrial round wood from the annual felling of different tree species in the Leningrad region according to Anuchin (1981) of the felled stem volume is for:

- spruce 15-25%
- pine 14-24%
- birch 46-74%
- aspen 56–78%

Characteristics and volumes of *energy wood* depend on:

- Stand composition (species, age, quality)
- Logging method (determined on the form in which wood is delivered from the forest to the road, for instance tree-length method[1], full tree method[2], Nordic cut-to-length method[3]) and logging system (a set of tools, equipment, machines and personnel involved in logging) (Pulkki 2006). In the case of the cut-to-length method all logging residues and non-industrial round wood are left in the cutting areas. In the case of tree-length and full tree methods, logging residues and non-industrial wood is accumulated at central processing yards of logging companies.
- Type of felling (final, thinning).

An amount of energy wood collected from logging operations at cutting areas was estimated by the calculation method shown in Equations 1-5 using annual statistics from the Ministry of Natural Resources for forest resources utilisation in the Leningrad region.

The total annual wood energy production (over bark, o.b.), including non-industrial round wood and logging residues not used for strip-road improvement, in a forest can be calculated as

$$THR = THRf_{TLM} + THRf_{CTL} + THRth, \qquad (1)$$

where

THR – annual energy wood volume from logging, m^3/year

$THRf_{TLM}$ – annual energy wood volume from final fellings by the tree length method, m^3/year

$THRf_{CTL}$– annual energy wood volume from final fellings by the cut-to-length method, m^3/year

THRth – annual energy wood volume from thinnings, m^3/year

For logging by the cut-to-length method, final felling

$$THRf_{CTL} = THVf*(1+BYf) – IRWVf, \qquad (2)$$

[1] Trees are felled (with chain saw or feller), bunched and skidded to the road side/loading site (known also as the upper landing) for transportation to a central processing yard (known also as the lower landing). Debranching is done either manually at the logging site or with a delimbing machine on the loading site, stems are cross-cut into timber assortments at the central processing yard

[2] Trees are felled (with chain saw or feller), but not debranched. Trees can be cut into shorter sections for forwarding, storing/chipping and transportation. Branches, needles and tops are included in harvested biomass.

[3] Trees are felled, debranched and cross-cut into timber assortments (with chain saw or harvester) at the stump and transported to the loading site with a forwarder. In Russia, this can refer also to a system where cross-cutting takes place at the loading site where stems are skidded, as in the tree-length method.

where

THVf – annual timber harvesting volume by final felling, m^3/year
IRWVf – industrial round wood volume by final felling, m^3/year
BYf – expansion factor for branches and tops from final felling, value 0-1.

For logging by the tree-length method, final felling

$$THRf_{TLM} = THVf*(LSf + BYf), \quad (3)$$

where

LSf – expansion factor for including lump stems and tops from final felling.

For logging by thinning operations (usually cut-to-length method is applied),

$$THRth = THVth*(1+BYth) – IRWVth, \quad (4)$$

where

THVth – annual timber harvesting volume by thinnings, m^3/year
IRWVth – industrial round wood volume by thinnings, m^3/year
BYth – expansion factor for including branches and tops from thinnings.

2.2.2 Cross-cutting at central processing yards

An estimation of wood residues collected from cross-cutting at central processing yards was arrived at by using the calculation method shown in Equation (5):

$$CPY = (THVf *(1- LSf) – IRWV f)*(1+ MCY), \quad (5)$$

where

CPY – annual wood residues and non-industrial round wood volume from cross-cutting at central processing yards, m^3/year
MCY – expansion factor for including lump stems and tops from cross-cutting at central processing yards.

The general data on CPY for the Leningrad region can be obtained from logging companies statistics or an assumption that it equals 2-3% of the felled stem volume over bark (Korobov at al. 1991).

2.2.3 Mechanical wood processing

An estimation of wood residues collected from sawmilling was arrived at by using the calculation method shown in Equation (6):

$$SMR = SMV * SMY, \quad (6)$$

where

SMR – annual wood residues volume from sawmilling, m^3/year o. b.
SMV – annual sawn timber production, m^3/year
SMY – expansion factor for the inclusion of wood residues from sawmilling operations

The data on SMV for the Leningrad region were obtained from the annual statistics of the State Statistical Committee of the Leningrad region (Goskomstat 2006). The data for the SMY were obtained from sawmilling norms and Russian round wood standards, varying from 0.5 to 0.6 (Rukovodiaschie tekhniko-economicheskie materialy 1991, OST 13-43-79).

2.3 Estimated energy wood resources

The estimated annual potential for energy wood production from logging operations is 3.5 million m^3 o. b. (equal to 7.0 GWh, assuming 50 % moisture content), based on 7.9 million m^3 o. b. actual cut in 2004 (Scenario *"Actual"* in Table 1). About 2.3 million m^3 is non-industrial round wood and felling residues in the cutting areas, and 1.2 million m^3 derives from the central processing yards. Wood residues from sawmilling based on 2004 production data were 0.6 million m^3, representing approximately 14% of the total amount of energy wood resources of 4.1 million m^3 in 2004. Characteristics of energy wood used in the calculations are presented in Appendix 1. Only wood residues from large and medium size enterprises (average number of employees more than 100) are considered in this estimate.

Two other scenarios have been calculated to describe how much energy wood could be available if certain measures would be implemented in the Leningrad region. The amount of energy wood available from logging and sawmilling could be as high as 6.3 million m^3 if the entire annual allowable cut would be utilised (Scenario *"Allowable"*), and about 9.2 million m^3 if thinnings would also be done in full scale (Scenario *"Potential"*), i.e. 54% and 124% more than the actual amounts in 2004, if collected. In practice the Scenario *Allowable* would mean that the annually harvested stem wood volume in the final felling would increase from the 2004 level of 5.1 million m^3 to 9.5 million m^3. Additionally, in the Scenario *Potential* thinnings would increase from the 2004 level of 1.5 million m^3 to 4.6 million m^3.

Table 1. Techically available energy wood potential in the Leningrad region (over bark).

Source	Scenario for energy wood resources					
	Actual[1)]		Allowable[2)]		Potential[3)]	
	million solid m^3	TWh	million solid m^3	TWh	million solid m^3	TWh
Timber harvesting	3.5	7.0	5.3	10.6	7.2	14.4
- at cutting areas	2.3	4.6	3.3	6.6	7.2	14.4
- at central processing yards	1.2	2.4	2.0	4.0	-	-
Sawmilling	0.6	1.2	1.0	2.0	2.0	4.0
Total energy wood	4.1	8.1	6.3	12.6	9.2	18.4

[1)] based on actual fellings (5.1 mill. m^3 final felling, 1.5 mill. m^3 thinning, 1.3 mill. m^3 other felling), and and sawmill production (0.6 mill. m^3 sawn wood)

[2)] based on full utilisation of annual allowable cut (9.5 mill. m^3 final felling, 1.5 mill. m^3 thinning and 1.3 mill. m^3 other felling), and sawmill production (1 mill. m^3 sawn wood)

[3)] based on also full utilisation of thinnings (9.5 mill. m^3 final felling, 4.6 mill. m^3 mill. m^3 thinning and 1.3 mill. m^3 other felling), and sawmill production (2 mill. m^3 sawn wood)

The amount of forest resources and their utilisation vary considerably within the Leningrad region. Utilisation levels of forest resources are highest in the western leskhozes[3] (Figure 1). In 2004, 66% of the energy wood from logging (2.3 million solid m^3) would have been available in the cutting areas and 34% (1.2 million solid m^3) in the central processing yards. Distribution of energy wood between cutting areas and central processing yards in western leskhozes (Severo-Zapadny, Rozhinsky) and eastern leskhozes (Tikhvinsky, Shugozersky) is different. The reason for this is the larger share of thinning operations in the Karelian Isthmus and near Saint-Petersburg city, compared to other parts of the region.

The distribution of energy wood from logging according to tree species (deciduous - birch and aspen; coniferous - pine and spruce) is presented in Figure 2. In total, 65% (2.3 million solid m^3) of the entire energy wood is deciduous and 35% (1.2 million solid m^3) is coniferous. However, the proportion between species differs among leskhozes. There is a larger share of conifers in the northern and eastern leskhozes (Severo-Zapadny, Tikhvinsky, Podporozhsky, Vinnitsky and Lodejnopolsky).

Figure 3 shows the accumulation of wood residues from sawmilling in large and medium size enterprises in the Leningrad region (Goskomstat of Leningrad region 2006). Most of the sawmilling capacity is concentrated among a few administrative districts with a well developed sawmill industry, such as Tikhvinsky, Priozorsky and Podporozhsky.

The amount of energy wood from loggings according to the three scenarios described earlier are also presented by leskhozes in Table 2. Due to past and current forest use, the structure of forest resources and thus possibilities to increase the use of forest resources vary between leskhozes. In the North-Western leskhozes (Severo-Zapadny, Priozersky, Rozhinsky, Sosnovsky and Lomonovsky) the annual allowable cut is already to a large extent in use and Scenario *Allowable* would not provide much more energy wood to enter the market. In the whole region, Scenario *Allowable* would provide nearly 2 million m^3 and Scenario *Potential* nearly 4 million m^3 of more energy wood annually to the market compared to the amount based on felling levels in 2004. It should be noted that these estimates are theoretical ones, and they could be even higher as the way in which increment and thus annual allowable cut is defined in Russia tends to underestimate current increment and sustainable logging possibilities. The amount energy wood available in the market depends entirely on the market situation, i.e. supply and demand, which is influenced by the price of energy wood and competing energy sources.

[3] Leskhoz – a primary forest management unit of the Russian forest administration

Table 2. Annual energy wood production according to three scenarios by leskhozes in the Leningrad region.

Name	1000 solid m^3 o. b. per year (increase to Scenario Actual, %)		
	Scenario Actual	Scenario Allowable	Scenario Potential
Boksitogorsky	166	251	333
Efimovsky	98	141	230
Gatchinsky	62	78	109
Kingiseppesky	92	114	123
Kirishsky	97	255	403
Kirovsky	94	126	180
Lisinsky	44	89	105
Lodejnopolsky	126	174	239
Lomonosovsky	74	77	77
Lubansky	132	222	325
Luzhsky	103	220	341
Ojatsky	53	83	128
Pashsky	29	65	100
Podborovsky	84	147	208
Podporozhsky	128	211	359
Priozersky	63	70	70
Rozhinsky	157	154	154
Severo-Zapadny	226	219	219
Shugozersky	126	259	443
Siversky Les	39	50	52
Slantsevsky	61	85	109
Sosnovsky	52	48	48
Tikhvinsky	148	203	271
Vinnitsky	62	145	232
Volkhovsky	110	190	300
Volovsky	175	228	295
Voznesensky	54	104	166
Vyritsky	71	132	171
Agricultural leskhozes	613	1031	1197
Other leskhozes	134	169	185
Total	3472	5344(+54%)	7174(+106%)

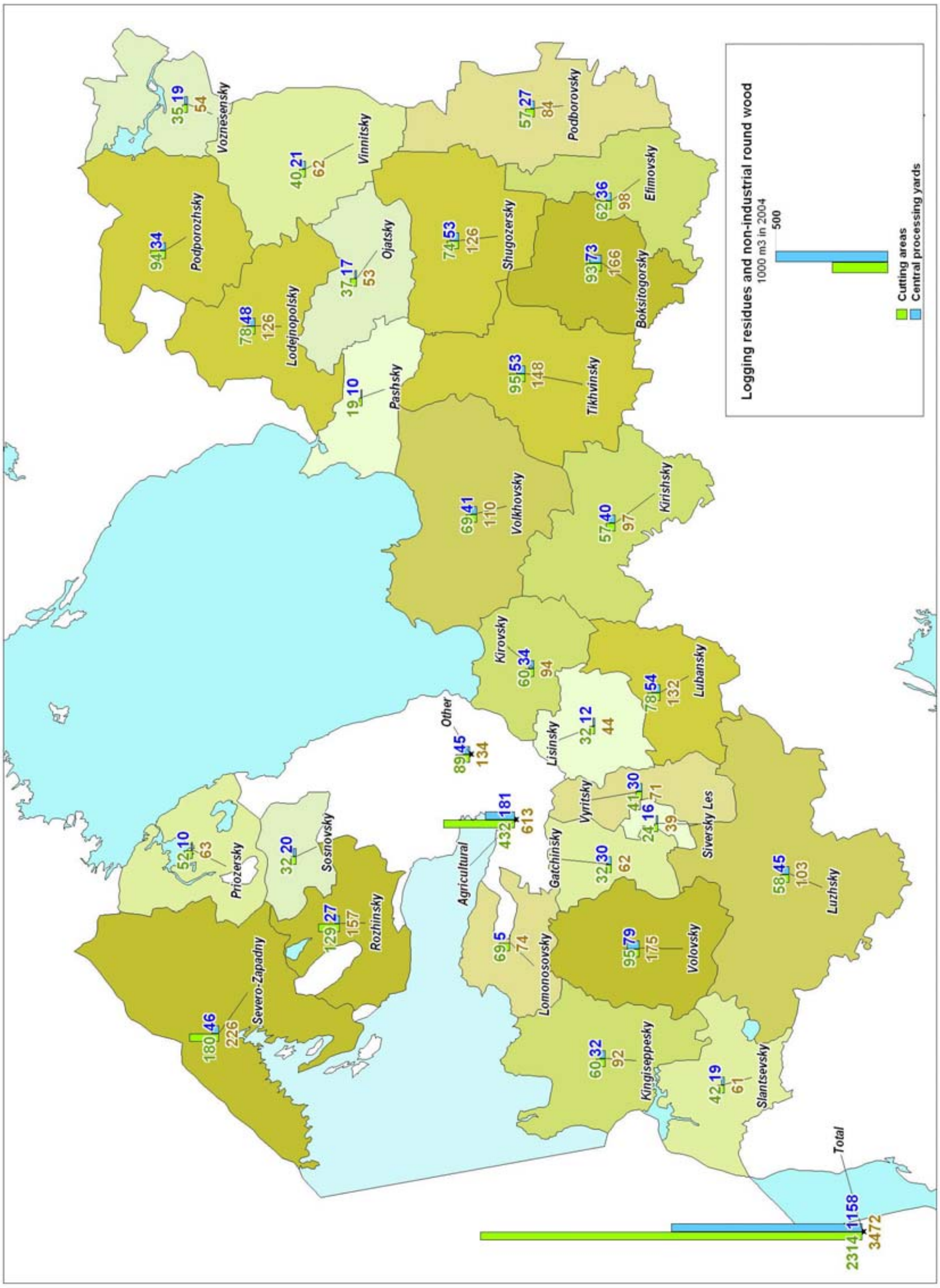

Figure 1. Accumulation of energy wood from logging according to leskhozes based on the cut in 2004 (Scenario *Actual*).

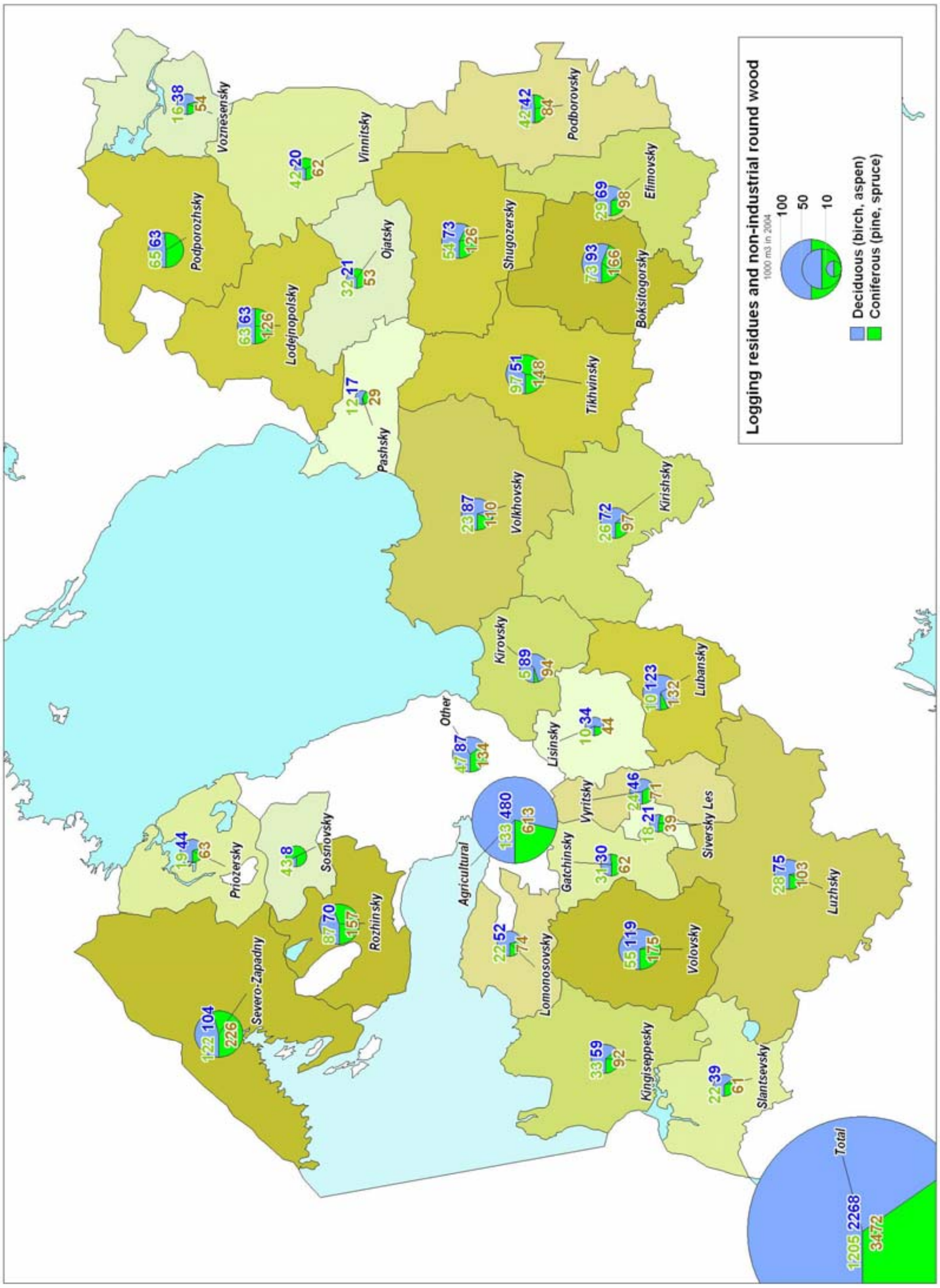

Figure 2. Accumulation of energy wood from logging according to species in leskhozes based on the cut in 2004 (Scenario *Actual*).

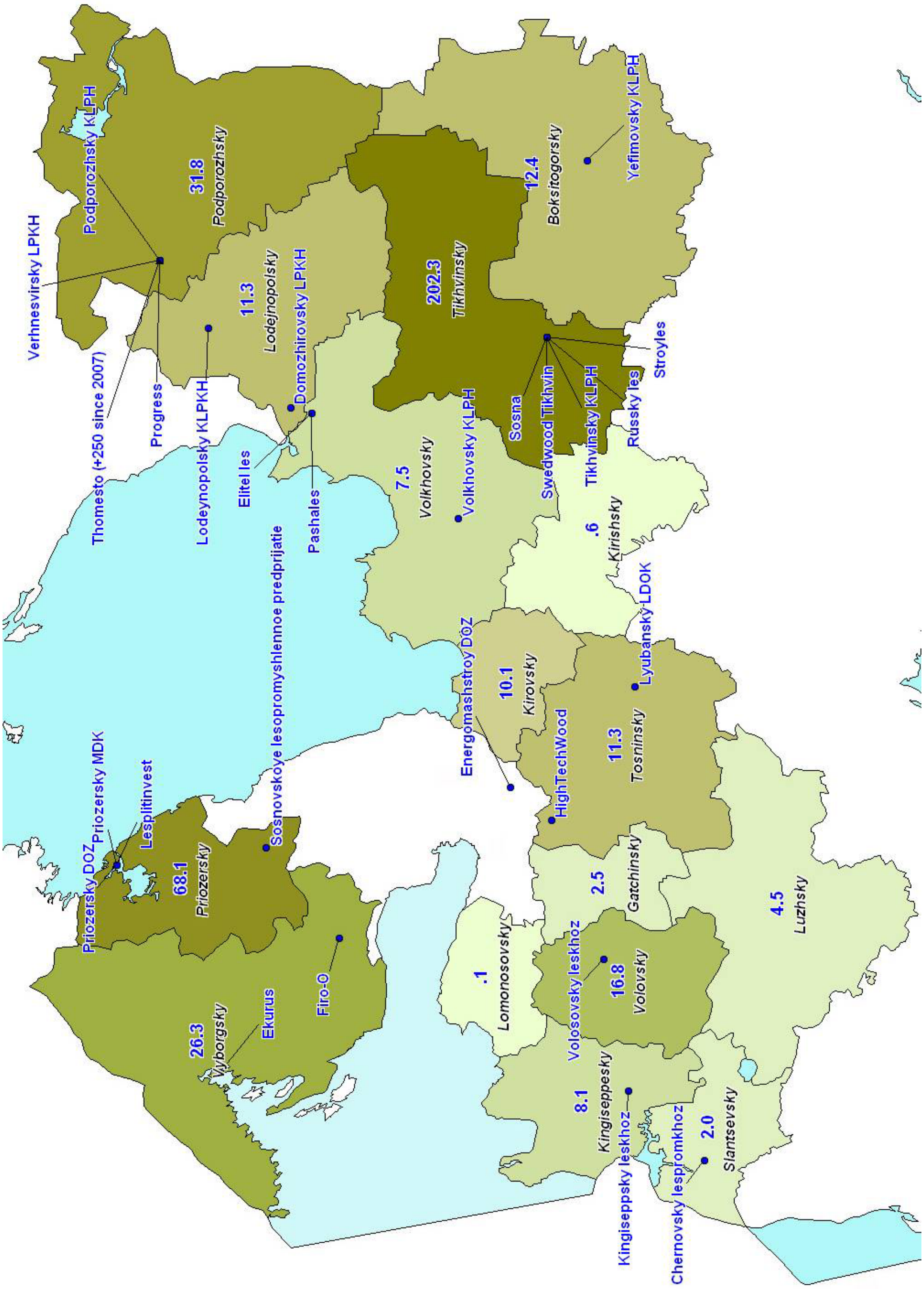

Figure 3. Distribution of energy wood from sawmilling according to administrative districts in 2004.

3 Energy wood supply costs

3.1 Overview of energy wood supply operations

The following energy wood sources were taken into account:

- biomass from thinning operations:
  - pre-commercial thinnings;
  - commercial thinnings (first and second);
- residues at final felling areas
- cross-cutting residues at central processing yards
- collection of wood biomass after sawmilling residues.

Supply costs include stumpage, felling, delimbing, bucking, forwarding, chipping, transportation and other costs. They are influenced by a number of factors including terrain, fuel loading, treatment prescription, contracting mechanism, equipment used, the average size of trees being removed and local market conditions for timber, and others. According to available information, there have not been any detailed studies carried out on the costs of the whole chain of forest operations in the Leningrad region.

The following energy wood harvesting methods were taken into account:

- Cut-to-length method (CTL)
- Tree-length (TL)
- Full tree method (FT)
- Chipping method (CHIP)

The following wood harvesting systems were taken into account:

- Chain-saw + forwarder + chipper at roadside + chip truck (CTL)
- Harvester + forwarder + chipper at roadside + chip truck (CTL)
- Chain-saw + forwarder + log truck + chipper at power plant (CTL)
- Harvester + forwarder + log truck + chipper at power plant (CTL)
- Energy wood harvester (harvester with an accumulating head) + forwarder + log truck + chipper at power plant (FT)
- Energy wood harwarder + chipper at roadside + chip truck (FT)
- Energy wood combi-machine (chipper at stand) + chip truck (CHIP)
- Chain-saw + skidder + chipper at roadside + chip truck (TL)
- Chain-saw + skidder + tree-length truck + chipper at power plant (TL)

3.2 Characteristics of cutting areas

The costs of wood chips production in many aspects depend on the concentration of the biomass volume at the cutting areas. This is determined by growing stock, species composition, age structure of stands and other factors. Stand characteristics of thinning and final felling plots were determined for the cost calculation according to average species composition, standing stock and felled volume in the region (Fomchenkov et al 2003). The thinning areas are described in Table 3.

The growing stock of the stands presented in Table 3 allows thinning at relatively high intensity. This means a bigger output of wood from the forest area, decreasing costs per 1 m^3 (higher productivity) and, as a result, effective utilisation of resources. However, the output of industrial wood is low and only half of the wood from thinnings has potential value for the forest industry.

To increase profitability of thinnings it is necessary to process non-industrial wood to a product, which has a market value, and to decrease costs.

Table 3. Characteristics of the thinning areas, volume of wood felled is over bark.

Species	Share, %	Stock, m^3/ha	Felling of stem wood, m^3/ha	Percent of removal	Stock after felling, m^3/ha
Pre-commercial thinning at age 30, felling area 6 ha, thinning intensity* 40 % of stock					
Spruce	52	44	4	12	40
Pine	40	34	25	73	9
Birch	6	5	2	6	3
Aspen	2	3	3	9	0
Total	100	86	34	100	52
1st commercial thinning at age 50, felling area 6 ha, thinning intensity* 35%					
Pine	47	78	10	17	68
Spruce	20	34	5	9	29
Birch	32	53	40	69	13
Aspen	2	3	3	5	0
Total	100	167	58	100	109
2nd commercial thinning at age 70, felling area 6 ha, thinning intensity* 35 %					
Pine	41	91	12	15	79
Spruce	34	75	10	13	65
Birch	22	49	49	63	0
Aspen	3	7	7	9	0
Total	100	222	78	100	144

* - Nastovleniay po rybkam uhoda…1994, no thinnings before

Anan’ev et al. (2005) reports that an average size of a thinning area in the Northwest Region of Russia is about 7 ha, but in the Leningrad region it is smaller. Therefore, we have assumed 6 ha as an average size of a thinning area. Moreover, we assumed that all the harvested wood from pre-commercial thinnings would be chipped due to the large share of birch and aspen wood in the output from pre-commercial thinnings and the low demand for small size wood in the region. The full tree harvesting method and the chipping method are applied due to the fact that debranching decreases the volume of wood for chipping as all the branches and tree-tops are left at cutting areas. Losses of biomass can amount up to 40-45 % of felled volume.

Table 4 shows the volume of biomass available for chipping after thinning operations in first and second thinnings and using full tree and tree length or cut-to-length methods.

A description of the average final cutting area and collectable volume of biomass for chipping is presented in Table 5. The average size of final felling areas in the calculations was 6 ha.

In all cases, it was assumed that about 70% of the logging residues can be collected for energy while the rest of the branches, tops and needles are scattered around the cutting area (Hakkila 2004) and all industrial wood was sold.

Table 4. The available volume of biomass for wood chips production in first and second thinnings.

Species	Volume of felled stem wood, m³/ha	Ratio of crown volume to volume of stem wood, %*	Volume of crowns, m³/ha	Volume of wood for chipping, m³/ha	
				Full tree	Tree length
The 1st commercial thinning, age 50, thinning intensity – 35%					
Pine	10.0	24	2.4	12.4	10.0
Spruce	5.0	46	2.3	7.3	5.0
Birch	40.0	10	4.0	44.0	40.0
Aspen	3.0	14	0.4	3.4	3.0
Total	58.0		9.1	67.1	58.0
The 2nd commercial thinning, age 70, thinning intensity – 35 %					
Pine	12.0	15	1.8	13.8	12.0
Spruce	10.0	42	4.3	14.3	10.0
Birch	49.0	12	5.9	54.9	49.0
Aspen	7.0	15	1.1	8.1	7.0
Total	78.0		13.1	91.1	78.0

* - Usol'tsev 2001

Table 5. Characteristics of final felling plots and available volume of biomass for chipping

Species	Stem volume, m³/ha	Ratio of crown volume to volume of felled wood, %*	Volume of crowns, m³/ha	Total removal of biomass, m³/ha	Industrial wood, m³/ha		Biomass for chipping, m³/ha	
					%*	m³/ha	Total	Collectable
Spruce	80	21	16.8	96.8	70	56.0	40.8	28.6
Pine	65	9	5.9	70.9	70	45.5	25.4	17.8
Birch	68	9	6.1	74.1	60	40.8	33.3	23.3
Aspen	49	15	7.4	56.4	40	19.6	36.8	25.8
Total	262		36.2	298.2		161.9	136.3	95.4

* - Usol'tsev 2001;
** - Bit and Vavilov 2001

3.3 Machinery for energy wood harvesting

There are a large number of machines designed in different countries for the supply of energy wood. The best known machines in the world are produced in the Nordic countries – in Finland and Sweden. Nowadays, in Russia, several companies have begun to produce machines for the cut-to-length method together with equipment for traditional Russian felling technology – the tree-length method. In Russia, domestic equipment for this method is widely used due to their lower investment costs compared to the costs of harvesters and forwarders.

Examples of machines suitable for energy wood supply are presented below with some key characteristics.

Approximate weight……………………….14850 kg
Minimum width………………………...2650 mm
Transport height, trailer position……..36000 mm
Engine power……………………………140 kW
Torque………………………………...740 Nm
Reach distance of the crane with head……..11 m
Cutting diameter………………………...480 mm

Figure 5. Harvester Valmet 901.3 (Valmet 901.3 2005)

Approximate weight…………………...13900 kg
Minimum width………………………..2840 mm
Height…………………………………3750 mm
Engine power…………………………...129 kW
Torque…………………………………675 Nm
Reach distance of the crane……………..10.1 m

Figure 6. Harvester Ponsse Beaver (www.ponsse.com)

Approximate weight........................16500 kg
Minimum width………….…………..2670 mm
Engine power……………..………...180 kW
Carrying capacity………………......14 000 kg
Cutting diameter…………………..520 mm

Figure 7. Harwarder BuffaloDual (www.ponsse.com)

Forest equipment of a lightweight class is usually used for thinnings. The utilisation of a harvester or harwarder equipped with an accumulating head (*energy wood harvester or harwarder*) increases productivity and allows chipping of all felled biomass, as it is easy to collect and to forward the harvested wood together with branches and treetops. Figure 8 shows an accumulating harvesting head at work.

Figure 8. Ponsse accumulating harvesting head at work. (Ponsse EH 25 energy wood harvesting head)

Approximate weight…………………..10500 kg
Minimum width……………………….2600 mm
Height………………………………...3526 mm
Engine power…………………………..132 kW
Reach distance of the crane………………9.3 m
Maximal load…………………………..9000 kg

Figure 9. Forwarder Valmet 830.1 (Valmet 830.1 2005)

Approximate weight ………………...11900 kg
Minimum width……………………...2520 mm
Transport height…………………….3526 mm
Engine power…………………………129 kW
Reach distance of the crane……………...10 m
Maximal load………………………..10000 kg

Figure 10. Forwarder Ponsse Gazelle (www.ponsse.com)

Approximate weight…………..……..17500 kg
Minimum width……………..……......…2720 mm
Height……………………………….3700 mm
Engine power……………………...….109 kW
Reach distance of the crane…………..……7.1 m
Maximal load……….………..............14000 kg

Figure 11. Russian forwarder SHLK6-44 (www.otz.ru)

Engine power……….........................….368 kW
Torque…………………………………2400Nm

Figure 12. Log truck Scania 500 GB6x4HNA (Photo: Vadim Goltsev)

Approximate weight……………………9800 kg
Engine power…………………………..465 kW
Torque…………………………………2780Nm

Figure 13. Log truck Sisu E18M (Sisu Forest)

Approximate weight…………………..9800 kg
Engine power…………………………194 kW
Reach distance of the crane…………….7.8 m
Maximal load………………………..13200 kg

Figure 14. Russian log truck KAMAZ-53228 (www.riat.ru)

The most common machines that are widely used in Russia for the manual tree-length method are presented in Figures 15a and 15b.

Approximate weight……………….……11200 kg
Width…………………………………2575 mm
Height………………………………...3000 mm
Engine power...120 kW
Maximal load……………………………..10 m^3

Figure 15a. Russian cable skidder TLT-100A (www.otz.ru)

Approximate weight…......…12740 kg
Engine power…………....….176 kW
Torque……….……………..883 Nm
Maximal load…….….........15300 kg

Figure 15b. Russian tree-length truck Ural 5960-10-01 (www.techno-trading.ru)

Equipment for the collection of loose logging residues, baling, chipping and transportation of chips are presented in Figures 16-18. Loose logging residues can be packed into bundles (residue logs) with a machine such as that in Figure 16 in order to increase bulk density before transportation to the use facility. It allows utilisation of standard log trucks instead of expensive biomass trucks for long distance transportation of logging residues.

Approximate weight……….………8400 kg
Width…………….......................…2120 mm
Height…………...……………..…2135 mm
Productivity……………….15-20 bundles/h

Figure 16. Residue baler Valmet WoodPac (Valmet WoodPac)

Total weight (without loader)……..8050 kg
Total length………….……..…5530 mm
Width…………………………..2350 mm
Width of feed orifice……….…..……600 m
Height of feed orifice……………...450 mm
Drum diameter…………………….570 mm
*Number of kni*ves…………………….6 pcs
Productivity………150 loose m^3/h of chips

Figure 17. Chipper Kesla C 4560 LF (Drum Chippers 2005)

Approximate weight……………….9800 kg
Engine power……………………...721 kW
Paying load………………………...140 m^3

Figure 18. Chips truck Scania R144 GB6x2 530 (Photo: Scania Image Bank, Ingemar Eriksson)

3.4 The costs of energy wood supply

3.4.1 Thinnings

Tables 6-8 provide an estimation of the average costs of wood chips production from the pre-, 1st and 2nd commercial thinnings. It should be noted that costs for each of the stages also include the costs of management, which is not presented separately here. Marketing costs are excluded from the calculations, because information on that is not available.

In the case of pre-commercial thinning (Table 6) and when the transportation distance from the stand is 50 km to the plant, the share of felling of the total cost is, in the case of manual felling, approximately 30%, while when using an energy wood harvester approximately 50% and when using an energy wood harwarder approximately 70%. Forwarding is approximately 35% of the total cost when using manual felling and approximately 20% when using an energy wood harvester, which is also the difference in the cost of felling when using an energy wood harvester or harwarder (in the latter case forwarding was included in the felling cost as the same machine was used for both operations). When chipping is at the power plant, it represents approximately 5% of the total cost, while chipping at the roadside seems to be approximately 20% of the total cost with a transportation distance of 50 km. With the same transportation distance, the share of transportation is 20-30% of the total cost. Manual felling seemed to provide the lowest total cost for wood chips supply.

Table 6. The costs of wood chips supply from pre-commercial thinning (average stem volume 0.022 m^3).

Inputs	Distance from the stand to the plant, km				
	0	20	50	100	150
	Cost, €/m³				
Energy wood harvester + Forwarder + Log truck + End facility chipping					
Felling and bunching	11.2	11.2	11.2	11.2	11.2
Forwarding	4.3	4.3	4.3	4.3	4.3
Transportation		3.4	5.4	9.5	12.5
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	16.6	20.0	22.0	26.1	29.1
Energy wood harwarder + Log truck + End facility chipping					
Felling, bunching and forwarding	17.5	17.5	17.5	17.5	17.5
Transportation		3.4	5.4	9.5	12.5
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	18.6	22.0	24.0	28.1	31.1
Chain-saw + Forwarder + Log truck + End facility chipping					
Felling and bunching	5.4	5.4	5.4	5.4	5.4
Forwarding	6.7	6.7	6.7	6.7	6.7
Transportation		3.4	5.4	9.5	12.5
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	13.2	16.6	18.6	22.7	25.7
Energy wood harvester + Forwarder + Chipper at the roadside + Chip truck					
Felling and bunching	11.2	11.2	11.2	11.2	11.2
Forwarding	4.3	4.3	4.3	4.3	4.3
Chipping at the roadside	4.6	4.6	4.6	4.6	4.6
Transportation of chips		2.7	4.0	5.7	7.2
Total cost	20.1	22.8	24.1	25.8	27.3
Energy wood harwarder + Chipper at the roadside + Chip truck					
Felling, bunching and forwarding	17.5	17.5	17.5	17.5	17.5
Chipping at the roadside	4.6	4.6	4.6	4.6	4.6
Transportation of chips		2.7	4.0	5.7	7.2
Total cost	22.1	24.8	26.1	27.8	29.3
Chain-saw + Forwarder + Chipper at the roadside + Chip truck					
Felling	5.4	5.4	5.4	5.4	5.4
Forwarding	6.7	6.7	6.7	6.7	6.7
Chipping at the roadside	4.6	4.6	4.6	4.6	4.6
Transportation of chips		2.7	4.0	5.7	7.2
Total cost	16.7	19.4	20.7	22.4	23.9

Figures 19 and 20 show how the costs of wood chips supply from pre-commercial thinning depend on the applied energy wood harvesting system and on the transportation distance. The total costs for wood chips were compared to an average price for wood chips in the Leningrad region to estimate the economic feasibility of the supply chains. The average price of wood chips (17 €/m^3) is based on the manufacturer's price information on the Internet. The maximum price for wood chips was 21 €/m^3 at a customer yard and the minimum was 12 €/m^3, corresponding with wood fuel prices of between 6 and 10.5 €/MWh.

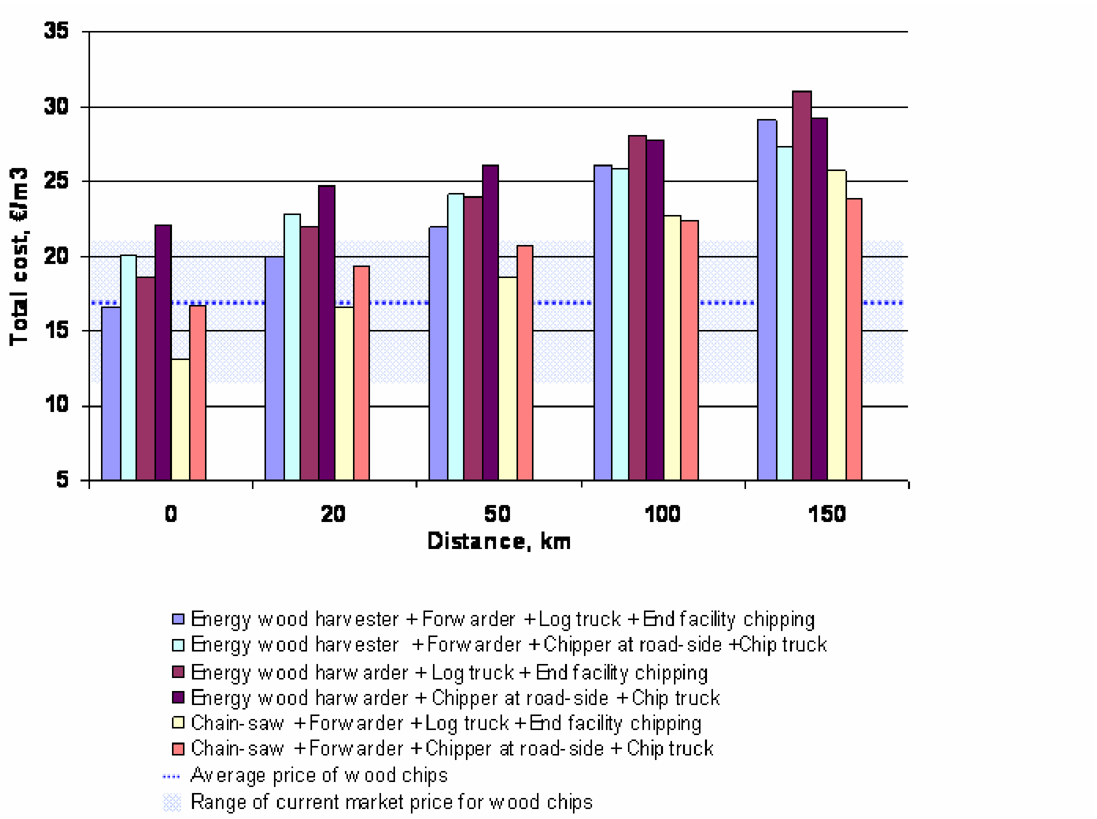

Figure 19. Total cost of wood chips supply from the pre-commercial thinning for different harvesting chains and transportation distance

Figure 19 shows that the total costs of energy wood procurement grows nonlinearly according to transportation distance. It can be explained by an influence of nonlinear growth of transportation costs.

Figure 19 demonstrates that the production of chips from wood from the pre-commercial thinning is not economically feasible, if the price limit for wood chips is set at 17 €/m^3(solid) (8,5 €/MWh). Even the most cost-effective production chain based on a chain-saw and end facility chipping does not allow the supply of wood chips with costs below or equivalent to the assumed market price of 17 €/m^3 if the transportation distance exceeds 20 km. Up to this limit, the system provides competitive energy wood supply costs, also for pre-commercial thinnings. However, the system can not ensure profitability for chips production, due to the small distinction between the full cost and the market price.

Figure 20 demonstrates the cost structure of wood chips supply for different chains for the pre-commercial thinning. For the conditions of the Leningrad region, manual logging and bunching provided 3.4 €/m^3 lower harvesting costs than energy wood harvesters. An energy wood harwarder could not compete with the other chains (Figure 20).

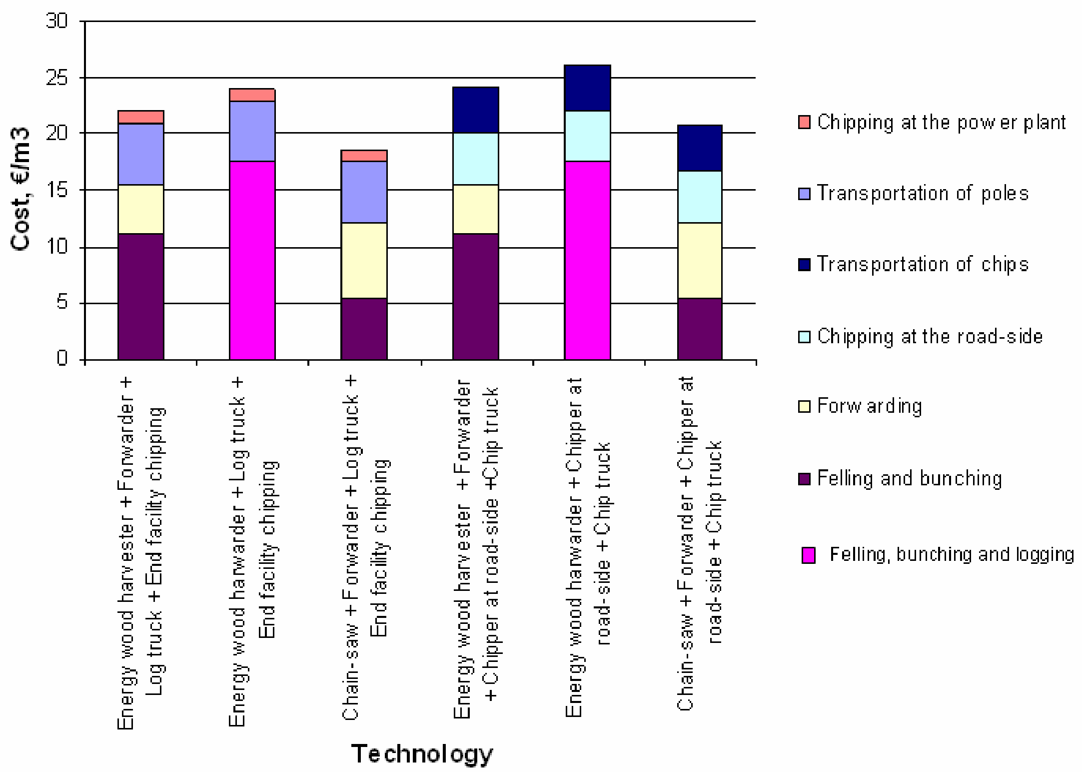

Figure 20. Costs of different chains for wood chips supply from pre-commercial thinning, with a 50 km transportation distance.

In the 1st commercial thinnings, the share of felling of the total cost was 45%, when using a harvester or 37%, when using an energy wood harvester, compared to approximately 30% when manual felling, when transportation distance was 50 km to the plant (Table 7). The share of forwarding/skidding was 30-35% of the total cost when manual felling was used, while in the case of a harvester or energy wood harvester it was approximately 20%. The cost of chipping at the power plant was less than 10% of the total cost while chipping at the road side was about 25% of the total cost.

In the 1st commercial thinnings, all the considered supply chains are economically feasible for the supply of wood chips if the transportation distance does not exceed 50 km (Fig. 21). Chains aimed at end facility chipping are more cost-effective and allow profitable energy wood supply for a distance of up to 100 km. There is no big cost distinction between the chains based on different felling methods, but which utilise the same chipping method. In this case, a choice of felling method and machinery is subject to local conditions. Figure 22 demonstrates the cost structure of wood chip supply for different chains from the 1st commercial thinning.

It was found that for the 1st commercial thinning there is practically no difference in the total costs of wood chips supply based on manual or entirely mechanized felling. Manual felling is cheaper, but lower productivity of the subsequent forwarding neutralises the cost benefit. An energy wood harvester is less feasible economically for the 1st commercial thinning in spite of bigger output of biomass in comparison to chains where the harvester is used. The costs of mobile chipping makes such supply chains less effective (Table 7).

Table 7. The costs of wood chips supply from the 1st commercial thinning (the average volume of a stem is 0.067 m^3 o.b.).

Inputs	Distance from the stand to the plant, km: 0	20	50	100	150
	Cost, €/m^3				
Harvester + Forwarder + Log truck + End facility chipping					
Felling	5.9	5.9	5.9	5.9	5.9
Forwarding	2.9	2.9	2.9	2.9	2.9
Transportation of non-industrial wood		2.0	3.2	5.6	7.4
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	9.9	11.9	13.1	15.5	17.3
Energy wood harvester + Forwarder + Chipper at the roadside + Chip truck					
Felling	5.6	5.6	5.6	5.6	5.6
Forwarding	2.9	2.9	2.9	2.9	2.9
Chipping at the roadside	3.7	3.7	3.7	3.7	3.7
Transportation of chips to consumers		2.0	3.1	5.4	7.1
Total cost	12.2	14.2	15.3	17.6	19.3
Chain-saw + Forwarder + Log truck + End facility chipping					
Felling	4.2	4.2	4.2	4.2	4.2
Forwarding	4.5	4.5	4.5	4.5	4.5
Transportation of wood		2.0	3.2	5.6	7.4
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	9.8	11.8	13.0	15.4	17.2
Chain-saw + Forwarder + Chipper at the roadside + Chip truck					
Felling	4.2	4.2	4.2	4.2	4.2
Forwarding	4.5	4.5	4.5	4.5	4.5
Chipping at roadside storage	3.7	3.7	3.7	3.7	3.7
Transportation of chips to consumers		2.0	3.1	5.4	7.1
Total cost	12.4	14.4	15.5	17.8	19.5
Chain-saw + Skidder + Chipper at the roadside + Chip truck					
Felling	4.2	4.2	4.2	4.2	4.2
Skidding	4.2	4.2	4.2	4.2	4.2
Chipping at the roadside	3.7	3.7	3.7	3.7	3.7
Transportation of chips to consumers		2.0	3.1	5.4	7.1
Total cost	12.1	14.1	15.2	17.5	19.2
Chain-saw + Skidder + Tree-length truck + End facility chipping					
Felling	4.2	4.2	4.2	4.2	4.2
Skidding	4.2	4.2	4.2	4.2	4.2
Transportation of tree lengths		2.8	5.2	8.6	11.4
Chipping	1.1	1.1	1.1	1.1	1.1
Total cost	9.5	12.3	14.7	18.1	20.9

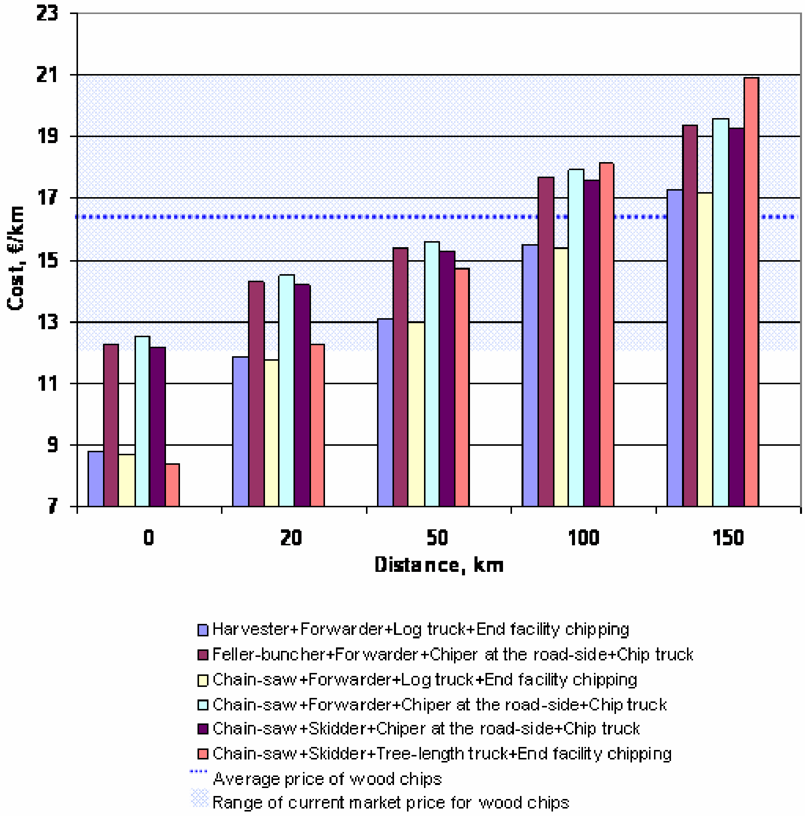

Figure 21. Total costs of wood chips supply from the 1st commercial thinning for different harvesting chains and transportation distances.

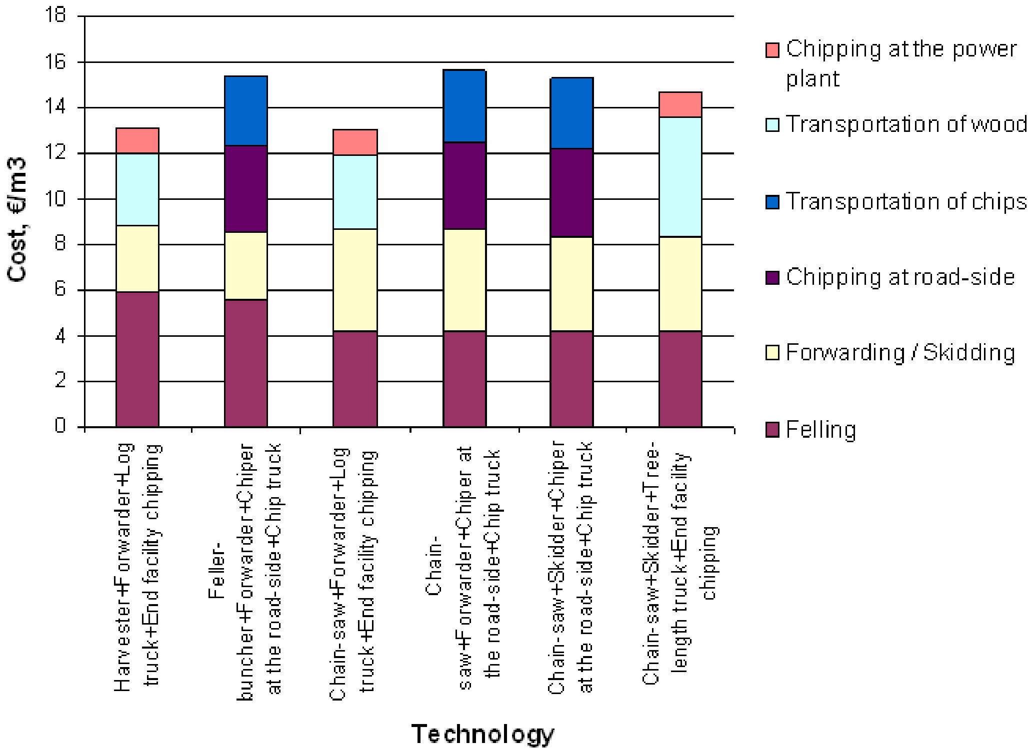

Figure 22. Costs for different chains of wood chip supply from the 1st commercial thinning with a 50 km transportation distance.

Table 8. The costs of wood chips supply from the 2nd commercial thinning (the average volume of a stem is 0.151 m^3 o.b.).

Inputs	Distance from the stand to the plant, km				
	0	20	50	100	150
	Cost, €/m³				
Harvester + Forwarder + Log truck + End facility chipping					
Felling	3.8	3.8	3.8	3.8	3.8
Forwarding	2.3	2.3	2.3	2.3	2.3
Transportation of wood		2.1	3.3	5.4	7.2
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	7.2	9.3	10.5	12.6	14.4
Energy wood harvester + Forwarder + Chipper at the roadside + Chip truck					
Felling	4.2	4.2	4.2	4.2	4.2
Forwarding	2.5	2.5	2.5	2.5	2.5
Chipping at roadside	3.3	3.3	3.3	3.3	3.3
Transportation of chips to consumers		1.8	3.4	5.1	6.5
Total cost	10.0	11.8	13.4	15.1	16.5
Chain-saw + Forwarder + Log truck + End facility chipping					
Felling	3.5	3.5	3.5	3.5	3.5
Forwarding	4.4	4.4	4.4	4.4	4.4
Transportation of wood		2.1	3.3	5.4	7.2
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	9.0	11.1	12.3	14.4	16.2
Chain-saw + Forwarder + Chipper at the roadside + Chip truck					
Felling	3.5	3.5	3.5	3.5	3.5
Forwarding	4.4	4.4	4.4	4.4	4.4
Chipping at roadside	3.3	3.3	3.3	3.3	3.3
Transportation of chips to consumers		1.8	3.4	5.1	6.5
Total cost	11.2	13.0	14.6	16.3	17.7
Chain-saw + Skidder + Chipper at the roadside + Chip truck					
Felling	3.5	3.5	3.5	3.5	3.5
Skidding	4.2	4.2	4.2	4.2	4.2
Chipping at roadside	3.3	3.3	3.3	3.3	3.3
Transportation of chips to consumers		1.8	3.4	5.1	6.5
Total cost	11.0	12.8	14.4	16.1	17.5
Chain-saw + Skidder + Tree-length truck + End facility chipping					
Felling	3.5	3.5	3.5	3.5	3.5
Skidding	4.2	4.2	4.2	4.2	4.2
Transportation of tree-lengths		2.9	5.1	8.2	11.3
Chipping	1.1	1.1	1.1	1.1	1.1
Total cost	8.8	11.7	13.9	17.0	20.1

In the case of the 2nd commercial thinning (Table 8) and with a transportation distance of 50 km to the plant, the share of forwarding of the total cost of the wood chips supply was approximately 20% for chains applying a harvester or energy wood harvester, but for chains applying manual felling it was more, 30-35%. Chipping at the roadside accounted for approximately 25% of the total cost, while chipping at the power plant equalled about 10% of the total cost.

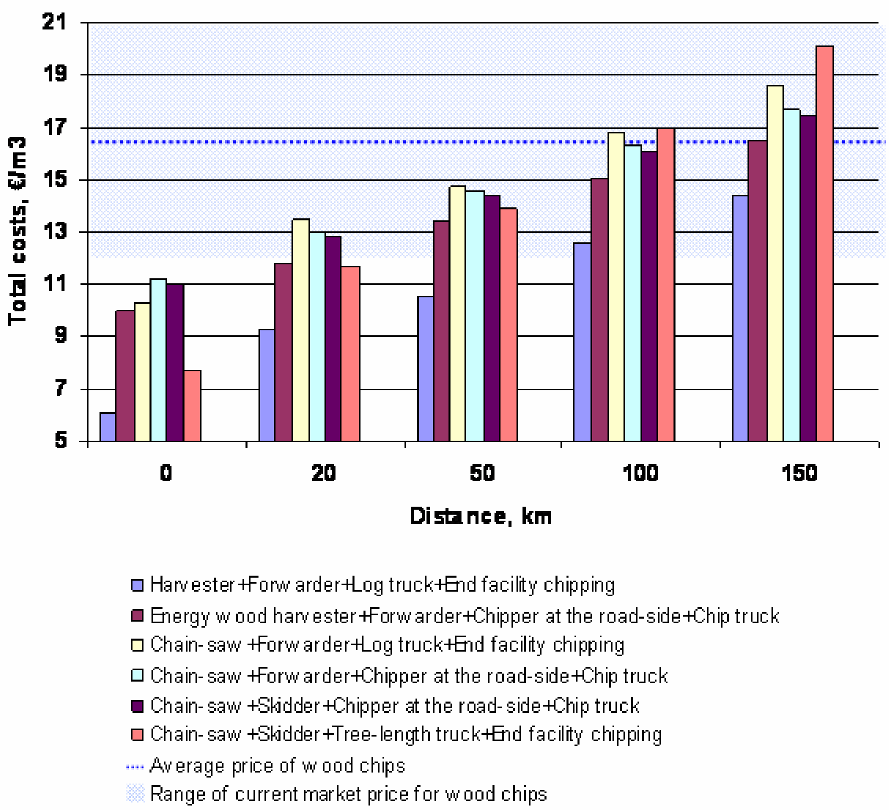

Figure 23. Total cost of wood chips from the 2nd commercial thinning for different harvesting chains and transportation distances.

In case of the 2nd commercial thinning the most economically feasible supply chain consists of a harvester, a forwarder, a log-truck and end facility chipping (Table 8). The reason for this is the comparatively high productivity of all the production stages of this chain. If the transportation distance is not more than 50 km all the systems allow a supply of wood chips with costs below the given market price limit. If the transportation distance is 100 km or more, the cost of chips from few of the supply chains stays below the market price (Figure 23).

The productivity of all the chains for the 2nd commercial thinning is higher than for the 1st commercial thinning due to the bigger average volume of tree stems. Therefore, here inputs for the production of 1 m^3 of wood chips are smaller. The high costs of forwarding after manual felling significantly increase the total costs of wood chips for the chains based on manual felling (Figure 24). This makes such chains less economically feasible. The chain based on manual felling and transportation of tree-lengths became less profitable due to high transportation costs.

Table 9 combines the costs of wood chips production from different harvesting systems and from different types of thinning into one sheet. We can see the significant influence of an applied harvesting system on cutting and forwarding costs, especially in the case of pre-commercial thinning.

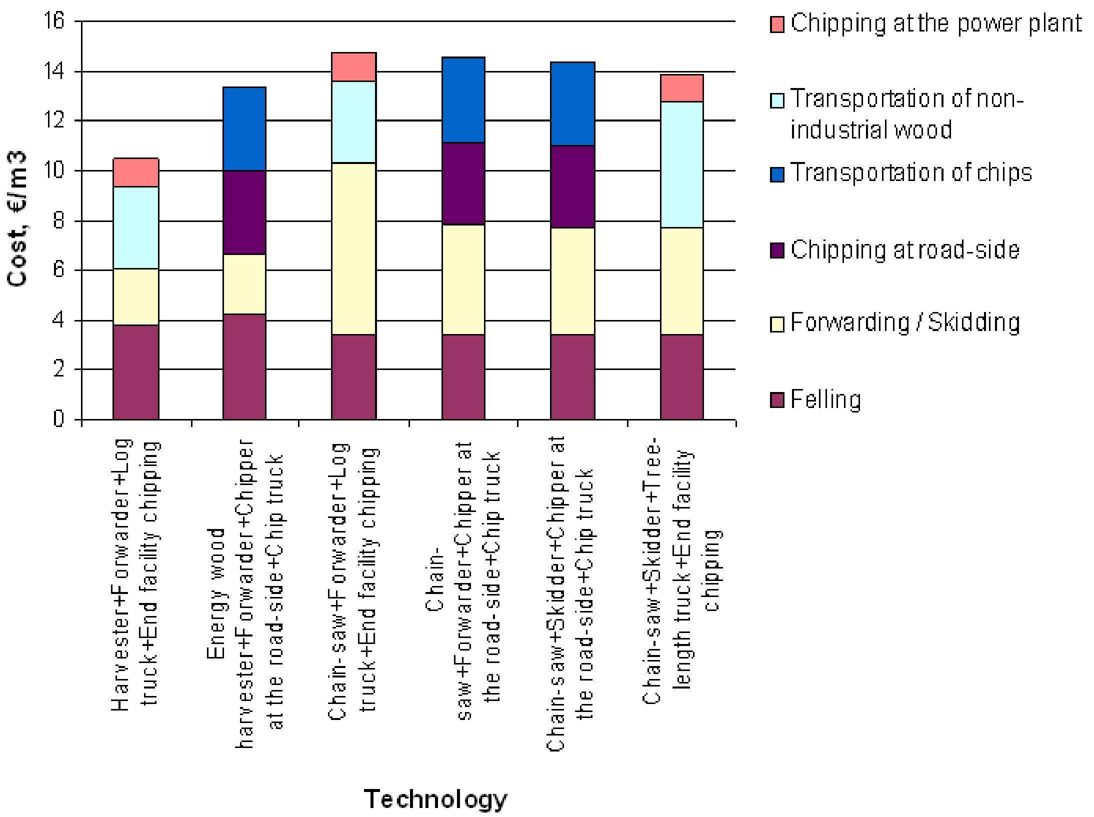

Figure 24. Costs of different chains for wood chip supply from the 2nd commercial thinning with a 50 km transportation distance.

3.4.2 Final fellings

Non-industrial round wood and logging residues after final felling, residues from central processing yards, and wood residues from sawmill yards are resources for chipping that, if there is a market, might cost according to quality, quantity and location. Therefore, it was necessary to determine the possible prices of these resources depending on type and location in order to calculate the costs of wood chips. Prices of wood biomass at final felling areas, at central processing yards and sawmill yards were obtained by phone interviews with 8 companies located in different parts of the Leningrad region (presented in Appendix 4).

The supply of wood chips from biomass after final felling includes the following stages:

- collection of wood biomass, forwarding, chipping and transportation of wood chips or
- collection, forwarding, transportation of energy wood and end facility chipping

The total costs of wood chips from final felling areas consist of purchase price of biomass, cost of forwarding, transportation and chipping. Table 10 shows the costs of wood chips for different chains from the final felling, and shows that there are relatively large differences in the total costs between different chains. The cost of non-industrial wood of 5.9 €/m³ at the stand represents 25-47% of the total cost, and therefore has a strong impact on the results. In instances where non-industrial wood has a lower price (other demand low for it), no price at all (no other demand) or negative price (no demand and logging companies paying penalties when leaving non-industrial wood in the forest), the use of non-industrial wood for energy purposes would be more competitive. In these cases, it would be, however, feasible to include the cost of felling in the total costs of wood chips from non-industrial wood.

Table 9. Costs for wood chips from intermediate felling

System	Cutting costs, €/ m^3			Forwarding costs, €/m^3			Chipping costs, €/m^3				Transportation costs, €/m^3, distance 50 km					
							at roadside			at power plant	of chips			of round wood		
	Pre-	1st	2nd	Pre-	1st	2nd	Pre-	1st	2nd		Pre-	1st	2nd	Pre-	1st	2nd
Chain-saw + forwarder + chipper at roadside + chip truck	5.4	4.2	3.5	6.7	4.5	4.4	4.6	3.7	3.3	no	4.0	3.1	3,4		no	
Chain-saw + forwarder + timber truck + chipper at power plant								no		1.1		no		5.1	3.2	3.3
Energy wood harvester + forwarder + chipper at roadside + chip truck	11.2	5.6	4.2	4.3	2.9	2.5	4.6	3.7	3.3	no	4.0	3.1	3,4		no	
Harvester + forwarder + timber truck + chipper at power plant		5.9	3.8		2.9	2.3		No		1.1		no		5.1	3.2	3.3
Chain-saw + Skidder + Chipper at the roadside + Chip truck	no			no			no	3.7	3.3	no	no	3.1	3,4		no	
Chain-saw + Skidder + Tree-length truck + End facility chipping		4.2	3.5		4.2	4.2		No		1.1		no		no	5.2	5.1

Table 10. Costs of wood chips from the final fellings

Inputs	Distance from the stand to the plant, km				
	0	20	50	100	150
	Cost, €/m³				
Chipper at the stand + Container chips truck					
Purchase price* of biomass**	2.9-5.9	2.9-5.9	2.9-5.9	2.9-5.9	2.9-5.9
Chipping and forwarding cost	10.4	10.4	10.4	10.4	10.4
Transportation of chips		4.0	7.5	13.0	18.0
Total cost	13.3-16.3	17.3-20.3	20.8-23.8	26.3-29.3	31.3-34.3
Forwarder + Chipper at roadside + Chips truck					
Purchase price of biomass*	2.9-5.9	2.9-5.9	2.9-5.9	2.9-5.9	2.9-5.9
Forwarding of biomass*	6.0-2.3	6.0-2.3	6.0-2.3	6.0-2.3	6.0-2.3
Chipping at roadside storage	3.3	3.3	3.3	3.3	3.3
Transportation of chips		1.8	3.4	5.1	6.5
Total cost	11.5-12.2	13.3-14.0	14.9-15.6	16.6-17.3	18.0-18.7
Forwarder + Log truck + End facility chipping					
Cost of non-industrial wood at the stand	5.9	5.9	5.9	5.9	5.9
Forwarding of non-industrial wood	2.3	2.3	2.3	2.3	2.3
Transportation of non-industrial wood		2.1	3.3	5.4	7.2
End facility chipping	1.1	1.1	1.1	1.1	1.1
Total cost	9.3	11.4	12.6	14.7	16.5
Residues baler + Forwarder + Log truck + End facility chipping					
Cost of loose logging residues at the stand	2.9	2.9	2.9	2.9	2.9
Baling	5.8	5.8	5.8	5.8	5.8
Forwarding	2.7	2.7	2.7	2.7	2.7
Transportation of bales		2.3	3.9	6.2	8.4
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	12.5	14.8	16.4	18.7	20.9

* Purchase price of biomass is included in total costs of wood chips in final fellings. The price is based on a survey describing the current price of logging residues and non-industrial wood at the stand in alternative use like domestic firewood and forest road improvement. The price depends of the local demand, and it can be also zero

** loose logging residues or/and non-industrial wood at the stand.

Figure 25 shows the total costs of wood chips depending on the harvesting chain and transportation distance.

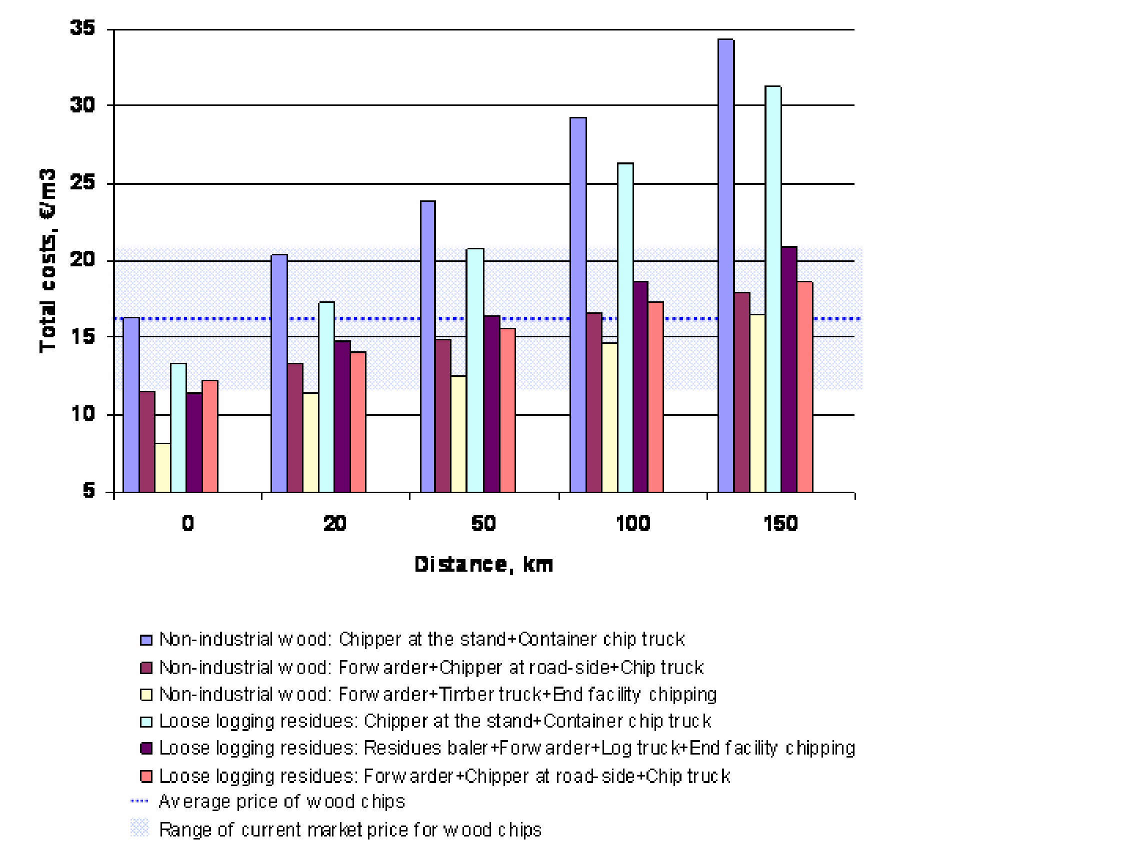

Figure 25. Total costs of wood chips from final fellings for different harvesting chains and transportation distances

Figure 25 shows that there are four supply chains that allow the supply of wood chips with costs less than the average market price if the transportation distance does not exceed 20 km. However, three of them, based on the mobile chipper or on the residue baler, cannot ensure a profit, as the cost of the product is so close to the market price. Only the supply chain consisting of a forwarder, log truck and end facility chipping can be considered as economically feasible if the transportation distance does not exceed 100 km.

Figure 26 presents the costs of different wood chip supply chains for wood collected after final felling.

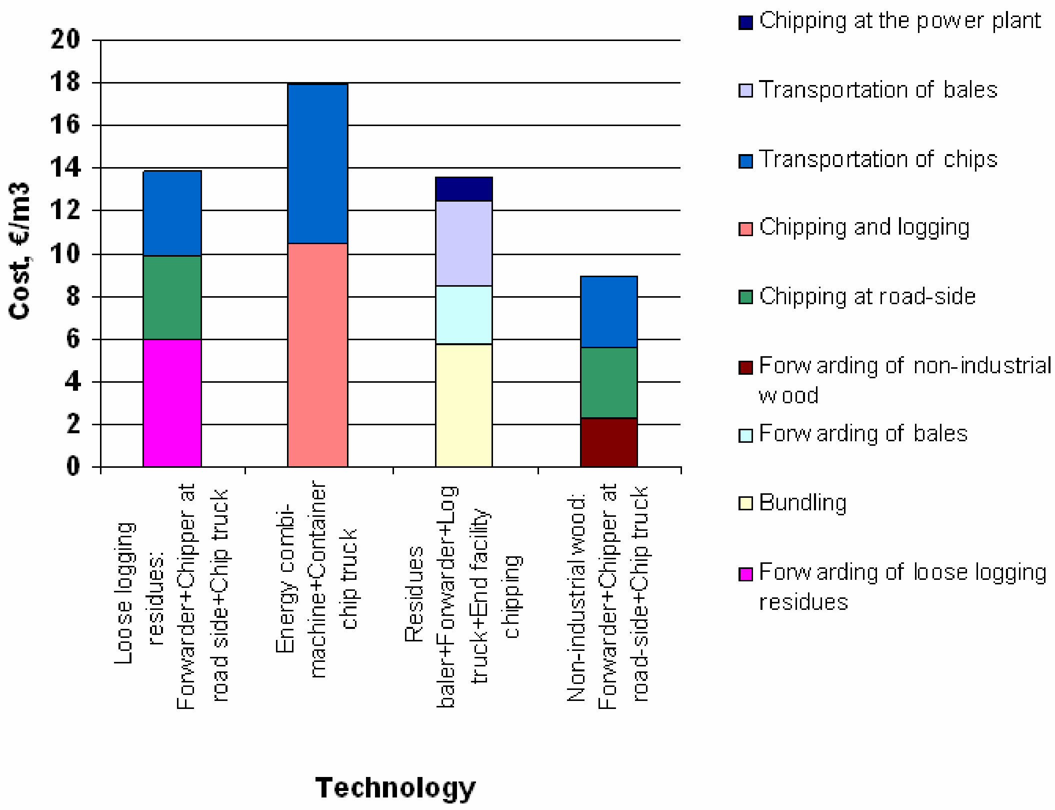

Figure 26. Costs of different chains of wood chip supply after the final felling with a 50 km transportation distance.

As in the case of the pre-commercial thinning, the chain based on the energy combi-machine for conditions of final felling is the least cost-effective chain. The necessity to pay for the resources and comparatively high costs of baling or forwarding of loose logging residues (Figure 26) makes the utilisation of loose logging residues for production of wood chips less profitable. The most feasible resource for wood chips in the case of final felling is non-industrial wood. The situation is different if a wood chips producer implements final felling himself. Utilisation of loose logging residues decreases inputs into the cleaning of cutting areas that has to be done, according to Russian forest legislation (Pravila rubok glavnogo pol'zovaniya…1993), by a logging company.

3.4.3 Central processing and sawmill yards

The production of chips from wood residues at central processing yards and sawmill yards does not demand special equipment for the collection of the resource when self-loading trucks and mobile chippers are used. In this case, there are 2 alternatives for a wood chip supply, based on the following chains: chipping and transportation of chips or transportation of uncomminuted wood biomass and end facility chipping. Utilisation of sawdust for energy production needs only transportation. The costs of loading the sawdust truck are included in the transport costs, but they can also be included in the purchase price of sawdust.

The prices for wood and residues are averages prices (Table 11) based on interviews of 8 companies located in different parts of the Leningrad region (see Appendix 4). When the transportation distance is 50 km to the plant, 30-50% of the cost is due to the purchase price of the material for energy production.

Table 11. Costs of wood chips from wood and process residues collected at central processing yards and sawmill yards.

Inputs	Distance from the plots to the plant, km				
	0	20	50	100	150
	Cost, €/m³				
Lump wood: Chipper + Chips truck					
Purchase price of lump wood	4.4	4.4	4.4	4.4	4.4
Chipping at central processing yards	3.3	3.3	3.3	3.3	3.3
Transportation of chips		1.8	3.4	5.1	6.5
Total	7.7	9.5	11.1	12.8	14.2
Lump wood: Truck + End facility chipping					
Purchase price of lump wood	4.4	4.4	4.4	4.4	4.4
Transportation of lump wood		1.4	2.6	4.1	5.7
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total	5.5	6.9	8.1	9.6	11.2
Sawdust truck					
Purchase price of sawdust	5.2	5.2	5.2	5.2	5.2
Transportation of sawdust		2.4	4.6	6.9	8.8
Total	5.2	7.6	9.8	12.1	14.0
Bark truck					
Purchase price of bark*	2.9	2.9	2.9	2.9	2.9
Transportation of bark		2.0	3.8	5.7	7.2
Total	2.9	4.9	6.7	8.6	10.1
Slabs: Chipper + Chips truck					
Purchase price of slabs	2.9	2.9	2.9	2.9	2.9
Chipping at central processing yards	3.3	3.3	3.3	3.3	3.3
Transportation of chips		1.8	3.4	5.1	6.5
Total	6.2	8	9.6	11.3	12.7
Slabs: Truck + End facility chipping					
Purchase price of slabs	2.9	2.9	2.9	2.9	2.9
Transportation of slabs		1.5	2.6	4.1	5.8
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total	4.0	5.5	6.6	8.1	9.8

* Including comminuting

Figure 27 shows the supply costs of wood chips, bark and sawdust from central processing and sawmill yards for different types of residues and transportation distances.

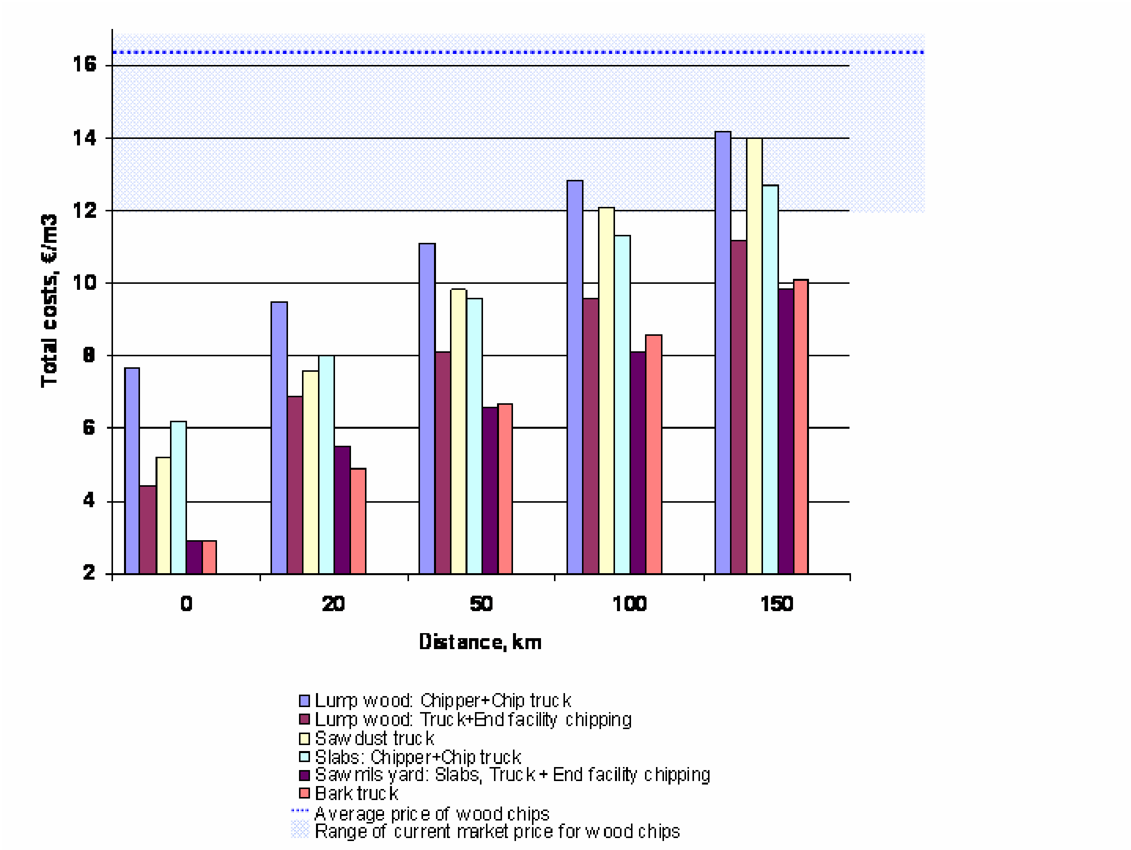

Figure 27. Supply costs of wood chips, bark and sawdust from sawmill yards and central processing yards for different types of energy wood and transportation distances.

The comparatively low prices of energy wood at central processing yards and sawmill yards make these sources very attractive for wood chip production (Figure 27). A choice of supply chain and a resource for chipping in this case is subject to availability of machinery and process residues. The most cost-efficient supply chain uses slabs as a resource for chipping.

The cost structure of wood chips and sawdust supply from sawmill yards and central processing yards is presented in Figure 28.

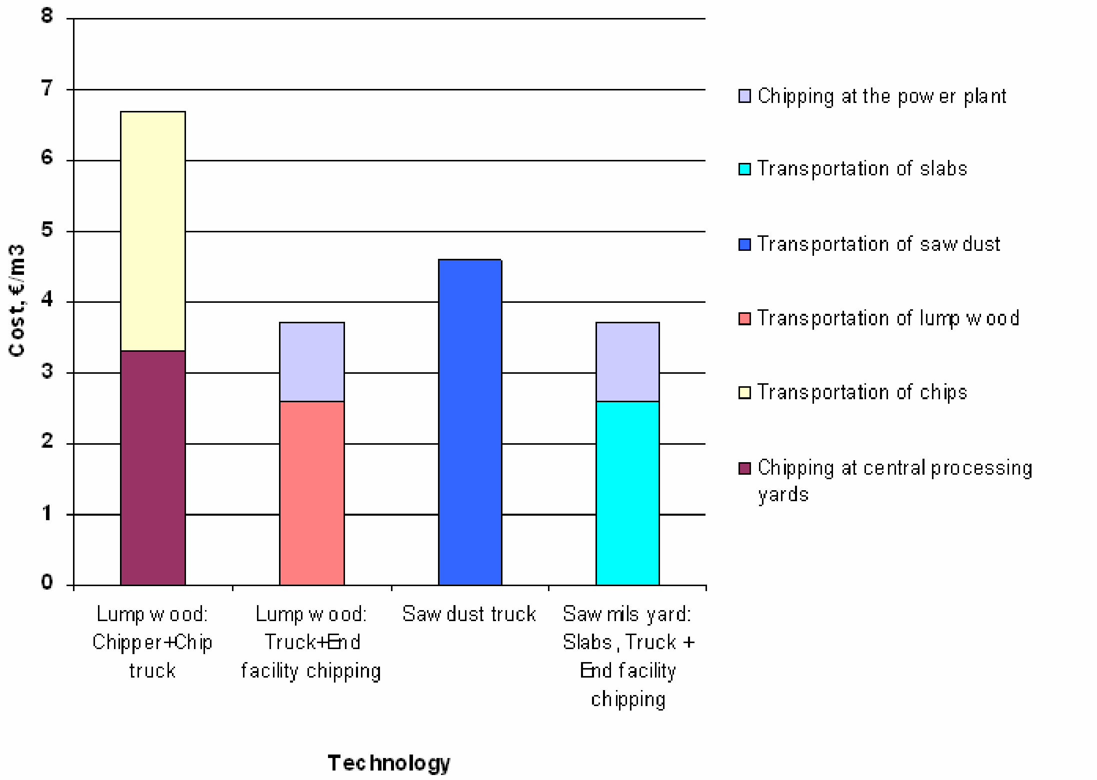

Figure 28. Cost structure of wood chips and sawdust supply from sawmills yards and central processing yards with a 50 km transportation distance.

Figure 28 shows that there is no reason to use a mobile chipper as the transportation cost for chips is much higher than for slabs or lump wood. Sawdust is also less competitive in comparison to uncomminuted process residues due to low bulk density in transportation.

Tables 12 and 13 provide the estimated costs for each chain of wood chips supply from wood collected at final felling areas, central processing yards and sawmill yards.

3.5 The most cost-efficient supply chains

An analysis of the productivity of different production stages and cost-effectiveness of the supply chains showed that manual felling remains competitive in comparison to mechanized felling in the pre-commercial thinning. In first thinnings, the costs of the most efficient chains were manual and mechanized felling, using a harvester with an accumulating harvester head. In later thinnings, utilisation of energy wood harvesters or harvesters is more feasible. The higher productivity of such machines results in lower supply costs compared to systems based on manual felling or an energy combi-machine. Table 14 present the costs of wood chips for the technological stages of the most economically feasible supply chains. Overhead costs were subtracted from management, communication, small insurance and other costs. When the transportation distance for the wood chips was 50 km, for the pre-commercial thinning and the 1st commercial thinning the largest share of the cost was due to forwarding (approximately one third), while for the 2nd commercial thinning the largest share (35 %) was due to felling and for final felling due to the cost of non-industrial wood at the stand (45%, could be regarded also due to felling). The share of transportation was about 25% of the total cost for supply chains based on material direct from the forest. It should be noted that those most efficient chains included end-facility chipping, and its share did not exceed 10% of the total cost.

Table 12. Costs of different chains of wood chips supply from energy wood collected from final felling areas.

<table>
<tr><th rowspan="2">Chain</th><th>Baling, €/m³</th><th colspan="3">Forwarding costs, €/m³</th><th colspan="3">Chipping costs, €/m³</th><th colspan="3">Transport costs, €/m³, distance is 50 km</th></tr>
<tr><th>of loose logging residues</th><th>of bales</th><th>of round wood</th><th>of loose logging residues</th><th>At the stand</th><th>At roadside</th><th>At power plant</th><th>of bales</th><th>of chips</th><th>of round wood</th></tr>
<tr><td>Chipper at the stand + Container chip truck</td><td rowspan="3">no</td><td colspan="3">no</td><td>10.4</td><td colspan="2">no</td><td rowspan="3">no</td><td>7.5</td><td rowspan="2">no</td></tr>
<tr><td>Forwarder + Chipper at roadside + Chip truck</td><td rowspan="2">2.7</td><td rowspan="2">2.3</td><td rowspan="2">6.0</td><td rowspan="3">no</td><td>3.3</td><td></td><td>3.4</td></tr>
<tr><td>Forwarder + Timber truck + End facility chipping</td><td rowspan="2">no</td><td>1.1</td><td rowspan="2">no</td><td>3.3</td></tr>
<tr><td>Residues baler + Forwarder + Log truck + End facility chipping</td><td>5.8</td><td>2.7</td><td colspan="2">no</td><td>1.1</td><td>3.9</td><td>no</td></tr>
</table>

Table 13. Supply costs of wood chips, sawdust and bark for central processing yards and sawmill yards.

<table>
<tr><th rowspan="2">Chain</th><th colspan="2">Chipping costs, €/m³</th><th colspan="5">Transportation costs, €/m³, 50 km distance</th></tr>
<tr><th>At yard</th><th>At power plant</th><th>for chips</th><th>for sawdust</th><th>for bark</th><th>for slabs</th><th>for lump wood</th></tr>
<tr><td>Chipper + Chip truck</td><td>3.3</td><td>no</td><td>3.4</td><td></td><td colspan="3">no</td></tr>
<tr><td>Truck + End facility chipping</td><td>no</td><td>1.1</td><td rowspan="2">no</td><td>no</td><td>no</td><td>2.6</td><td>2.6</td></tr>
<tr><td>Truck</td><td colspan="2">no</td><td>4.6</td><td>3.8</td><td colspan="2">no</td></tr>
</table>

Table 14. Costs of wood chips for the most economically feasible supply chains

Inputs	Distance from the areas to the plant, km				
	0	20	50	100	150
	Cost, €/m³				
The pre-commercial thinning					
Chain-saw + Forwarder + Log truck + End facility chipping					
Felling and bunching	5.2	5.2	5.2	5.2	5.2
Forwarding	6.4	6.4	6.4	6.4	6.4
Transportation of wood		3.3	5.2	9.1	12.0
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Overhead costs	0.5	0.7	0.7	0.9	1.0
Total cost	13.2	16.7	18.6	22.7	25.7
The 1st commercial thinning					
Chain-saw + Forwarder + Log truck + End facility chipping					
Felling	4.0	4.0	4.0	4.0	4.0
Forwarding	4.3	4.3	4.3	4.3	4.3
Transportation of wood		1.9	3.1	5.4	7.1
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Overhead costs	0.4	0.5	0.5	0.6	0.7
Total cost	9.8	11.8	13.0	15.4	17.2
Harvester + Forwarder + Log truck + End facility chipping					
Felling	5.9	5.9	5.9	5.9	5.9
Forwarding	2.9	2.9	2.9	2.9	2.9
Transportation of wood		2.0	3.2	5.6	7.4
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Total cost	9.9	11.9	13.1	15.5	17.3
The 2nd commercial thinning					
Harvester + Forwarder + Log truck + End facility chipping					
Felling	3.6	3.6	3.6	3.6	3.6
Forwarding	2.2	2.2	2.2	2.2	2.2
Transportation of wood		2.0	3.2	5.2	6.9
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Overhead costs	0.3	0.4	0.4	0.5	0.6
Total cost	7.2	9.3	10.5	12.6	14.4
The final felling					
Forwarder + Log truck + End facility chipping					
Cost of non-industrial wood at the stand	5.9	5.9	5.9	5.9	5.9
Forwarding of non-industrial wood	2.2	2.2	2.2	2.2	2.2
Transportation of non-industrial wood		2.0	3.2	5.2	6.9
End facility chipping	1.1	1.1	1.1	1.1	1.1
Overhead costs	0.1	0.2	0.3	0.3	0.4
Total cost	9.3	11.4	12.7	14.7	16.5

Continue table 14

Inputs	Distance from the areas to the power plant, km				
	0	20	50	100	150
	Cost, €/m³				
Central processing yards					
Lump wood: Truck + End facility chipping					
Market price of lump wood	4.4	4.4	4.4	4.4	4.4
Transportation of lump wood		1.3	2.5	3.9	5.5
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Overhead costs	0.0	0.1	0.1	0.2	0.2
Total cost	5.5	6.9	8.1	9.6	11.2
Sawmills yards					
Slabs: Truck + End facility chipping					
Purchase price of slabs	2.9	2.9	2.9	2.9	2.9
Transportation of slabs		1.4	2.5	3.9	5.6
Chipping at the power plant	1.1	1.1	1.1	1.1	1.1
Overhead costs	0.0	0.1	0.1	0.2	0.2
Total cost	4.0	5.5	6.6	8.1	9.8

Figure 29 shows *the most cost-efficient wood chips supply chains* for intermediate fellings, final fellings and for utilisation of wood residues from central processing yards and sawmills. The total production costs for chips for all chains were less than the average market price for wood chips, except for pre-commercial thinning which was more expensive at distances of 20 or more.

The most economically feasible resource for the supply of wood chips is slabs at sawmill yards. There are only transportation costs to the power plant and chipping for this chain. The advantages of this chain are a small number of technological stages and simplicity of management. However, it is possible to say that development of energy wood markets will rise the prices of wood resources, especially convenient resources for wood chips production such as slabs and non-industrial wood.

The selection of the most cost-efficient supply-chains is only trend-setting describing the situation in average stand conditions for each of the harvesting types. Also the infrastructure in a specific area as well as size and location of users of energy wood consumers define the efficiency of different supply-chain options. The stand conditions have a large variation between stands and regions, and existing machinery in logging organizations defines what is economically feasible in short term operations. Thus, in reality selection of the most efficient supply-chain for energy wood is both stand and region specific.

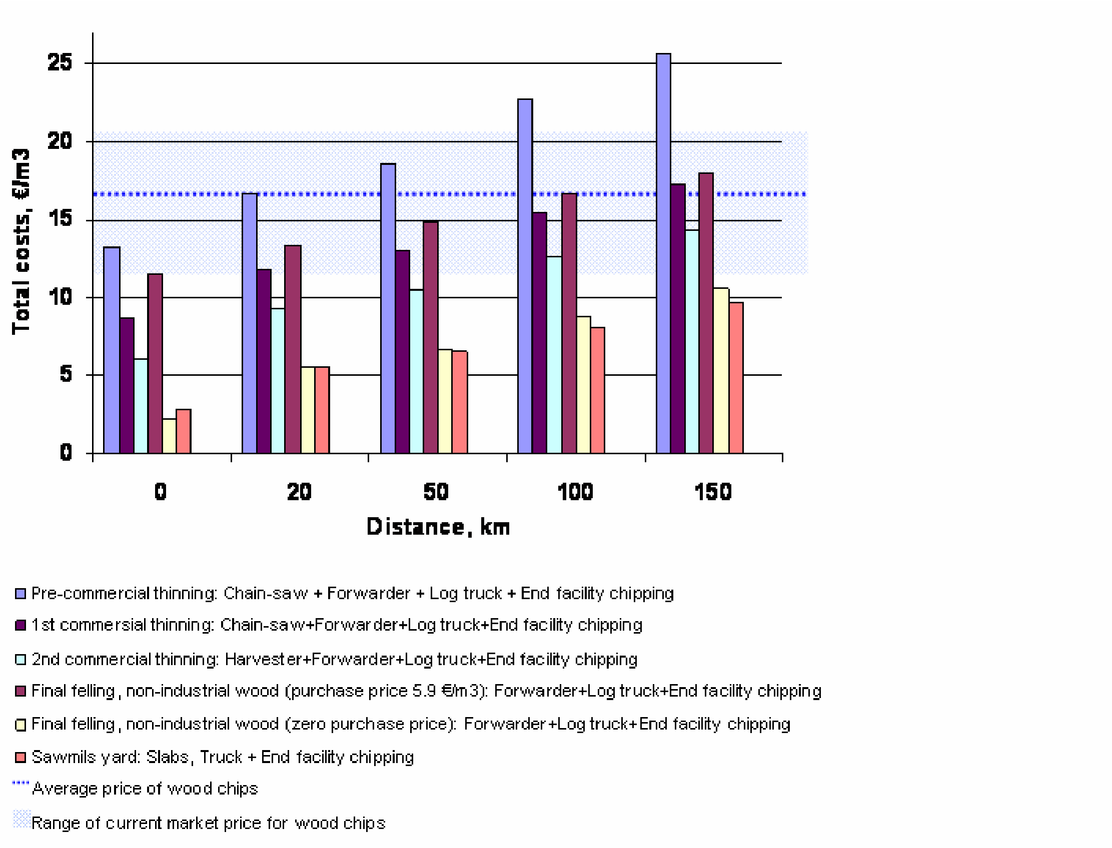

Figure 29. The most cost-efficient wood chips supply chains

Compared to Finnish conditions a weaker infrastructure (roads, machinery maintenance services etc.) together with lower productivity in North-West Russia probably increase the real procurement costs compared to the estimates of this study. On the other hand, the energy wood harvesting can be focused to stands having better conditions than an average logging area. This means easily available stands with high energy wood yield per hectare, and high average volume of removed stems in thinnings. The economy of industrial timber harvesting can be improved, if collection of energy wood helps to avoid extra costs and obligations for wasting the logging residues after harvesting.

The overall reliability of the whole wood chip supply-chain must be carefully considered, especially in the harsh winter conditions. “Hot” supply chains like terminal chipping, but also pure road-side chipping without buffer storages are vulnerable for disturbances in transportation. Breaks in supply-chain can be easily caused by machinery break-downs, defects in logistic planning, accessibility of road-side storages in winter etc. Supply-chains based on large terminals and storages near consumers and large storages and end facility chipping are more tolerant for disturbances. High investment costs reduce the end facility chipping to large plants, where the lack of storage space usually is a problem. The existing central processing yards are usually near town and consumers, located along good transportation connections and planned to process large amounts of timber. They also produce a lot of wood residues in processing of industrial timber. Especially if they could serve several clients at the same time, the central processing yards could operate quite efficiently as fuel terminals providing high efficiency of centralized comminution together with security of having buffer storages.

4. Conclusions

The Leningrad region of the Russian Federation has abundant resources of energy wood. In 2004, the volume of energy wood from thinnings, final felling, central processing yards and sawmill yards was estimated to be 4.1 million m^3. The deciduous tree species (birch, aspen) are dominant (65% of the total volume). There are large differences in the potentials within the region due to current intensity in forest use. However, this demonstrates theoretical potentials in the Leningrad region only, which are large if compared to the use of solid wood fuels for energy generation in Finland, 19.5 million m^3 in 2004 including use for heating, power plants, and small-sized dwellings (Finnish Forest Research Institute 2005).

It is possible to intensify the utilisation of forest resources in Northwest Russia and thereby also to increase the use of wood in energy production. The annual supply of energy wood would be 3.5 million m^3 based on 2004 fellings and could be increased to 5.3 million m^3 or 54% higher, if the allowable cut would be utilised completely and even to 7.2 million m^3 or 106% higher, if thinnings could also be conducted at a full scale. There are, however, big differences within the region, as the current rate of utilisation of forest resources vary in the region. It should be noted that better utilisation of allowable cut and thinnings would require investments in infrastructure, building of new roads and better maintenance of existing roads.

Nearly 86% of the 4.1 million m^3 potential is non-industrial round wood and felling residues in cutting areas (56%) and central processing yards (30%). The rest (14%) is by-products from sawmilling. Currently, non-industrial round wood in central processing yards and residues from sawmills are usually utilised, for instance for house heating by inhabitants, indicating that all the potential would not be additional. Although intensive forest management would also provide more material for energy production, it would also mean that the major part of energy wood would be concentrated in cutting areas. It would limit energy wood resources available in near residential areas where central processing yards and sawmills are located and would require development of technology for large-scale production of forest chips.

Economic and technical availability of energy wood in the region varies over a wide range depending on sources. In current conditions, the pre-commercial thinnings cannot be considered a source of energy wood due to economic reasons. Despite well developed technologies, the high costs of the pre-commercial thinning (production cost of 17-31 €/solid m^3 for chips depending on distance and technology) make the supply of energy wood unprofitable in this case. Later thinnings are economically more attractive (production cost of 9-21 €/solid m^3) as sources of energy wood. However, a choice of energy wood procurement chain for the 1st commercial thinnings is limited by costs factors. Chains based on chipping by the roadside are less competitive in comparison with chains utilising stationary chippers. A big-size stationary chipper at the power plant is relatively more expensive than a mobile one in the forest, only advanced companies could widely utilise wood from the 1st commercial thinning for production of chips. There are more possibilities for energy wood supply from the 2nd commercial thinnings. The most cost-efficient supply chain based on a harvester and a forwarder allow profitable energy wood supply for a distance of up to 150 km (9-14 €/solid m^3). Economical availability of wood energy from final felling can be decreased because growing demand for wood fuels may increase the prices of wood residues at final felling areas. Currently, at final felling areas, non-industrial wood is an economically feasible resource for energy production (total cost 11-17 €/solid m^3 for the most effective chain). The same applies to the availability of process residues at central processing yards (total cost 7-11 €/solid m³ for the most effective chain) and sawmills (total cost 6-10 €/solid m³ for the most effective chain), where lump wood and slabs are the most cost-efficient resources for wood chip production and now these sources of energy wood look very attractive.

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Appendix 1. Characteristics of energy wood

Table 15. Characteristics of uncomminuted energy wood at cutting areas (Bit and Vavilov 2001)

Characteristics	Poles		Non-industrial wood	Logging residues			
	Birch	Aspen		Birch	Aspen	Pine	Spruce
Average length, m	< 6.0	<6.0	<16.0	>2.0	>2.0	>2.0	>2.0
Diameter, cm	7.0-10.0	7.0-10.0	>3.0	-	-	-	-
Density, kg/m^3	880	670	620-880	880	670	700	620
Stacking factor	0.28	0.28	0.47	0.1	0.1	0.1	0.1

Table 16. Characteristics of uncomminuted energy wood at central processing yards and sawmill yards. (Instrukciya po proektirovaniu…1982)

Characteristics	Lump wood	Wood chips	Sawdust	Slabs	Bark
Average length, m	< 1.0	-	-	> 1.0	-
Staking factor	0.57	0.36	0.28	0.56	0.34

Appendix 2. Procedure for costs calculation

Energy wood costs depend on many factors, such as the type of felling, the wood harvesting method applied, equipment used, and stand characteristics, such as the average stem volume, age and volume of growing stock. Also, the transportation distance of wood from the cutting area to the place of utilisation has a strong influence on the total cost of energy wood. The supply of *wood chips*, depending on technological chain can include several stages – felling, delimbing, cross-cutting, forwarding, transport and chipping. Some methods have additional stages such as storage and baling. Therefore, the total costs of 1 solid m^3 of energy wood are the sum of the costs of different production stages:

$$TCW = \Sigma C_i , \qquad (7)$$

where

TCW – total cost of 1 m^3 of *energy wood*, €/solid m^3
C_i – cost of 1 m^3 of *energy wood* on i production stage, €/solid m^3
i – production stage: felling, forwarding, long distance transportation or chipping

An assumption was made for the costs calculation of the energy wood supply that mobile machines such as harvesters, forwarders, chippers and trucks were leased because of several advantages gained from leasing in comparison with bank loans (Seliverstov 2005). Leasing allows one to accelerate depreciation of the leased key assets by agreement between parties on a leasing contract (Federal'nyi zakon # 164-F3), but in order to simplify the cost calculations, accelerated depreciation will not be used.

Fixed costs include leasing or interest for a bank loan, depreciation, insurance, and other costs. Variable costs include salaries, costs of fuels, engine and gearbox oils, hydraulic liquids, cost of maintenance and repair of equipment. These costs were calculated on the basis of data obtained from the Federal State Statistic Service (http://www.gks.ru) and from Seliverstov 2005.

Two factors determine the costs of production of *wood chips* for each production stage: felling, delimbing, cross-cutting, forwarding, chipping, transporting or their combinations. These are *costs of equipment exploitation* and *productivity of technology*:

$$C_i = HC_i / Ph_i, \qquad (8)$$

where:

C_i – cost of 1 m^3 *of energy wood* on production stage i, €/solid m^3
HC_i – hourly cost of equipment exploitation, €/h
PH_i – hourly productivity of equipment, solid m^3/h

The hourly productivity of equipment HP_i is mainly determined by the current conditions of exploitation and qualification of operators. Therefore, it is possible to estimate costs of production for different conditions. This offers a possibility to exclude factors that influence the costs and to determine a volume of inputs, which guarantees profitability of equipment utilization.

Productivity models were used to calculate the hourly productivity of equipment HP_i. The methodology for calculation of productivity is described in Laitila and Asikainen (2006), and in Salo and Uusitalo (2001).

The next subsections show some examples of hourly costs calculation for the following set of machines used in the 1st commercial thinning: Valmet 901.3 harvester + Valmet 830.1 forwarder + Kesla C 4560 LF chipper + Volvo chip truck.

Appendix 3. Calculation of costs

The hourly costs of equipment exploitation are calculated by:

$$HC_i=(FC_i+VC_i)/(TWT_i-TT_i-TRB_i), \quad (9)$$

where

HC_i – hourly costs of production of i production stage, €/h
FC_i – fixed costs of i production stage, €/yr
VC_i – variable costs of i production stage, €/yr
TWT_i – total working time for i production stage, hours/yr
TT_i – transfer time, h
TRB_i – time for repairs and breaks, h

Total working time was divided into time components (exploitation time, transfer time and time for repairs, breaks and maintenance work) according to Mäkelä (1986) to calculate time inputs into production and, as a result, to find hourly costs for production. The total working time during a year for felling operations was estimated by:

$$TWT_i=(DS_1*NM_1+2*DS_2*NM_2+3*DS_3*NM_3)*ND_i, \quad (10)$$

where

TWT_i – total working time, h/yr
$NM_{1/2/3}$ – number of months during a year with a 1, 2 or 3 shift working regime
$DS_{1/2/3}$ – duration of the 1st, the 2nd or the 3rd working shift, hours
ND_i – average number of working days, days/month

For the following after felling productions stages the total working time was calculated as:

$$TWT_i=ET_i+TT_i+TRB_i \quad (11)$$

where:

TWT_i – total working time, h/yr
TT_i – annual transfer time, h/yr
TRB_i –average time for repairs, breaks, maintenance and preparation works, h/yr
ET_i – annual exploitation time, h/yr

Annual exploitation time for the felling equipment can be estimated by the following equation:

$$ET_i=TWT_i-TT_i-TRB_i, \quad (12)$$

where:

ET_i – annual exploitation time, h/yr
TWT_i – total working time, h/yr
TT_i – annual transfer time, h/yr
TRB_i – annual time for repairs, breaks, maintenance and preparation works, h/yr

Exploitation time of machines following the harvester or lumberjack was determined on the basis of the annual productivity of the felling equipment and hourly productivity of the machines:

$$ET_i=APF/HP_i \tag{13}$$

where:

ET_i – exploitation time, h/yr
APF – annual productivity for the felling equipment, m^3/yr
HP_i – hourly productivity, m^3/h

Annual productivity for the felling equipment is:

$$APF=ET_f*HP_i, \tag{14}$$

where:

APF – annual productivity for the felling equipment, m^3/yr
ET_f – exploitation time of the felling equipment, h/yr
HP_f – hourly productivity for the felling equipment

Annual average transfer time TT_i depends on several factors, such as the volume of timber removal from cutting areas, productivity of equipment and the distance between the cutting areas. It can be approximately estimated by:

$$TT_i=NA*(D_i/TS_i+TL) \tag{15}$$

where:

TT_i – annual transfer time, h/yr
NA – number of cutting areas per year
D_i – average distance between the cutting areas, km
TS_i – average transfer speed, km/h
TL – time for loading and unloading of equipment onto/off a trailer, h

It is possible to estimate the number of cutting areas per year with the following equation:

$$NA=TWT_i/TA_i \tag{16}$$

where:

NA – number of cutting areas per year
TWT_i – total working time, h/yr
TA_i – total time of work at a cutting area, h/area

The total time of work at one cutting area TA_i depends on the volume of wood removal from the area and hourly productivity of equipment:

$$TA_i=VB*S/HP_i+TRB_i+(D_i/TS_i+TL) \tag{17}$$

where:

TA_i – total time of work at one cutting area, h/area
VB – volume of biomass available for harvesting/chipping, m^3/ha
S – area of felling, ha
HP_i – hourly productivity of equipment, m^3/h
TRB_i – average time for repairs, breaks, maintenance and preparation works for one cutting area, h/area
D_i – average distance between the cutting plots, km
TS_i – average transfer speed, km/h
TL – time for loading and unloading of equipment onto/off a trailer, h

The following equation gives an estimation of the annual volume of biomass available for chipping at cutting area:

$$AVB=VB*S*NA, \qquad (18)$$

where:

AVB – annual volume of biomass available for chipping at cutting areas
VB – volume of biomass available for chipping, m^3/ha
S – area of felling, ha
NA – number of cutting areas per year

The average time for repairs, breaks, maintenance and preparation works TRB_i is determined on the basis of experience from the previous exploitation year (Anan'ev et al 2005) and can be approximately estimated by:

$$TRB_i=ET_i*RR_i/100, \qquad (19)$$

where:

TRB_i –average time for repairs, breaks, maintenance and preparation works, h/yr
ET_i – exploitation time, h/y
RR_i – average time for repairs, breaks, maintenance and preparation works to exploitation time, percents

Fixed costs. Equipment wears out during exploitation, harvesters and forwarders have to be changed after 4 – 5 years of 2 shift utilization (Uusitalo 2004). Annual deterioration or annul inputs into the renewal of equipments can be calculated on the basis of duration of operation life, turn-in and the exchange value of machines. The operation life of equipment depends on working conditions and annual exploitation time. It is possible to estimate the duration of operation life by the following (Salo and Uusitalo 2001):

$$OL_i=NOT_i/TE_i, \qquad (20)$$

where:

OL_i – operation life of the equipment, yrs
NOT_i – normative operation time, hours
TE_i – annual exploitation time, h/yr

The estimation of the operation life OL_i allows the calculation of turn-in TIR_i (Salo and Uusitalo 2001):

$$TIR_i=(1-RC_i/100)^{OLi}*100, \qquad (21)$$

where:

TIR_i – turn-in of equipment, %
RC_i – rate of consideration, %
OL_i – operation life of the equipment, yrs

Then the exchange value EV_i, the price of the equipment at the end of exploitation, can be estimated by (Anan'ev et al. 2005):

$$EV_i=PP_i*TIR_i/100, \qquad (22)$$

where:

EV_i – exchange value, €
PP_i – purchasing price, €
TIR_i – turn-in, %

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Annual deterioration, according to Salo and Uusitalo 2001, is:

$$D_i=(PP_i-EV_i)/ OL_i \quad (23)$$

where:

D_i – annual deterioration, €/yr
PP_i – purchasing price, €
EV_i – exchange value, €
OL_i – operation life, yrs

The cost of equipment leasing L_i is (Salo and Uusitalo 2001):

$$L_i=LR_i/100*((OL_i +1)*PP_i+(OL_i -1)*EV_i)/(2* OL_i), \quad (24)$$

where:

L_i – cost of leasing, €/yr
LR_i – rate of leasing, %
OL_i – operation life of a machine, €
PP_i – purchasing price of a machine, €
EV_i – exchange value of a machine, €

In many cases, the leasing of equipment demands the insurance of leased objects. The cost of insurance is:

$$CI_i=PP_i*IR_i/100, \quad (25)$$

where:

CI_i – cost of insurance, €/yr
PP_i – purchasing price, €/yr
IR_i – insurance, %

Costs for repairs, maintenance works and the size of other costs are usually determined on basis of data from the previous exploitation year (Anan'ev et al. 2005). Therefore, the values of inputs into repairing, maintenance works and other costs were estimated by interview (Tyukina 2006). Other costs ROC was estimated at approximately 4 % of the fixed or variable costs and for inputs into repairs and maintenance works RR_i were assumed to equal 6 % of the purchase price PP_i of the machines (Tyukina 2006). Thus, other fixed costs are:

$$OFC_i=(L_i+D_i+IC_i)*ROC/100, \quad (26)$$

where:

OFC_i – other fixed costs, €/yr
L_i – cost of leasing, €/yr
D_i – annual deterioration, €/yr
IC_i – cost of insurance, €/yr
ROC –other costs, %

The fixed costs are the sum of leasing cost, deterioration, cost of insurance and other costs (Anan'ev et al. 2005):

$$FC_i=L_i+D_i+IC_i+OFC_i, \quad (27)$$

where:

FC_i – fixed costs, €/yr
L_i – cost of leasing, €/yr
D_i – annual deterioration, €/yr
IC_i – cost of insurance, €/yr
OFC_i – other fixed costs, €/yr

Variable cost. Inputs into fuel, oils and hydraulic liquids can be determined by the following formula (Salo and Uusitalo 2001):

$$IF_i=\Sigma(C_i*AP_i)*ET_i \tag{28}$$

where:
IF_i - inputs into fuel, oils and hydraulic liquids, €/yr
C_i – consumption of fuel, oils or hydraulic liquids by a machine, kg/h
AP_i – an average purchase price of fuel, oils or hydraulic liquids, €/kg
ET_i – operation time of a machine, h/yr

The annual costs of repair, spare parts and maintenance works CR_i are:

$$CR_i=PP_i*RR_i/100, \tag{29}$$

where:
CR_i – costs of repair, spare parts and maintenance works, €/yr
PP_i – purchase price, €
RR_i –inputs into repair, spare parts and maintenance works, %

The value of the annual basic salary S_b of a machine's operator is calculated by taking into account machine utilization degree MUD_i:

$$S_{bi}=NM_1*NDM*DS_1*MUD_i*HP_i*W_i, \tag{30}$$

where:
S_{bi} – annual base salary, €/yr
NM_1 – number of months during a year for day shift work, months/yr
NDM – average number of working days/m
DS_1 – duration of day shift, h
MUD_i - machine utilisation degree
HP_i – hourly productivity, m^3/h
W_i – wage, €/h

If a shift regime for work is used, then according to the Labour Code of the Russian Federation (Trudovoy Kodeks Rossiiskoy Federacii. 2005), extra payments have to be paid to workers for evening and night shifts. The size of the extra payments is 20 % and 40 % of the basic (day-shift) salary respectively. Annual volume of salary for evening or night shifts can be estimated as:

$$S_{si}=S_{bi}*(M_{si}/12+REP_s/100) \tag{31}$$

Where:
S_{si} – annual volume of salary for evening or night shifts, €/yr
S_{bi} – annual volume of basic salary, €/shift
M_{si} – quantity of months when evening or night shifts are used, m/yr
REP_s –extra payment for evening or night shifts, %

Then the total volume for salaries is:

$$S_{ti}=S_{bi}+S_{ei}+S_{ni}, \quad (32)$$

where:

S_{ti} – total volume of salary, €/yr
S_{bi} – basic salary, €/yr
S_{ei} – salary for evening shifts, €/yr
S_{ni} – salary for night shifts, €/yr

The costs of the labour force also include social and medical levies. In Russia, the Internal Revenue Code of the Russian Federation (Nalogoviy Kodeks Rossiiskoy Federacii 2005) regulates these levies. The Code determines the volume of the levies depending on the size of the annual salary. According to the Code, the levies corresponding to the calculated volume of the salary are 31.9%. It is possible to calculate the annual size of the social and medical assignment by:

$$A_i=S_{ti}*RSA_i/100, \quad (33)$$

where:

A_i – social and medical levies, €/yr
S_{ti} – total salary, €/yr
RSA_i –social and medical levies, %

Other variable costs are:

$$OVC_i=(IF_i+IR_i+S_{ti}+A_i)*ROC/100, \quad (34)$$

where:

OVC_i – other variable costs, €/yr
IF_i - inputs into fuel, oils and hydraulic liquids, €/yr
IR_i – inputs into repair, spare parts and maintenance works, €/yr
S_{ti} – total volume of salary, €/yr
A_i – social and medical levies, €/yr
ROC –other costs

The total variable costs are:

$$VC_i=IF_i+IR_i+S_t+A_i+OVC_i, \quad (35)$$

where:

IF_i - inputs into fuel, oils and hydraulic liquids, €/yr
IR_i – inputs into repair, spare parts and maintenance works, €/yr
S_t – total volume of salary, €/yr
A_i – social and medical levies, €/yr
OVC_i – other variable costs, €/yr

A reserve fund RF_i was included in the cost calculation to insure against unforeseeable expenses. The volume of the reserve fund depends on the sum of the fixed and variable costs (Anan'ev et al 2005):

$$RF_i=(FC_i+VC_i)*RR/100, \quad (36)$$

where:

RF_i – reserve fund, €/yr
FC_i – fixed costs, €/yr

VC_i – variable costs, €/yr
RR – risk rate, %

The total costs for equipment exploitation are the sum of the fixed costs FX_i, the variable costs VC_i and the reserve fund RF_i:

$$TC_i=FX_i+VC_i+RF_i, \tag{37}$$

where:
TC_i – total cost for equipment exploitation, €/yr
FX_i – fixed costs, €/yr
VC_i – variable costs, €/yr
RF_i – reserve fund, €/yr

The hourly cost for equipment exploitation is:

$$HC_i=TC_i/TWT_i-TT_i-TRB_i, \tag{38}$$

where:
HC_i – hourly cost for equipment exploitation, €/h
TC_i – total costs for equipment exploitation, €/yr
TWT_i – total working time, h/yr
TT_i – annual transfer time, h/yr
TRB_i – annual time for repairs, breaks, maintenance and preparation works, h/yr

The cost of 1 m^3 of energy wood on i production stage is:

$$C_i=HC_i/HP_i \tag{39}$$

where:
C_i – cost of 1 m^3 for *energy wood* on i production stage, €/solid m^3
HC_i – hourly cost for equipment exploitation, €/h
HP_i – hourly productivity of equipment, m^3/h

Costs calculation for energy wood felling, cross-cutting and bunching

A Valmet 901.3 model has been selected as the test harvester, equipped with an accumulating head, to be used for the 1st commercial thinning. The harvester productivity limits productivity of the following technological stages.

Due to high cost of the machine, the working regime of the harvester was 3 shifts per day, 8 hours each shift. The total working time TWT_i of the harvester per year is 6048 h/yr (10):

$$3*8*12*21=6048 \text{ h/yr}$$

The structure and data for the total working time for harvesters and forwarders is presented in Anan'ev et al. (2005). The transfer time TT_i for harvesters depends on the growing stock of the cutting area, spatial distribution of the stands and on the quality of the road networks. The average transfer time TT_i for harvesters is 122 h/yr (15):

$$102*(35/50+0.5)=122 \text{ h/yr}$$

The annual time for repairs, breaks, maintenance and preparation works TRB_i is approximately 16 % of the exploitation time (Anan'ev et al 2005) or 816 h/yr (19):

$$370/7.4*16/100*102=816 \text{ h/yr}$$

The exploitation time TE_i of the harvester is estimated as the rest of the total working time after subtraction of transfer time, time of breaks, repairing, maintenance and preparation works. It is 5110 h/yr (12).

$$6048-122-816=5110 \text{ h/yr}$$

If the exploitation time TEi of the harvester per year is 5017 hours and the average normative operation time of a harvester is 24000 hours (Siuro 2006), then the operation life OLi of the harvester is 5.0 yr (20):

$$24000/5110=5.0 \text{ yr}$$

Consideration RC_i for key assets are defined by the state norms (Klassifikaciya osnovnih sredstv… 2003), and for harvesters it is 25%. Then the turn-in TIR_i of the harvester is 24% (21):

$$(1-25/100)^{5.0}*100=24 \text{ \%}$$

Turn-in TIR_i of the harvester is 24%, thereby the exchange value EV_i of the harvester is 84240 € (22):

$$351000*24/100=84240 \text{ €}$$

The annual deterioration D_i of the harvester is 53352 €/yr (23):

$$(351000-84240)/5.0=53352 \text{ €/yr}$$

The cost of leasing L_i for the harvester is 29316 €/yr (24):

$$12/100*((5.0+1)*351000+(5.0-1)*84240)/(2*5.0)=29316 \text{ €/yr}$$

The average insurance IR for leasing operations is 2% of the purchasing price PP_i (Seliverstov 2005), thereby the cost of insurance CI_i is 7020 €/yr (25):

$$351000*2/100=7020 \text{ €/yr}$$

Other fixed costs OFC_i are 3588 €/yr (26):

$$(53352+29316+7020)*4/100=3588 \text{ €/yr}$$

The total fixed costs FC_i are 93276 €/yr (27):

53352+29316+7020+3588=93276 €/yr

Table 17 shows the calculated inputs for fuel, oils and hydraulic liquids for the harvesting.

Table 17. Total costs of fuel, oils and hydraulic liquids for Valmet 901.3

Consumption		Exploitation time, h/yr	Total consumption, kg/year	Average purchasing prices, €/kg	Total cost, €**
Fuel and lubricants	kg/h*				
Diesel fuel	9.3	5110	47523	0.68	32316
Motor oil	0.003	5110	15	0.92	14
Gearbox oil	0.09	5110	460	0.65	299
Hydraulic liquid	0.053	5110	271	2	542
Head oil	0.35	5110	1789	4.59	8212
Marking paint	0.3	5110	1533	5.94	9106
Total					50489

* - Salo and Uusitalo 2001, Siuro 2006
** - calculated according to formula 28 of the Appendix 3

Costs of repair, spare parts and maintenance works CR_i are 21060 €/yr (29):

351000*6/100=21060 €/yr

Wage W_i of the Russian harvester's operator was assumed to be 0.54 €/m^3 (Lesnoi vestnik. 2005). Annual basic salary of the harvester's operator is 6767 €/yr (30):

12*21*8*0.84*7.4*0.54=6767 €/yr

Annual volume of salary for evening shifts is 8120 €/yr (31):

6767*(12/12+0.2)=8120 €/yr

Annual volume of salary for night shifts is 9474 €/yr (31):

6767*(12/12+0.4)=9474 €/yr

Then the total salary is 24361 €/yr (32):

6767+8120+9474=24361 €/yr

The social and medical levy A_i paid from the calculated salary is 7771 €/yr (33):

24361*31.9/100=7771 €/yr

Other variable costs OVC_i are 4147 €/yr (34):

(50489+21060+24361+7771)*4/100=4147 €/yr

Total variable costs VC_i are 107828 €/yr (35):

50489+21060+24361+7771+4147=107828 €/yr

Reserve fund RF_i is 5 % of total fixed and variable costs 10055 €/yr (36):

(93276+107828)*5/100=10055€/yr

Total costs TC_i of utilization of the harvester for the 1st commercial thinning are 211159 €/yr (37):

93276+107828+10055=211159 €/yr

Hence, the hourly cost HC_i of the harvester exploitation is 41.32 €/h (38):

211159/(6048-132-816)=41.32 €/h.

Table 18. Cost structure of wood felling, delimbing and cross-cutting.

Harvester Valmet 901.3			
Factors and costs	Symbols in the formulas	Values	
Number of shifts	NS_i	3	
Duration of 1 shift	DS_i	8 hours	
Total number of working days per year	NDY_i	252	
Average number of working days per month	NDM_i	21	
Number of month during a year with 1/2/3 shifts	$NM_i1/2/3$	0/0/12	
Total working time per year	TWT_i	6048 hours	
Total transfer time per year	TT_i	122 hours	
Time for repairs, breaks, maintenance and preparation work	TRB_i	816 hours	
Exploitation time per year	TE_i	5110 hours	
Productivity hourly/annual	HP_i/AP_i	7.4/37814 m^3	
Machine utilization degree	MUD_i	0.84	
Purchase price	PP_i	351000 €	
Operating life	OL_i	5.0 years	
Consideration	RC_i	25 %	
Turn-in	TIR_i	24 %	
Leasing	LR_i	12 %	
Exchange value	EV_i	84240 €	
Extra payment for evening and night shifts	REP_s	20 and 40 %	
Social levies (including medical levies)	RSA_i	31.9 %	
Other costs	ROC_i	6 %	
Insurance	IR_i	2 %	
Risk rate	RR_i	5 %	
Fixed cost		€/yr	€/h
Deterioration	D_i	53352	10.44
Leasing	L_i	29316	5.74
Insurances	CI_i	7020	1.37
Other	OFC_i	3588	0.70
Total fixed costs	**FC_i**	**93276**	**18.25**
Variable costs		€/yr	€/h
Inputs for fuel, oils and liquids	IF_i	50489	9.88
Repairs and maintenance	CR_i	21060	4.12
Salaries	S_{ti}	24361	4.77
Social levies	A_i	7771	1.52
Other	OVC_i	4147	0.81
Total variable costs	**VC_i**	**107828**	**21.10**
Reserve fund	RF_i	10055	1.97
Costs, total	**C_i**	**211159**	**41.32**

Costs calculation of energy wood forwarding

A Valmet 830.1 model has been selected as a tested forwarder and was used for the 1st commercial thinning. The productivity of the forwarder exceeds the productivity of the harvester for the same amount of total working time. It can result in an increment in idle time for the forwarder. Therefore, the technological stages of the wood chips production must have equal productivities to minimize downtime. It is possible to equalise productivities of the production stages by time management. At the same time, it has to be taken into account that forwarding all the year round very often is not possible in conditions of boreal forest. For this reason, it was assumed that the forwarder operates 11 months per year. Total volume of the harvested biomass to be forwarded is 37814 m^3/yr (Table 18). Forwarding of that wood needs 3125 h/yr of exploitation time TE_i (13):

$$37814/12.1=3125 \text{ h/yr}$$

As the forwarder follows the harvester and transfer conditions are the same for both machines, transfer time TT_i of the forwarder is 122 h/yr. Time for repairs, breaks, maintenance and preparation works TRB_i is about 10% of the exploitation time (Anan'ev et al 2005) or 313 h/yr (19):

$$3125*10/100=313 \text{ h/yr}$$

The total working time of the forwarder is 3560 h/yr (11):

$$3125+122+313=3560 \text{ h/yr}$$

The working regime of the forwarder is 1 shift/day for 0.8 months and 2 shifts/day for 10.2 months per year or 1.9 shifts/day on average.

If the exploitation time TE_i of the forwarder per year is 3125 hours and the normative operation time of the forwarder is 24000 hours, then the operation life OL_i of the forwarder is 8.0 yrs (20):

$$24000/3125=8.0 \text{ yrs}$$

The normative of consideration C_i for the forwarder is 25%, thus the turn-in TIR_i of the forwarder is 10% (21):

$$(1-25/100)^{8.0}*100=10\%$$

The turn-in of the forwarder is 10% (21), thereby the exchange value EV_i of the forwarder is 25000 € (22):

$$250000*10/100=25000 \text{ €}$$

The annual deterioration of the forwarder is 28125 €/yr (23):

$$(250000-25000)/8.0=28125 \text{ €/yr}$$

The cost of leasing for the forwarder is 18188 €/yr (24):

12/100*((8.0+1)*250000+(8.0-1)*25000)/(2*8.0)=18188 €/yr

The average insurance for leasing operations is 2% of the purchase price PP_i or 5000 €/yr (25):

250000*2/100=5000 €/yr

The other fixed costs are 2053 €/yr (26):

(28125+18188+5000)*4/100=2053 €/yr

The total fixed costs are 53366 €/yr (27):

28125+18188+5000+2053=53366 €/yr

Table 19 shows the calculated inputs for fuel, oils and hydraulic liquids for the harvesting.

Table 19. Total costs for fuel, oils and hydraulic liquids for Valmet 830.1

Consumption		Exploitation time, h/yr	Total consumption, kg/yr	Average purchasing prices, €/kg	Total cost, €**
Fuel and lubricants	kg/h*				
Diesel fuel	8,43	3125	26344	0.68	17914
Motor oil	0,003	3125	9	0.92	8
Gearbox oil	0,09	3125	281	0.65	183
Hydraulic liquid	0,018	3125	56	2	112
Total					18217

* - Salo, T. and Uusitalo, J. 2001
** - calculated according to formula 28 of the Appendix 3

The costs of repair, spare parts and maintenance works are 15000 €/yr (29):

250000*6/100=15000 €/yr

In the Leningrad region the salaries of a harvester's and a forwarder's operators are very similar. Therefore, the monthly salary of the forwarder's operator for day shifts was assumed to be equal to the monthly salary of the harvester's operator - 564 €/month or 6204 €/yr. According to the Labour Code of the Russian Federation (Trudovoy Kodeks Rossiiskoy Federacii 2005), additional payments have to be paid to workers for work during evening and night shifts. The size of the payments is 20% and 40% of day shift salary respectively. Thereby, the volume of the annual salary for evening shifts is 6513 €/yr (21):

6204*(10.2/12+0.2)=6513 €/yr

The total salary is 12716 €/yr (32):

6204+6513=12716 €/yr

The social levy paid from the calculated salary is 31.9% (Nalogoviy Kodeks Rossiiskoy Federacii 2005) or 4056 €/yr (33):

12716*31.9/100=4056 €/yr

The other variable costs are 2000 €/yr (34):

(18217+15000+12716+4056)*4/100=2000 €/yr

The total variable costs are 51989 €/yr (35):

18217+15000+12716+4056+2000=51989 €/yr

The risk rate (reserve fund) is 5 % of the total fixed and variable costs or 5268 €/yr (36):

5/100*(53366+51989)=5268 €/yr

The ttal costs of utilization of the forwarder for the 1st commercial thinning are 110623 €/yr (37):

53366+51989+5268=110623 €/yr

Therefore, the hourly cost of the forwarder exploitation is 35.40 €/h (38):

110623/(3560-122-313)=35.40 €/h

Table 20. Cost structure of forwarding.

Forwarder Valmet 830.1			
Factors and costs	Symbols in the formulas	Values	
Number of shifts	NS_i	1.9	
Duration of 1 shift	DS_i	8 hours	
Total number of working days per year	NDY_i	231	
Average number of working days per month	NDM_i	21	
Number of month during a year with 1/2/3 shifts	NM_i1/2/3	0.8/10.2/0	
Total working time per year	TWT_i	3560 hours	
Total transfer time per year	TT_i	122 hours	
Time for repairs, breaks, maintenance and preparation work	TR_i	313 hours	
Exploitation time per year	ET_i	3125 hours	
Machine utilization degree	MUD_i	0.88	
Purchase price	PP_i	250000 €	
Operating life	OL_i	5.0 years	
Consideration	C_i	25 %	
Turn-in	TIR_i	24 %	
Leasing	LR_i	12 %	
Exchange value	EV_i	60000 €	
Extra payment for evening and night shifts	REP_s	20 and 40 %	
Social levies (including medical levies)	RSA_i	31.9 %	
Other costs	ROC_i	6 %	
Insurance	IR_i	2 %	
Fixed cost		€/yr	€/h
Deterioration	D_i	28125	9.00
Leasing	L_i	18188	5.82
Insurances	CI_i	5000	1.60
Other	OFC_i	2053	0.66
Total fixed costs	**FC_i**	**53366**	**17.08**
Variable costs		€/h	€/h
Inputs for fuel, oils and liquids	IF_i	18217	5.83
Repairs and maintenance	CR_i	15000	4.80
Salaries	S_{ti}	12716	4.07
Social levies	A_i	4056	1.30
Other	OVC_i	2000	0.08
Total variable costs	**VC_i**	**51989**	**16.64**
Reserve fond	RF_i	5268	0.29
Total	**C_i**	**110623**	**35.40**

Costs calculation for chipping

A Kesla C 4560 LF model has been selected as the test mobile chipper. The total working time TWT_i of the chipper strongly depends on local conditions, such as the volume of the biomass at each cutting plot, distance between the plots and distance for the wood chips transportation. Total working time TWT_i of the chipper can be calculated by applying the equation:

$$TWT_i = ET_i + TT_i + WT_i + TRB_i \qquad (39)$$

Where:

TWT_i – total working time, h/yr
ETi – exploitation time, h/yr
TT_i – transfer time, h/yr
WT_i – time for waiting for a chip truck, h/yr
TRB_i – time for repairs, breaks, maintenance and preparation works, h/yr

The hourly productivity of the chipper can be up to 150 loose m^3, but it can vary significantly depending on the specific conditions (Drum Chippers 2005). In order to foresee the influence of the specific conditions, it was assumed that the chipper's productivity is 70 loose m^3 or 25.2 solid m^3/h, on average.

During a year, the output of biomass for chipping from the 1st commercial thinning is 37814 m^3. Chipping of the collected biomass needs 1501 h/yr of exploitation time from the chipper (13):

$$37814/25.2 = 1501 \text{ h/yr}$$

The annual transfer time of the chipper is the same as for other machines, 122 h/yr. Because the chipper has no own chip container, the wood chips are loaded directly to the chip truck. Therefore, some part of the total working time of the chipper is spent waiting for the chip truck, while the wood chips are transported to a consumer (Hakkila 2004). The waiting time WT_i mainly depends on the distance for the wood chips transportation (number of the chip truck runs) and can be approximately estimated by:

$$WT_i = ((NR - 1) * DT_i / S_i * 2) * NP \qquad (40)$$

Where:

WT_i – time of waiting, h/yr
NR – number of chips truck runs per cutting area
DT_i – average distance of wood chips transportation, km
S_i – average speed of a chip truck, km/h
NA– a number of cutting areas per year

The quantity of the chips truck runs NR can be found by the following and because of the following calculations it has to be a whole number.

$$NR = VB_i / VT_i \qquad (41)$$

Where

NR – number of chips truck runs, runs/plot
VB_i – volume of biomass for chipping on a cutting area, m^3

`

VT_i – volume of transported wood chips per run of a chip truck, m^3

370/41.4=8.9=9 runs/area

The annual time of waiting WT_i is 1360 hr (40):

((9-1)*50/60*2)*102=1360 hr

The annual transfer time TT_i of the chipper was assumed to be the same as for the harvester and the forwarder, 122 h/yr.

Due to a lack of information about the exploitation of the chipper in the Leningrad region of Russia, the time of breaks, repairing, maintenance and preparation works was assumed to equal 10 % of the exploitation time ET_i or 113 h/yr (19):

1501 *10/100=150 h/yr

The total working time of the chipper is 3133 (11):

1501+122+1360+150=3133 h/yr

The following work regime was chosen for the chipper: 1 shift per day for 3.4 months and 2 shifts per day for 7.6 months or 1.7 shifts per day on average. The average number of shifts per day needed for chipping the harvested wood is quite small. This means that owing to the high productivity of the chipper, this machine can be used for chipping of process residues at sawmill yards, or any other sources of wood chips, along with the chipping of wood from thinnings.

The operation life of the chipper under the chosen working regime is 13 years (20):

20000/1501=13 yr

The normative consideration C_i for the chipper is 6%, thus the turn-in TIR_i of the chipper is 34% (21):

$(1-6/100)^{13}*100=34\%$

The turn-in of the chipper is 34%, thereby the exchange value EV_i of the chipper is 97920 € (22):

288000*34/100=97920 €

The annual deterioration of the chipper is 14622 €/yr (23):

(288000-97920)/13=14622 €/yr

The cost of leasing for the chipper is 24032 €/yr (24):

12/100*((13+1)*288000+(13-1)*97920)/(2*13)=24032 €/yr

The average insurance for leasing operations is 2% of the purchase price PP_i or 5760 €/yr (25):

288000*2/100=5760 €/yr

Other fixed costs are 1777 €/yr (26):

(14622 +24032+5760)*4/100=1777 €/yr

The total fixed costs are 46191 €/yr (27):

14622 +24032+5760+1777=46191 €/yr

Table 21 shows the calculated inputs for fuel, oils and hydraulic liquids for chipping.

Table 21. Total costs for fuel, oils and hydraulic liquids for Kesla C 4560 LF

Consumption		Exploitation time, h/yr	Total consumption, kg/yr	Average purchasing prices, €/kg	Total cost, €*
Fuel and lubricants	kg/h				
Diesel fuel	42.5	1501	63793	0.68	43379
Motor oil	0.086	1501	129	0.92	119
Gearbox oil			No data		
Hydraulic liquid	0.1	1501	150	2.00	300
Total					43798

* - calculated according to formula 28 of the Appendix 3

The costs of repair, spare parts and maintenance works are 17280 €/yr (29):

288000*6/100=17280 €/yr

The wage of the chipper's operator for day-shifts was assumed to be 0.43 €/m^3. The annual salary for day shifts is 9612 €/yr (30):

11*21*8*0.48*25.2*0.43=9612 €/yr

The additional payments for evening shift are 20% of the day-shift salary. Thereby, the volume of the annual salary for the evening-shifts is 8010 €/yr (31):

9612*(7.6/12+0.2)=8010 €/yr

Therefore, the total salary is 17622 €/yr (32):

9612+8010=17622 €/yr

The social levy paid from the calculated salary is 31.9% or 5621 €/yr (33):

17622*31.9/100=5621 €/yr

The other variable costs are 3373 €/yr (34):

(43798+17280+17622+5621)*4/100=3373 €/yr

The total variable costs are 87694 €/yr (35):

43798+17280+17622+5621+3373=87694 €/yr

The risk rate (reserve fund) is 5% of the total fixed and variable costs or 6694 €/yr (36):

5/100*(46191+87694)=6694 €/yr

The total costs of utilization of the chipper for the 1st commercial thinning are 140579 €/yr (37):

46191+87694+6694=140579 €/yr

Hence, the hourly cost of the chipper exploitation is 93.66 €/h (38):

140579/(3133-122-150-1360)=93.66 €/h

Table 22. Cost structure of energy wood chipping.

Chipper Kesla C 4560 LF			
Factors and costs	Symbols in the formulas	Values	
Number of shifts	NS_i	1.7	
Duration of 1 shift	DS_i	8 hours	
Total number of working days per year	NDY_i	231	
Average number of working days per month	NDM_i	21	
Total working time per year	TWT_i	3133 hours	
Transfer time	TT_i	122 hours	
Time for repairs, breaks, maintenance and preparation work	TR_i	150 hours	
Waiting time	WT_i	1360 hours	
Exploitation time per year	ETi	1501 hours	
Machine utilization degree	MUD_i	0.48	
Purchase price	PP_i	288000 €	
Operating life	OL_i	13 years	
Consideration	C_i	8 %	
Turn-in	TIR_i	34 %	
Leasing	LR_i	12 %	
Exchange value	EV_i	97920 €	
Extra payment for evening and night shifts	REP_s	20 and 40 %	
Social levies (including medical levies)	RSA_i	31.9 %	
Other costs	ROC_i	6 %	
Insurance	IR_i	2 %	
Fixed cost		€/yr	€/h
Deterioration	D_i	14622	9.74
Leasing	L_i	24032	16.01
Insurances	CI_i	5760	3.84
Other	OFC_i	1777	1.18
Total fixed costs	**FC_i**	**46191**	**30.77**
Variable costs		€/h	€/h
Inputs for fuel, oils and liquids	IF_i	43798	29.18
Repair and maintenance	CR_i	17280	11.51
Salaries	S_{ti}	17622	11.74
Social levies	A_i	5621	3.74
Other	OVC_i	3373	2.25
Total variable costs	**VC_i**	**87694**	**58.42**
Risk rate	RF_i	6694	4.46
Total	**C_i**	**140579**	**93.66**

Costs calculation of wood chips transportation

We estimated the cost-effectiveness of several trucks designed for transportation of round wood and chips. Some characteristics of the trucks are presented in Table 23.

Table 23. Characteristics of trucks.

Model of the truck	Maximum load capacity, kg	Current price, €			
		Truck	Trailer	Manipulator	Total
Log truck KAMAZ, volume of truck's body is 56.4 m^3	31000	31676	10294	16176	58146
Log truck MAZ, volume of truck's body is 56.4 m^3	28200	42294	9029	16176	67499
Log truck Scania, volume of truck's body is 71.9 m^3	38000	150000	60000	20000	230000
Chip truck KAMAZ, truck's body is 54.0 m^3	15475	36995	17500	-	54495
Chip truck MAZ, truck's body is 40.0 m^3	13300	37264	17500	-	54764
Chip truck Volvo, volume of truck's body is 115.0 m^3	38000	250000	100000		350000
Tree-length truck Ural, volume of truck's body is 42.5 m^3	20650	28240	7300	11200	46740

The costs of wood transportation by the selected trucks were calculated for the 1st and the 2nd commercial thinnings and the most cost-effective trucks were chosen. The wood transportation costs are presented in Figures 30 and 31.

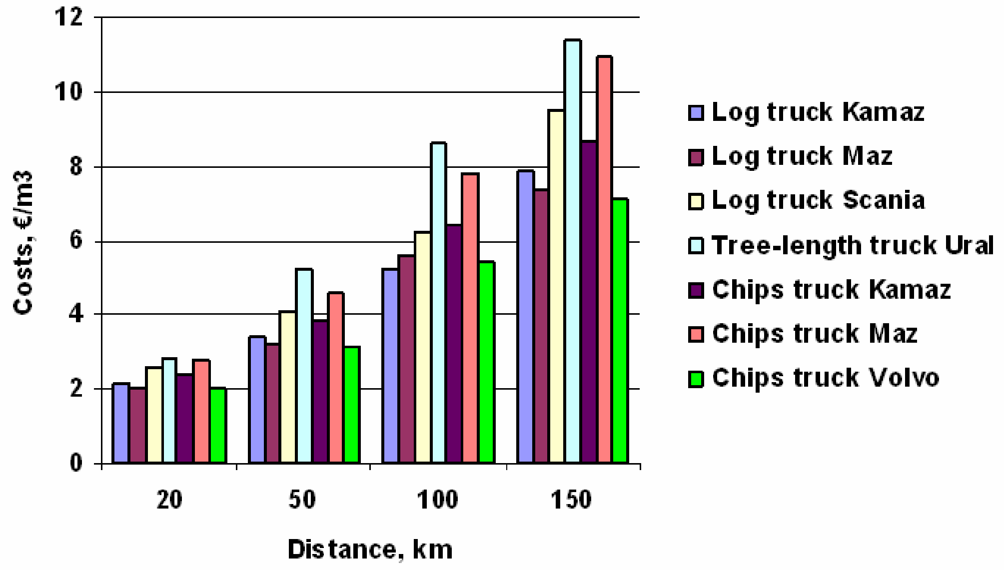

Figure 30. Costs of wood transportation for the 1st commercial thinning.

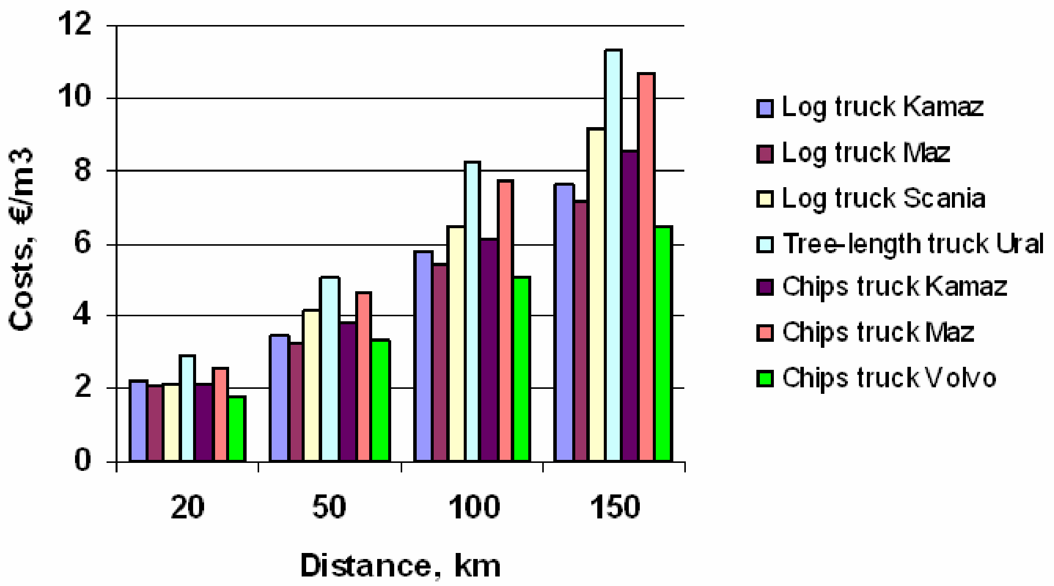

Figure 31. Costs of wood transportation for the 2nd commercial thinning.

Figure 30 shows us that log truck MAZ is the most economically reasonable choice for transportation of round wood for the 1st commercial thinning. Chip truck Volvo is the most inexpensive for transportation of wood chips among the three chip trucks considered.

Figure 31 shows that the same trucks are the most cost-effective for transportation of wood or chips for the 2nd commercial thinning and therefore they were also chosen for the transportation of wood biomass from the final felling and for transportation of process residues and chips from low landings and sawmill yards.

Taking into account the result mentioned above, the Volvo model has been selected as the test chip truck. The productivity of the chip truck depends on the distance of the wood chip transportation. When the transportation distance is 50 km, the productivity of the chip truck is about 10 m^3 per hour of exploitation time (Salo and Uusitalo 2001). Thus, exploitation time is 3781 h/yr (13):

$$37814*10.0=3781 \text{ h/yr}$$

The time for repairs, breaks, maintenance and preparation work TRB_i of the chip truck is about 13% of the exploitation time or 492 h/yr (19):

$$3781*13/100=492 \text{ h/yr}$$

The total working time of the chips truck is 4273 h/yr (11):

$$3781+492=4273 \text{ h/yr}$$

According to the calculated volume of total working time, the work regime for the chip truck is 2 shifts for 7.6 months and 3 shifts for 3.4 months, or 2.3 shifts per day on average.

The average annual run of the chip truck per year is about 91340 km (Salo and Uusitalo 2001). If the total normative run of the chip truck and the trailer is 600000 km and 900000 km respectively, then the operation life OL_i of the chip truck and the trailer is, respectively, 7 yrs and 10 yrs (20):

$$600000/91340=7 \text{ yrs}$$

and

$$900000/91340=10 \text{ yrs}$$

The normative consideration C_i for the chip truck is 14% and for the trailer it is 10%, thus, the turn-in TIR_i of the chip truck and the trailer are 35% (21):

$$(1-14/100)^7*100=35\%$$

and

$$(1-10/100)^{10}*100=35\%$$

The turn-in of the chip truck and the trailer are 35 %, thereby the exchange values of the chip truck and the trailer are 49000 € and 35000 € respectively (22):

$$140000*35/100=49000 \text{ €}$$

and

$$100000*35/100=35000 \text{ €}$$

The total exchange value EV_i is 84000 €:

49000+35000=84000 €

The annual deterioration of the chip truck is 13000 €/yr (23):

(140000-49000)/7=13000 €/yr

The annual deterioration of the trailer is 6500 €/yr (23):

(100000-35000)/10=6500 €/yr

The total annual deterioration of the chip truck and the trailer is 19500 €/yr:

13000+6500=19500 €/yr

The cost of leasing for the chip truck and trailer is 12120 €/yr and 8490 €/yr respectively (24):

12/100*((7+1)*140000+(7-1)*49000)/(2*7)=12120 €/yr

and

12/100*((10+1)*100000+(10-1)*35000)/(2*10)=8490 €/yr

The total cost of leasing is 20610 €/yr:

11876+8535=20610 €/yr

The average insurance for leasing operations is 2% of the purchase price PP_i of the whole truck or 4800 €/yr (25):

240000*2/100=4800 €/yr

The other fixed costs are 1796 €/yr (26):

(19500+20610+4800)*4/100=1796 €/yr

The total fixed costs are 46706 €/yr (27):

19500+20610+4800+1796=46706 €/yr

Table 24 shows the calculated inputs for fuel, oils and hydraulic liquids for the harvesting.

Table 24. Total costs for fuel, oils and hydraulic liquids for Volvo wood chips truck.

Consumption*		Annual run,	Total consumption,	Average purchasing	Total cost,
Fuel and lubricants	kg/km	km/yr	kg/yr	prices, €/kg	€**
Diesel fuel	0.5	91340	45670	0.68	31056
Motor oil	0.0006	91340	55	0.92	51
Gearbox oil	0.0002	91340	18	0.65	12
Total					31119

* - Salo, T. and Uusitalo, J. 2001
** - calculated according to formula 28 of the Appendix 3

The costs of repair, spare parts (including wheels) and maintenance works are 14400 €/yr (29):

240000*6/100=14400 €/yr

The salary of the chip truck's operator for day-shifts was assumed to be 0.31 €/m^3 of transported wood chips. The annual salary for day-shifts is 5041 €/yr (30):

11*21*8*10*0.88*0.31=5041 €/yr

The volume of annual salary for evening-shifts is 4201 €/yr (31):

5041*(7.6/12+0.2)=4201 €/yr

The annual salary for night-shifts is 3445 €/yr (31)

5041*(3.4/12+0.4)=3445 €/yr

Therefore, the total salary is 12687 €/yr (32):

5041+4201+3445=12687 €/yr

The social levy paid from the calculated salary is 31.9% or 4047 €/yr (33):

12687*31.9/100=4047 €/yr

The other variable costs are 2490 €/yr (34):

(31119+14400+12687+4047)*4/100=2490 €/yr

The total variable costs are 64743 €/yr (35):

31119+14400+12687+4047+2490=64743 €/yr

The risk rate (reserve fund) is 5% of total fixed and variable costs or 5572 €/yr (36):

5/100*(46706+64743)=5572 €/yr

The total costs of the utilization of the chip truck for the 1st commercial thinning are 117021 €/yr (37):

46706+64743+5572=117021 €/yr

Hence, the hourly cost of the chip truck exploitation is (38) 30.95 €/h:

117021/(4273-492)=30.95 €/h

Table 25. Cost structure of long-distance transportation.

Volvo wood chips truck, volume of body is 115 m^3			
Factors and costs	Symbols in the equations	Values	
Number of shifts	NS_i	2.3	
Duration of 1 shift	DS_i	8 hours	
Total number of working days per year	NDY_i	231	
Average number of working days per month	NDM_i	21	
Number of months during a year with 1/2/3 shifts	NM_i1/2/3	0/7,6/3,4	
Total working time per year	TWT_i	4273 hours	
Time for repairs, breaks, maintenance and preparation work	TR_i	492 hours	
Exploitation time per year	ETi	3781 hours	
Annual run		91340 km	
Machine utilization degree	MUD_i	0.88	
Purchase price: truck / trailer	PP_i	140000 / 100000 Euro	
Operation life: truck / trailer	OL_i	7 / 10 years	
Consideration: truck / trailer	C_i	14 / 10 %	
Turn-in: truck / trailer	TIR_i	35 / 35 %	
Total exchange value	EV_i	84000 €	
Leasing	LR_i	12 %	
Extra payment for evening and night shifts	REP_s	20 and 40 %	
Social levies (including medical levies)	RSA_i	31.9 %	
Other costs	ROC_i	6 %	
Insurance	IR_i	2 %	
Fixed cost		€/yr	€/h
Deterioration, total	D_i	19500	5.16
Leasing, total	L_i	20610	5.45
Insurances	CI_i	4800	1.27
Other	OFC_i	1796	0.48
Total fixed costs	$\mathbf{FC_i}$	**46706**	**12.35**
Variable costs		€/yr	€/h
Inputs for fuel, oils and liquids	IF_i	31119	8.23
Repair and maintenance	CR_i	14400	3.81
Salaries	S_{ti}	12687	3.36
Social levies	A_i	4047	1.07
Other	OVC_i	2490	0.66
Total variable costs	$\mathbf{VC_i}$	**64743**	**17.12**
Risk rate	RF_i	5572	1.47
Total	$\mathbf{C_i}$	**117021**	**30.95**

Total costs of wood chips supply for the 1st commercial thinnings

The cost calculation software developed by Laitila (2004, 2006), and Salo and Uusitalo (2001), based on methodology by Mäkelä (1986), was used to estimate the costs of wood chips supply. The calculation software and the methodology were adapted to Russian conditions. The methodology is described in Appendix 2. Costs calculations were made for different supply chains and thinnings, final felling. Central processing yards and sawmill yards were considered as sources of energy wood. As an example, detailed costs calculations for wood chips supply with a Valmet 903.1 with an accumulating head, a forwarder Valmet 830.1, a chipper Kesla C 4560 LF and a chips truck Volvo are presented in Appendix 3. In this example, wood from the 1st commercial thinning was used as a resource. The results of cost calculations for wood chip supply by this system of machines are shown in Table 26. Management cost was estimated as 4% of the production costs presented in Table 14. The total cost of wood chips was 15.32 €/m^3, which is close to the results of some other studies (Holodkov and Rogozin 2005).

Table 26. Total cost of 1 m^3 of wood chips.

Production stage	Cost, €/h	Productivity, m^3/h	Cost, €/m^3
Felling and bunching	39.73	7.40	5.37
Forwarding	34.04	12.10	2.81
Chipping	90.05	25.20	3.57
Transportation	29.76	10.00	2.98
Overhead costs	7.74		0.59
Total			15.32

Depending on local conditions, there are several ways to decrease the total cost of wood chips. As can be seen from Table 14, felling and bunching of wood demand the biggest inputs per 1 m^3 of energy wood due to the lower productivity of the operation compared to other stages. It significantly increases the total cost. Therefore, it is necessary to look at means to increase productivity of harvesting in current conditions. This may require the utilisation of harvesters specially designed for thinning operations.

Appendix 4. Prices of energy wood at final felling areas, central processing yards and sawmill yards

The prices of logging residues and non-industrial wood at final felling areas, and the prices of process residues at central processing yards and sawmill yards were obtained by phone interviews of logging companies and sawmills located in the Leningrad Region. From the total number of interviewees, 4 were big logging companies (average annual output 300 000 m3) and 4 were medium and small size sawmills (average annual output 50 000 m3).

The following companies were interviewed:

- “Domojirovskiy lespromhoz”, a logging company/sawmill
- “Efimovskiy kompleksniy lespromhoz”, a logging company
- “Russkiy les”, a logging company
- “Sampo”, a sawmill
- “Slavaynka”, a sawmill
- “Sosna”, a sawmill
- “Tihvinskiy kompleksniy lespromhoz”, a logging company/sawmill
- “Freza”, a sawmill

The interviews showed that logging companies could not define a selling price for loose logging residues from their cutting areas or lump stems and cross-cut ends at the central processing yards. Sawmills had difficulties in defining the price of bark. Two logging companies were willing to give the loose logging residues for free. Two companies wished only to sell loose logging residues. They were ready to say the price only after additional negotiations when purchase volumes of the loose logging residues had been agreed upon. The occurrence of logging companies who would like to sell the loose logging residues shows that with the development of a local energy wood market, the number of companies providing the loose logging residues for free will decrease. Therefore, to complete the calculation, the cost of loose logging residues and bark was placed at 2.9 €/ m^3 – the lowest recent price of wood resources for chips production.

All the logging companies provide information about prices of non-industrial wood (aspen). However, the prices of non-industrial wood varied significantly.

It was discovered during the interviews that sawmills use their wood residues for the heating of buildings or for timber drying. Only 2 companies out of 4 sawmills had non-utilised process residues and were able to sell it. Table 27 presents energy wood prices obtained from the interviews.

Table 27 Energy wood prices

Wood biomass	Selling price, €/m^3			
	At cutting areas		At central processing yard	
	Range	Average	Range	Average
Loose logging residues		2.9 (no answers)		-
Lump stems		-	2.9-5.9	4.4
Cross-cut ends		-	2.9-5.9	4.4
Non-industrial wood (Aspen)	2.9-8.8	5.9	7.3-19.1	13.2
Slabs		-	2.9	2.9
Strips of wood		-		No answers
Sawdust		-	4.6-5.7	5.2
Bark		-		2.9 (no answers)