Mapping the market of unrefined forest industry by-products in northern Sweden

– Industry by-product variation, county supply-demand balance, and optimization of transport cost.

Kartläggning av marknaden för oraffinerade skogsindustri biprodukter i Norra Sverige – Variationen mellan industriers biproduktproduktion, balans mellan länens utbud och efterfrågan, samt optimering av transportkostnad.

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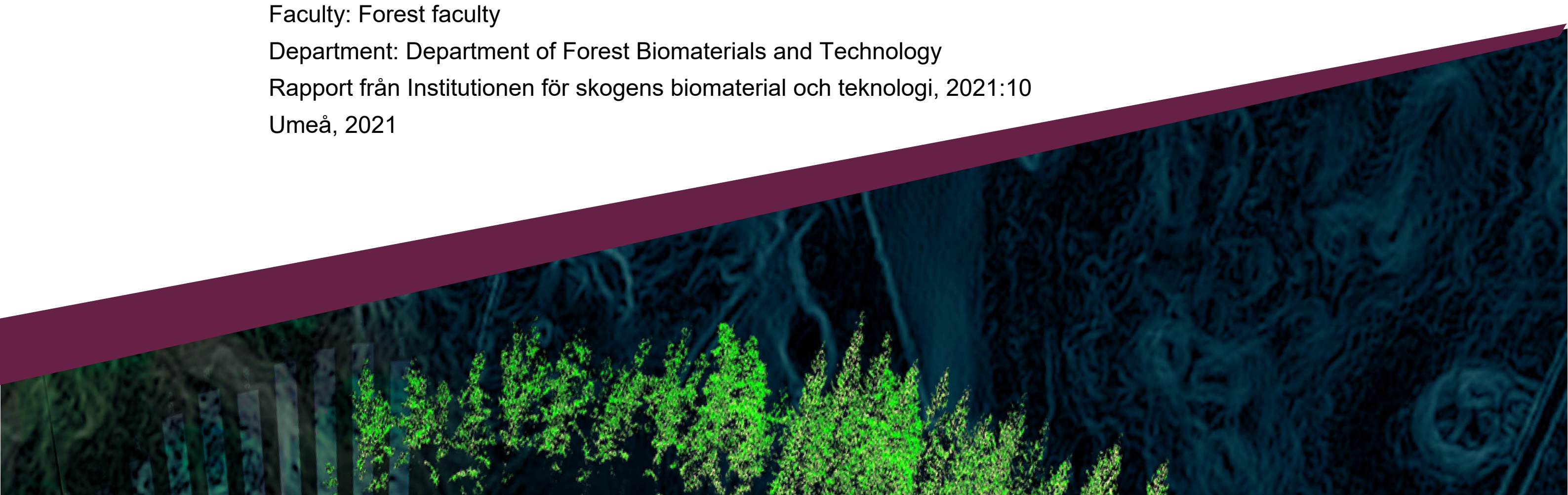

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Abstract

The forest industry plays an important role in the climate system. The need to reduce emissions of greenhouse gases is emergent, from a global perspective they are the driving force behind climate change. To reduce emissions, by-products from the forest industry can substitute fossil-based products. A global concern is the availability of by-products. And selection of business partners is of concern for the forest industry when it comes to refining by-product assortments. In this study the market for unrefined by-products in the four northern counties has been mapped and a balance between supply and demand for each county has been calculated. The data was collected from saw and pulp mills, public sources and from a transportation company. Further, the average cost of by-product transportation per MWh was minimized, using a linear optimization model. The results from the optimization were then used to calculate the average transport distance for each by-product..

The results of this study indicate a deficit of by-products in Northern Sweden, and that demands are likely to increase. In addition, the results showed a variation of by-product production between the categories of sawmills and pulp mills. Variation was also found within the categories. The sawmill with the highest production, produced 40 % more by-products per m^3sw than the one with the least production. The lumber yield makes a difference, but other factors are also important for share of by-products. These include integration with district heating, efficiency and assortment mix for the onsite sawmill boiler. Tree species and utilized technology at the supply unit, are other factors.
A key conclusion in this study is that such factors affect the prerequisites for market supply calculations. Therefore, these factors need to be addressed, to adapt to the future market demand. By-product users can use the results as an information base for new investments, and to improve established business connections.

Future studies should include larger sample sizes for demand and supply units, to determine what affects the market for and the production of by-products.

Keywords: Sawdust, Pulp mill, Sawmill

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Abbreviations

CO_2	Carbon dioxide
MWh	Megawatt-hour
GWh	Gigawatt-hour
TWh	Terawatt-hour
Mega	1 000 000
Kilo	1 000
M^3sub	Cubic meter of solid volume under bark
Km^3sub	Kilo cubic meter of solid volume under bark
M^3sw	Cubic meter of sawn wood
Km^3sw	Kilo cubic meters of sawn wood
SEK	Swedish Crowns
Supply unit	Sawmills and pulp mills
Demand unit	Heat and powerplants and pellet producers
BIU	Before internal use
AIU	After internal use
CV	Coefficient of variation
CTMP	Chemical-thermomechanical pulp
Lumber yield	Share of lumber from a volume of timber
SD	Standard deviation
n	Sample
2g	Second generation
UUWS	Unspecified unrefined wood assortment
C-chips	Cellulose chips

1. Introduction

1.1. Background

In 2017, Sweden adopted a framework to reduce emissions of greenhouse gases (Naturvårdsverket 2019). A long term goal in the framework, is to reduce emission with 85%, from the benchmark year 1990 to 2045 (Morfeldt et al. 2019). In 1990, Sweden's emissions were around 70 mega tons of CO_2 equivalent (ibid). These emissions cause detrimental effects to the global community (Scholze et al. 2006). From a global perspective, emissions of greenhouse gases resulting in climate change poses wide-ranging risks. These include large scale drought, forest dieback, wildfires, and other full-scale biome shifts (ibid).

One of the tools to meet the Swedish climate goals is to increase use of biomass to substitute fossil fuels (Bonde et al. 2020). In Sweden most of bioenergy is produced with forest industry by-products. Overall the Swedish climate council sees sustainable biomass as an important matter in order to meet the climate goals (ibid). Forest industry produces several by-product assortments, each with different applications from an industry perspective as well as terminology (figure 1).

Terminology for tree fuels is relatively wide and incorporates several different assortments. For this study, the following definition has been used as a starting point. 'Tree fuels can be defined as tree or tree parts that has not passed any chemical process and stems directly from the forest or indirectly through pulp and sawmills' (Sandin et al. 2019).

Depending on origin, tree fuels can be divided into three categories (figure 1). 1) Energy forest fuel, i.e., quick growing species such as aspen, salix or poplar. 2) Recycled wood fuels, demolition timber, packaging wood, formwork timber and spillage from construction. 3) Forest biofuels, raw materials with no prior use (ibid).

In addition, forest biofuels can then be divided into three separate categories (figure 1). 1) Logging residues such as branches and tops (figure 1). 2) Round wood without industrial use such as wood with rot damages and other discharged logs from industries (figure 1). 3) By-products from the industries such as dry chips, c-chips sawdust, bark and shavings (figure 1) (ibid).

Forest biofuels can be further divided depending on if the fuel is unrefined or refined (ibid). In the unrefined fuels assortments firewood, bark (Figure 2: A), chips (Figure 2: B), sawdust (Figure 2:C), and shavings (Figure 2:D) belong. Some of these unrefined fuels go on to be refined and those include, fuel pellets, briquettes and wood powder (ibid).

This study focuses on unrefined by-products. For assortments this means sawmill by-products, more specifically the assortments of c-chips, dry chips, sawdust, bark, and shavings. Since some sawdust and bark is also produced at pulp mills these are included in the study.

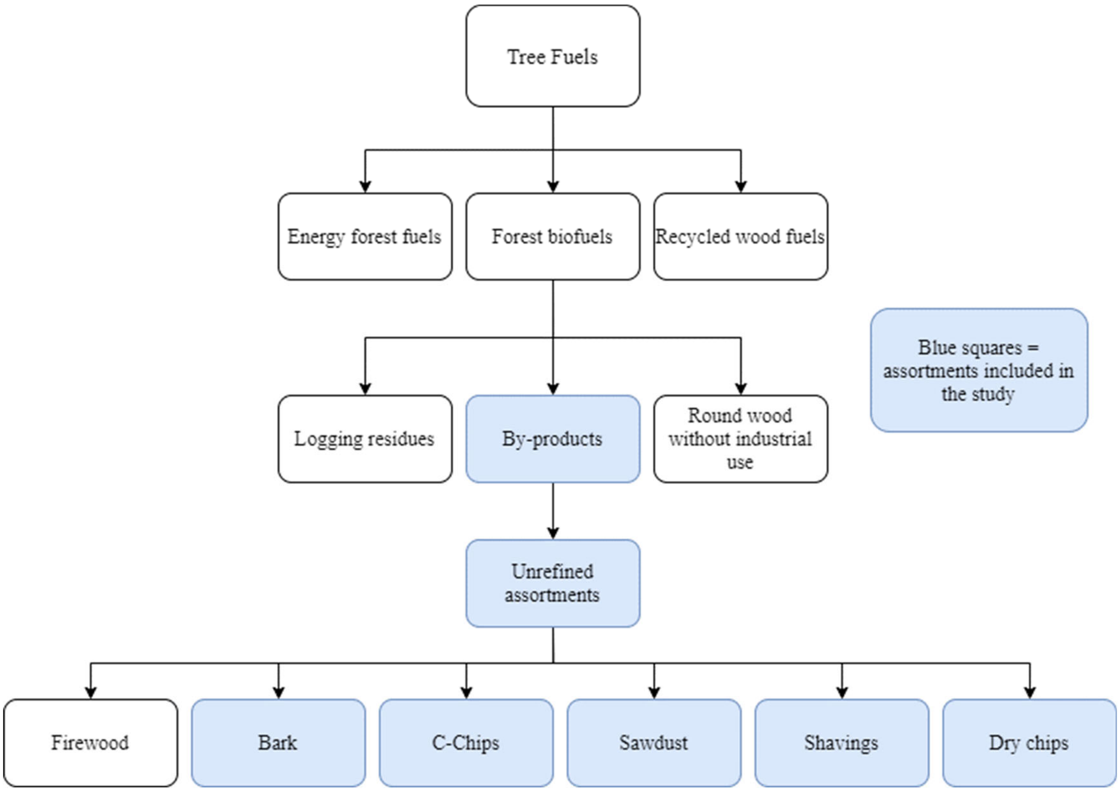

Figure 1: Illustration for the terminology of tree fuels. Tree fuels is divided into three categories. Energy forest fuels, forest biofuels, recycled wood fuels. Forest biofuels are divided into three categories. Logging residues, by-products, and round wood without industrial use. Some by-products from industry are unrefined assortments such as, firewood, bark, c-chips (cellulose chips, chips from raw saw logs), sawdust, shavings, and dry chips (Sandin et al. 2019).

Among the Nordic countries, Sweden has the most work to do to reach their climate goals by 2030 (Calmfors et al. 2019). Sweden must reduce emissions with 34%, while Norway must reduce with 28%, and Finland 23%. For the European union as a whole, the emissions must be decreased with 12%, to reach the climate goals by 2030. These changes entail consequences for unrefined forest fuels. The assortments sawdust, dry chips and shavings have four qualities that make them desirable (Brown et al. 2020). 1) They are homogenous which makes them better, from an industrial processing perspective. 2) They already exist in large quantities, so the infrastructure for procurement is available. 3) The prices for these assortments are low. The price for logging residues is generally twice as high (ibid). 4) The assortments can be used in combination with BECCS (bioenergy with carbon capture and storage) technology to reach net negative emissions of carbon (Fridahl & Lehtveer 2018). Thus, these four qualities combined could increase demand in the future.

For unrefined by-product assortments (figure 1) there are three angles to consider for the future availability on the market. First, the local supply and demand. Second, the price of purchase and transport. Third, the potential usage technologies in the future. In this study the first and second angle is in focus.

Figure 2. Picture of assortments, A = Bark, B = Cellulose-Chips, C = Sawdust and D = Shavings (Grabbe 2020).

As by-products come from a main process such as sawing wood at a sawmill, the potential volume available of these by-product assortments is connected to the volume the sawmill processes (Fridh & Christiansen 2015). From roundwood volume, around 50% becomes sawn wood products, 20% sawdust, 10% bark, 20% chips and 1 ton shavings/10m^{3}sw product (Staffas et al. 2015). During the year of 2013, the total estimation for all Sweden's forest industry by-products was around 23 TWh. The same year the estimated sold volume of by-products from only the sawmill industry was estimated to 6.4 mega m^{3}sub (Fridh & Christiansen 2015).

The market for by-products already exists, the question is how it will look in the future. Staffas et al. (2015) concluded the report by saying the following ‘With a changed price picture todays by-streams could become the main product that will drive the market but in today’s situation such is not the case’.

The global price of forest industrial by-products is low. Generally, by-products can be purchased from zero to 15 Euro for 1 MWh (Brown et al. 2020). The low price of by-products can be partly explained with collection and production costs. These costs are included when the price of the main product is calculated. Some biomasses can be pre-treated to produce feedstock with higher energy density, wood pellets from sawdust are such an example and is being refined in many places in the world. The market for pellets is international and large ships transport pellets in bulk. For example, countries within the European union buys pellets for clean power generation. Once the by-product is refined into pellets costs can range between 30-45 euro for 1 MWh (ibid).

Plants to refine feedstock such as sawdust are anticipated eventually to be located close to large amounts of low-cost feedstock and then hauled to user destination in an more energy dense form. In the short term when the by-product price is low, customers may profit just from buying at a low price. When the market starts to mature and there is more contention between customers it is likely that the feedstock will acquire value linked to final product price (Brown et al. 2020).

One study suggested that 2g biofuel production is a likely future use of by-products (Bryngemark 2019). Bryngemark (2019) performed a forecast scenario analysis where the scenarios were between 5-30 TWh of increased 2g biofuel production in Sweden by 2030. The implementation has started and one existing example of 2g biofuel production is in Kastet where Pyrocell has started production of pyrolysis oil (Setra Group 2020). Refined from 80 kilo tonnes of sawdust from the sawmill located next to the pyrolysis plant the production of pyrolysis oil could reach 25 kilo tonnes in 2021 (ibid).

To succeed with 2g biofuel production there is one factor that is most important. Festel et al (2014) concludes that raw material costs were the single largest driving factor for costs of production and thus the most important. To determine the future price of by-products The Swedish Environmental Research Institute (Sandin et al. 2019) has published factors they deem will affect future supply and price, they list transport distance and local/regional competition for supply as two of the factors. This study focuses on both the regional market and transport distances. Furthermore, collaborating this narrative Brown et al (2020) suggested that there is more work to be done when it comes to availability of feedstock. As Brown et al (2020) notes when commenting on feedstock, ‘Given the complex local considerations that influence likely availability and costs, such assessments are best carried out at national and regional level'.

This study focuses on the regional market for by-products in the four northern counties in Sweden, Norrbotten, Västerbotten, Västernorrland and Jämtland. The regional supply has also been overlooked in the official statistics; the Swedish Energy Agency has published official measurements in GWh since 2013. In the official statistics, there is only a breakdown for the whole country (Energimyndighetens statistikdatabas 2020). Another source, Björklund & Persson (2020) published for Biometria sawmill by-product amounts in Sweden from 2015 to 2019. The amounts were in kilo m^3f for 2019, 11408 for c-chips, sawdust, 5001, shavings, 793, and bark, 3613. The report series suggest that these statistics are published with low certainty, Björklund & Persson (2020) commented on their results saying, 'Many different units of measurements and recalculations in several stages' were behind the calculation for their results. Thus, within this area of research this study is one of the first to dive deeper into these statistics. These data are only available on national level and thus lacks the regional considerations applied in this study.

Few previous studies have examined the chosen study area; however, some have studied the area as a part of a larger study area. One study has looked at the effects of increasing demand for second generation biofuels domestically in Sweden. When simulating scenarios for increased biofuel production by 5-30 TWh Bryngemark (2019) showed that all prices for by-products increased with increased competition, meaning that even a small increase in demand affected the market price. Moreover, roundwood harvesting increased because of increased demands. Feedstock for heat and power plants changed where shortages of sawdust were covered by using harvesting residues (partly as more was available due to increased harvesting levels). All scenarios suggested that heat and powerplant industry would be affected most by increased competition. The heat and power industry would most likely have to increase use of other sources to substitute by-products (ibid).

1.2. Purpose

The purpose of this study is to describe the supply and demand situation for unrefined forest industry by-products in northern Sweden, and to present an optimization of transport costs.

Aims of the study:

1. Map the current 1) quantities of by-products produced 2) quantities of by-products demanded in the study area.
2. Analyse the market surplus or deficit at county level.
3. Calculate the cost of transport and average transport distance for dry chips, sawdust, shavings, and bark.

Delimitations

1. The study area will be in the four northern counties in Sweden, Jämtland, Västerbotten, Norrbotten and Västernorrland.
2. The study will include the following by-products, chips, dry chips, shavings, sawdust, and bark. Chips, dry chips, and shavings supply nodes will only be sawmills while bark and sawdust supply nodes can be saw-, and pulp mills.
3. Demand users are pellet producers and district heating networks.

2. Method and material

2.1. Mapping the market for forest industry's unrefined by-products in the four northern counties in Sweden

2.1.1. Conversion rates

To calculate the market supply and demand it was important to determine conversion rates between ton, m^3sub, MWh for the assortments sawdust, bark, c-chips, dry chips, and shavings. The conversion rates used in this study came from a transport company[1] that measured assortments coming from sawmills they co-operate with.

Table 1: Conversion rates between ton, m^3sub, MWh for the assortments sawdust, bark, c-chips, dry chips, and shavings with the measured moisture content in percent. Nd stands for no data.

Assortment	Ton	m^3sub	MWh	Moisture content (%)
Sawdust	1.0	1.2	2.3	50%
Bark	1.0	1.3	2.0	55%
C-Chips	1.0	1.1	2.2	50%
Dry Chips	1.0	2.0	4.3	17%
Shavings	1.0	Nd	4.2	Nd

2.1.2. Supply

In order to correctly map the market for forest industry by-products two sides had to be considered, the supply and the demand. The market supply relies heavily on a few producers i.e., sawmills and pulp mills. A Swedish forestry agency report (Skogstyrelsen 2014) was used to collect data on the current producers. Furthermore, the data provided an outline for which industries to include in the study. A report from the Swedish forest industries federation (Skogsindustrierna,

[1] Personal correspondence with employee of the transport company august 2020.

2020) further corroborated the list from the Swedish forest agency as there are available records of members in their organisation by county.

A transport company provided a list of current producers in the four northern counties in Sweden. This list was checked against the already created list and thus a final list of producers was created from these two sources. The transport company also provided production data on the sawmills and pulp mills for the calendar year 2019. For one of the sawmills, (Örarna) data on the amount of sawn wood produced was missing. Relevant data were then collected from the company´s website (Stenvalls Trä 2020). Several of the other companies in the producer´s list had provided information for current production pace online. This information was used to compare with the data on the producers list.

Further data collection involved information on how much forest by-products were created for a calendar year divided by each assortment, how much was consumed for internal purposes at the sawmill or pulp mill and finally for what year the data applied. Data collection took place by contacting company people responsible for selling forest by-products from locations on the list. When connection had been established, the companies were asked if they could provide the required numbers. In the cases where the companies answered yes, they were sent an e-mail detailing what information to provide.

When the supply data collection was finalised, all data was imported to Microsoft Excel where it was used to create a template. To create the template first all data had to be converted to the same unit, MWh was chosen for that purpose. The data for amounts of by-product (MWh) before and after internal use was then used in combination with the amount of pulp and sawn wood produced. This combination was used to create a ratio of by-products by assortment based on how large the supply unit's production was. The ratio was created individually for each of the sawmills and pulp mills that had provided data. The individual ratios was then used to create a weighted average ratio that took into account the varying production of sawn wood. A weighted average ratio was chosen over an arithmetic average as the data pointed to larger production units creating less by-products for each unit produced. For the pulp mills an arithmetic average was used. The final ratio was then applied to each of the saw- and pulp mills in the study area. The final product was the supply by assortment in MWh for each of the individual supply units. The final product also contained MWh by assortment both before and after internal use at the supply units. The internal use was in some cases detailed by the information provider as before and after internal use, while some internal use had to be estimated. The estimation for internal use at two sawmill cases where effect of the combustion yearly and fuel assortment mix was only described. A combustion rate of 89,1 % was used to recreate the initial supply. The combustion rate and fuel mix were based on information from personal correspondence with the company in question.

2.1.3. Coefficient of variation

Coefficient of variation (CV) is a measurement for independent numbers where variability can be compared. It is calculated by dividing the standard deviation (SD) with the mean of the sample (n) (Abdi 2010):

$$CV = SD/n$$

This was used in the study to compare sawmill data to one another in Tables 4 and 5. The greater the CV is the larger the variation in the data is.

2.1.4. Data validation

To validate the gathered data from the sawmill samples to the population of sawmills descriptive statistics was used. Descriptive statistics can be used to express the base information about a sample or a measure (Mishra et al. 2019). In this study, in order to analyse the sawmill sample the descriptive statistics used were percent and frequency. The frequency of sawmills within a production range between the population and the sample was compared. Furthermore, the percent of sawn wood production was compared within the ranges between the sample and the population. The ranges were from 0-150 km^3sw, 150-400 km^3sw and, 400-600 km^3sw.

Sawmill data sample compared to the population

Table 2 illustrates the differences between the sample and the population of sawmills in the study area. Closer inspection of the table shows that there is a difference in the distribution of sawmills in the sample compared to the population. The percentage of small sawmills (0-150 km^3sw) was larger in the population by 20% compared to the sample. For medium sawmills (150-400 km^3sw) the result was 7% smaller than the sample. For large sawmills (400-600 km^3sw) the percentage for number of sawmills in the range was smaller with 14%. Interestingly, the differences in the sample were smaller in comparison to the population when comparing production. The sample had a larger share of large sawmill production compared to the population with 8 percent shares. Furthermore, the sample has a smaller share of medium sawmills compared to the population with 7 percent shares.

Table 2: Number of sawmills in the population and sample within the production range of 0-150 km^{3}sw, 150-400 km^{3}sw and, 400-600 km^{3}sw. Percentage of number of sawmills within the range of 0-150 km^{3}sw, 150-400 km^{3}sw and, 400-600 km^{3}sw for the population and sample. Percentage of total production within the range of 0-150 km^{3}sw, 150-400 km^{3}sw and, 400-600 km^{3}sw for the population and the sample.

	0-150 (km^{3}sw)	150-400 (km^{3}sw)	400-600 (km^{3}sw)
Number of sawmills in the population	17	6	4
Number of sawmills in the sample	3	2	2
Percentage of total for population (%)	63%	22%	15%
Percentage of total for sample (%)	43%	29%	29%
Percentage of total production for population (%)	26%	35%	38%
Percentage of total production for sample (%)	27%	28%	46%

2.1.5. Demand

To estimate the demand in the study area several sources had to be used. At first determining who uses sawmill by-products was important. Bryngemark (2019) was used to model the domestic market for forest industry by-products. In the report the users of by-products were heat and power, pellets, wood boards, particle boards and, second-generation biofuels. For this study, the main users that have been considered are, pellet producers, district heating and biofuel production. Particle and wood board production has not been considered in this study as no production units are located in the study area.

Heat and powerplants

To estimate the use of by-products in the heat and power market there is data available from the industry organization Energiföretagen. The data series is updated annually; a timeline exists from 2014-2019. The data is reported in Excel format and is reported for each district heating network individually. Assortments are reported in GWh usage annually (Energiföretagen 2019). Shavings and sawdust are reported together, however bark is separated. Each network was checked geographically against the study area and only networks inside the studied area was included. The dataset included usage of several other resources, thus this had to be excluded for this study and only the relevant data was later imported to Excel.

Pellet producers

In order to estimate production of pellets in the study area Svebio's pellet map was used (Svenska Bioenergiföreningen 2019). The map is based on survey data gathered by Svebio. This dataset included tons of pellet production for each production unit individually. The production units were checked geographically against the study area and only units inside the area were included. To determine the raw-material consumption figure to produce 1-ton of pellets personal correspondence with one pellet producer was used. Thus, the ratio of 2.045 tons of raw sawdust with 50% moisture content to produce 1-ton of pellets was established. After that the demand was calculated in tons for sawdust it was converted to MWh with the conversion rate described in Table 1. The final demand was imported into Excel.

2.1.6. Distances from supply and demand nodes

The supply and demand nodes had to be described with coordinates. This was done with the help of a digital map service (Eniro 2020) where coordinates could be extracted in Swe ref 99 tm format by selecting location. For some district heating networks there was several boilers spread out, in this case the coordinates where the network had commitment to was chosen. For example, for Umeå Energy several boilers exist and thus the coordinates for the town Umeå were used. Coordinates could later be used to calculate distance between all locations. The calculation result was road distances in meters, this was later imported to Excel.

2.2. Linear programming theory

Linear programming is a part of the mathematic branch, applicable mathematics, and optimization theory. Optimization modelling can be used to analyse and describe linear problems. The purpose is to increase knowledge of the problem while presenting an optimal solution, given constrains the model is built on. Models are built on three parts, target function, constraints, and variables. The target function is the function that the user wants to optimize, functions can be either minimized or maximised. Constraints are what sets limits to variables. Variables are what the model can change to compute the optimal solution of the target function (Lundgren et al. 2008).

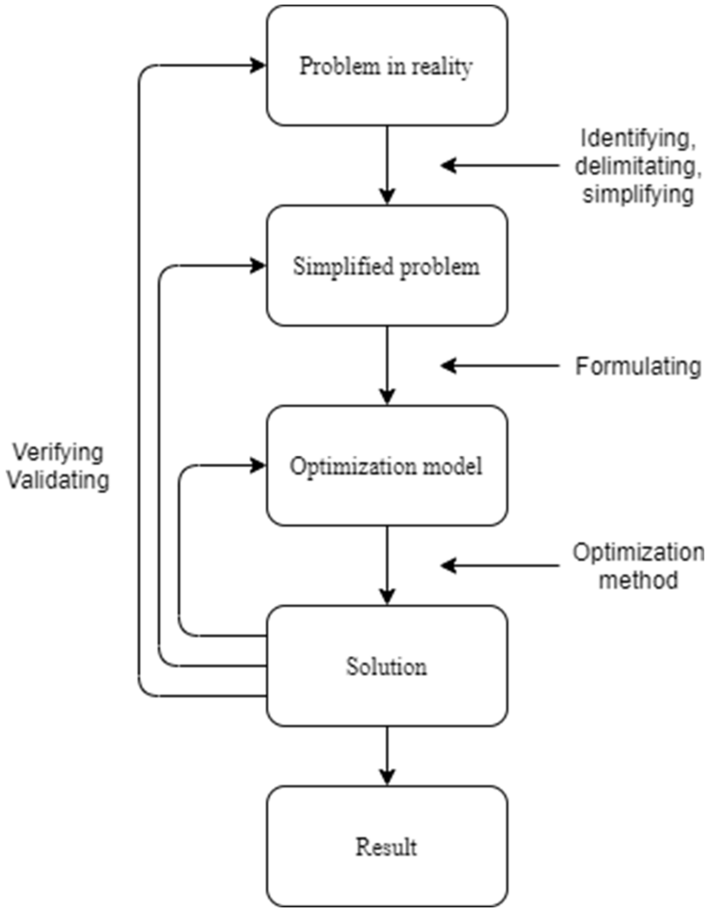

Figure 3: Schematic picture of the optimization process. Translation from: (Lundgren et al. 2008:9)

As described in Figure 3, the process anchors in a real problem. Real optimization problems can be complex. The complexity means that for models to have higher chances to be successful, delimitating and simplifying the problems is used. To do this it is important to identify the important parts to model. Problems can be streamlined to specifically answer what question the user is interested in answering. Thus, using this method the simplified problem is created. The next step is formulating an optimization model. Optimization models are built on target functions, constraints, and variables. Optimization method is usually either heuristic or exact. The exact method finds the solution that is the best. Heuristic method finds solution close to optimum. What kind of optimization model used depends on the problem and the desired results. The solution must be verified and validated against every previous step in the process. Once the user is satisfied with the solution this can be presented as results (Lundgren et al. 2008).

For this study, the real problem is characterised as a resource problem. This means there is a finite number of resources for the demand units. The objective function has calculated the total minimised cost of transport for each assortment from supply units to demand units. An objective function can be described as **f(x)** where **x**= (x_1, $x_2 \ldots x_n$) is a vector of decision variables. The values **x** could take defines the number of allowed solutions that exist. Constrains set the terms of how the objective function should be optimized. For example, one possible constraint could be built on resources available at supply nodes. Constraints restricts the possible values that **x** could take in the target function. For this study, minimization of the objective function was used when solving the linear programming problem. To formulate the general, minimize transportation problem the following terms must be described:

$$xij = transported\ units\ from\ supply\ unit\ i\ to\ customer\ j\ ,$$
$$i = 1, \dots, m\ \ j = 1, \dots, n$$
$$cij = transport\ cost\ (per\ unit)\ from\ supply\ unit\ i\ to\ demand\ unit\ j\ ,$$
$$i = 1, \dots, m\ \ j = 1, \dots, n$$
$$si = supply\ at\ unit\ i, \qquad i = 1, \dots, m$$
$$dj = demand\ at\ unit\ j, \qquad j = 1, \dots, n$$
$$z = The\ objective\ function(total\ minimized\ transport\ cost)$$

Then the model can be formulated as:

$$Min\ z = \sum_{i=1}^{m} \sum_{j=1}^{n} cij\ xij$$

Under the constraints:
$\sum_{j=1}^{n} xij \leq si,\ \ i = 1, \dots, m$ (supply)
$\sum_{i=1}^{m} xij = dj,\ \ j = 1, \dots, n$ (demand)
$xij \geq 0\ \ i = 1, \dots, m; j = 1, \dots, n$
(Lundgren et al. 2008:58–59).

2.2.1. Function used to calculate transport cost

To calculate cost of transportation a transport cost function from a transport company[2] was used.

$$c = 12{,}533x + 0{,}692y * x$$

Where c is the cost in SEK for transport of one truck load of by-products, y is transportation distance in km and x is amount transported in one truckload (tons). The different values that x can take are illustrated in Table 3. The values for x are also illustrated in Table 3 in MWh for comparison purposes.

Table 3: Normal truck loading volume in tons. Basis for payment in tons. Normal truck load in MWh. SEK for transporting 1 ton 1 kilometre. One-time cost in SEK per ton. One-time cost in SEK per MWh. Divided by the assortments, sawdust, bark, cellulose-chips, dry chips and shavings.

	Sawdust	Bark	C-Chips	Dry Chips	Shavings

[2] Personal communication with employee from the transport company september 2020

Loading volume (tons)	41.50	41.50	41.50	22.50	22.50
Basis for payment (tons)[3]	41.50	41.50	41.50	41.50	41.50
Loading volume (MWh)	95.50	83.00	91.30	96.80	94.50
SEK/km	0.69	0.69	0.69	0.69	0.69
One time cost SEK/ton[4]	12.53	12.53	12.53	12.53	12.53
One time cost SEK/MWh	5.45	6.27	5.70	5.38	5.50

As described in Table 3 the load weight in tons changes depending on the assortment transported, this is also the value inserted into x in the cost function. For dry chips and shavings, the load weight was lower, in the cost function the full load weight was used. No costs after delivery to demand units has been used for model purposes. Most companies deliver their load free industry meaning the industry pays for any additional cost that happens when inside the industry. One such cost is for measuring the amount delivered at the demand unit, this cost is paid by the buyer.

2.2.2. Optimization function used in the study

For this study, the model was altered to fit the problem. The real-world problem is different from the general model in two ways. The resources available at supply units are in total less than the demanded amount at demand units. Incentive for the model to send units was introduced by adding a cost for deficit at demand units. The artificial cost was set to a value of 10000 SEK, meaning for each truckload in deficit at demand unit j the cost would be 10000 SEK. Thus, the model used was the following.

$$xij = truck\ loads\ from\ supply\ unit\ i\ to\ demand\ unit\ j\ ,\quad i = 1, \ldots, m\ \ j = 1, \ldots, n$$

$$cij = transportcost\ (per\ truck\ load)\ from\ supply\ unit\ i\ to\ demand\ unit\ j\ ,\quad i = 1, \ldots, m\ \ j = 1, \ldots, n$$

$$si = total\ supply\ (truck\ loads)\ at\ unit\ i, \qquad i = 1, \ldots, m$$

$$dj = total\ demand\ (truck\ loads)\ at\ unit\ j, \qquad j = 1, \ldots, n$$

$$yj = defict\ (truck\ loads)\ at\ unit\ j, \qquad j = 1, \ldots, n$$

[3] In this study the basis for payment is set at 41,5 tons, this is because of the transport company as they take out full payment even if the load weighed less than the capacity of the truck.

[4] The one-time cost is for loading at the supply unit and driving to the supply unit.

$qj = \ cost\ for\ deficit\ (per\ truck\ load)\ at\ demand\ unit\ j, \qquad j = 1, \dots, n$

The objective function is formulated as:

$$Min\ z = \sum_{i=1}^{m} \sum_{j=1}^{n} cij\ xij + \sum_{j=1}^{n} yj\ qj$$

Under the constraints:

$\sum_{j=1}^{n} xij \leq si, \ \ i = 1, \dots, m$ (supply)

$\sum_{i=1}^{m} xij + yj = dj, \ \ j = 1, \dots, n$ (deficit amount)

$xij \geq 0 \ \ i = 1, \dots, m; j = 1, \dots, n$

$yj \geq 0 \ \ j = 1, \dots, n$

The objective function (min Z) calculates the total cost of transporting all assortments from supply users to demand users. This was minimized and the result is the lowest cost of transport for the function.

In cases where specific assortment demand existed this was handled by filling those volumes first. Meaning that for example sawdust demand at demand units were filled with sawdust first. If additional deficit still existed at demand units, the model would fill that with other acceptable assortments. For sawdust and bark demand other acceptable assortments were dry chips and shavings. Bark could not replace sawdust, dry chips, or shavings at demand users. The cost of deficit (qj in the model) was removed when calculating the cost of transport.

3. Results

3.1. Results from sawmill data collection

Table 4 below illustrates all sawmills in the study and their production in 2019. What stands out in this table is the variation in production between the larger sawmills and the smaller sawmills. This is particularly apparent in Västernorrland where Edsele Såg AB produces 28 km^3sw in comparison to SCA Wood in Bollsta with 550 km^3sw.

Table 4: Sawmills in the study area, location, owner, county, and production in km³sw for the year 2019.

Location	Owner	County	Production km³sw/year
Korpilombolo	Jutos Timber	Norrbotten	60
Tärendö	Krekula & Lauri	Norrbotten	52
Piteå, Munksund	SCA Wood	Norrbotten	420
Piteå, Lövholmen	Stenvalls trä	Norrbotten	140
Sikfors	Stenvalls trä	Norrbotten	140
Seskarö	Stenvalls trä	Norrbotten	0
Luleå, Örarna	Stenvalls trä	Norrbotten	65
Glommersträsk	Glommers Timber	Norrbotten	50
Älvsbyn	Älvsbyhus	Norrbotten	40
Brattby	Brattbysågverk	Västerbotten	50
Rundvik	SCA Wood	Västerbotten	315
Malå	Setra Trävaror AB	Västerbotten	210
Vännäs	NK Lundströms	Västerbotten	65
Sävar	Norra Skog	Västerbotten	256
Kåge	Norra Skog	Västerbotten	263
Agnäs	Norra Skog	Västerbotten	18
Bygdsiljum	Martinsson/Holmen	Västerbotten	430
Kroksjön, Skellefteå	Martinsson/Holmen	Västerbotten	117
Hissmofors	Norra Skog	Jämtland	120
Gällö	SCA Wood/Persson Invest	Jämtland	360
Svenstavik	Rödins Trä AB	Jämtland	78
Bollsta	SCA Wood	Västernorrland	550
Tunadal	SCA Wood	Västernorrland	550
Ullånger	MST Sågverk Ullånger AB	Västernorrland	35
Örnsköldsvik	Högland	Västernorrland	50
Anudsjö, Bredbyn	Högland	Västernorrland	190
Fränsta	Callans Trä AB	Västernorrland	85
Edsele	Edsele Såg AB	Västernorrland	28

Table 5 below illustrates the results of data collection for individual sawmills as well as conversion rates (MWh/m³sw) for amounts of by-products before internal use. The data from seven sawmills shows a large variation in between sawmills for MWh of by-products from producing one m³sw. In Table 5 the largest CV was obtained for shavings 95%, followed by dry chips 56%. The high CV is a surprising result, for example, the lowest value in Table 4 for shavings was 0.001 MWh (sawmill 5) and the highest 0.218 MWh (sawmill 3). Thus, sawmill 3 produced around 253 times more shavings per m³sw than sawmill 5. Conversion rates described in Table 5 shows there being a difference between a weighted and an arithmetic average. What further stands out from this table is three things. First, bark increased in average between the weighted and the arithmetic. Second, sawdust decreased with the weighted over the arithmetic average. Third, the difference of the total largest amount produced and the smallest amount. The weighted average total maximum value BIU (Table 5) was 2.467 MWh (sawmill 1) compared to the min value of 1.763 MWh (sawmill 7) with a CV of 11%. Thus, sawmill 1 produced 40% more by-products than sawmill 7 BIU. The weighted average total maximum value AIU (Table 6) was 1.968 MWh (sawmill 1) compared to the min value of 1.459 MWh (sawmill 7) with a CV of 11%. Thus, sawmill 1 produced 35% more by-products than sawmill 7 AIU.

Table 5: Amount of sawdust, bark, c-chips, dry chips, and shavings in MWh after producing 1 m^{3}sw at seven different sawmills. Standard deviation in MWh for sawdust, bark, c-chips, dry chips, and shavings. Coefficient of variation in precent (CV) for sawdust, bark, c-chips, dry chips, shavings and in total. Weighted(arithmetic) average for production BIU (before internal use) of sawdust, bark, c-chips, dry chips, and shavings in MWh after producing one m^{3}sw.

	Sawdust	Bark	C-Chips	Dry chips	Shavings	Total
Sawmill 1	0.586	0.329	1.262	0.174	0.116	2.467
Sawmill 2	0.724	0.397	0.785	0.145	0.006	2.057
Sawmill 3	0.246	0.391	1.200	0.000	0.218	2.055
Sawmill 4	0.452	0.277	1.103	0.068	0.090	1.990
Sawmill 5	0.365	0.417	0.976	0.103	0.001	1.862
Sawmill 6	0.548	0.190	0.952	0.060	0.036	1.786
Sawmill 7	0.430	0.250	0.904	0.127	0.051	1.763
SD	0.145	0.079	0.157	0.055	0.071	0.222
CV	30%	25%	15%	56%	95%	11%
MWh/m^{3}sw BIU	0.501(0.479)	0.295(0.332)	0.947(1.026)	0.102(0.097)	0.042(0.074)	1.887(1.997)

The arrangement in Table 6 below is the same as in Table 5, however the table illustrates the values after internal use. In comparison to Table 5, the CV had grown to 111% for shavings and dry chips to 73%. Closer inspection of the tables shows that the CV has increased for all assortments except c-chips and the total sum of MWh produced. In comparison to Table 5, the data shows that the SD for total MWh after internal use was lowered from 0.222 MWh to 0.184 MWh. There are two likely causes to increased CV and decreased SD in total. First, the assortment specific internal use between sawmills variated. For example, sawmill 4 consumed 0.267 MWh of sawdust for internal use while sawmill 5 and 6 consumed no sawdust. Second, the internal use in total was larger for sawmill 1 and 2 than sawmill 6 and 7 thus, bringing the min and max values closer to each other.

Table 6: Amount left after internal use of sawdust, bark, c-chips, dry chips, and shavings, in MWh after producing 1 m^3sw at seven different sawmills. Standard deviation in MWh for sawdust, bark, c-chips, dry chips, and shavings. Coefficient of variation in precent (CV) for sawdust, bark, c-chips, dry chips, shavings and in total. Weighted(arithmetic) average for production AIU (after internal use) of sawdust, bark, c-chips, dry chips, and shavings in MWh after producing one m^3sw.

	Sawdust	Bark	C-Chips	Dry chips	Shavings	Total
Sawmill 1	0.382	0.133	1.262	0.122	0.069	1.968
Sawmill 2	0.522	0.303	0.785	0.129	0.006	1.745
Sawmill 3	0.160	0.391	1.200	0.000	0.185	1.935
Sawmill 4	0.185	0.188	1.103	0.054	0.071	1.601
Sawmill 5	0.365	0.129	0.976	0.071	0.001	1.542
Sawmill 6	0.548	0.071	0.952	0.000	0.000	1.571
Sawmill 7	0.220	0.157	0.904	0.127	0.051	1.459
SD	0.146	0.103	0.157	0.053	0.061	0.184
CV	43%	53%	15%	73%	111%	11%
MWh/m^3sw AIU	0.381(0.340)	0.163(0.196)	0.947(1.026)	0.076(0.072)	0.029(0.055)	1.595(1.689)

3.2. Results from pulp mill data collection

Table 7 below illustrates the pulp mill roundwood usage. The roundwood usage variates between the counties. Norrbotten had a roundwood usage of 4850 km^3sub in 2019. Västerbotten only has one pulp mill active with 1100 km3sub (Obbola). Västernorrland had the largest roundwood consumption in the study area of 10815 km^3sub. What stands out for Table 7 is that for Jämtland county there is no active pulp mill.

One of purposes of data collection for pulp mills were to determine the conversion rates for by-products from pulp mills. It was found that most pulp mills in the study area were net users of by-products. As pulp mills were not considered demand units in this study only the mills with net excess of by-products were used to describe the market available amounts. The results showed that per m^3sub consumed of roundwood the pulp mills on average produced 0.020 MWh of sawdust and 0.204 MWh of bark. The amounts available for market (after own consumption of by-products) per m^3sub consumed were significantly lower, 0.0007 MWh of sawdust and 0.0146 MWh of bark.

Table 7: Pulp mills in the study area, location, owner, county the pulp mill is located in, and roundwood usage in km^3sub for the year 2019.

Location	Owner	County	Roundwood km^3sub
Karlsborg	Billerud Korsnäs	Norrbotten	1550

Lövholmen	Smurfit Kappa	Norrbotten	2200
Munksund	SCA	Norrbotten	1100
Obbola	SCA	Västerbotten	1100
Husum	Metsä Board	Västernorrland	3000
Östrand, Timrå	SCA	Västernorrland	4365
Ortviken	SCA	Västernorrland	950
Väja	Mondi Dynäs	Västernorrland	1200
Domsjö	Aditya Birla	Västernorrland	1300

3.3. Results for supply and demand in the study area

Table 8 illustrates the result of combining conversion rates for pulp and sawmills with the roundwood consumption and production of sawn wood. The demand figures are calculated with appendix 1 for district heating and appendix 2 for pellets. The most striking result to emerge from the data is that none the counties are self-sufficient on by-products in total. When compared Jämtland county has the largest energy deficit with 450.2 GWh. The second largest deficit is in Norrbotten county with 63.8 GWh. The third largest deficit is in Västerbotten county with 55.3 GWh. The fourth largest deficit is in Västernorrland county with 40.8 GWh. Norrbotten county was the only county self-sufficient on one assortment, bark with a surplus of 118.8 GWh.

Table 8: County supply and demand in GWh for sawdust, bark, c-chips (cellulose-chips), dry chips, and shavings for the calendar year 2019.

		Sawdust	Bark	C-Chips	Dry Chips	Shavings
Västerbotten	Supply	656.7	280.7	1632.5	130.2	49.2
	Demand	728.5	443.6	-[5]	*[6]	+[7]
Norrbotten	Supply	368.3	157.5	915.7	73.1	27.6
	Demand	651.6	38.6	-	*	+
Jämtland	Supply	212.5	90.9	528.4	42.2	15.9
	Demand	626.3	185.4	-	*	+
Västernorrland	Supply	584.9	635.9	1409.0	112.4	42.4
	Demand	1015.9	400.6	-	-	-
SUM	Supply	1822.5	1165.0	4485.6	357.9	135.1
	Demand	3022.2	1068.2	-	-	-

[5] C-Chips demand is not listed as everything is assumed to be sent to pulp mills directly.

[6] Specific dry chips demand does not exist, instead dry chips can fill deficit of bark or sawdust.

a[7] Specific shavings demand does not exist, instead shavings can fill deficit of bark or sawdust.

3.4. Linear programming results

One of the aims of the study were with help of linear programming to model the cost of transport and average transport distance for sawdust, bark, dry chips, and shavings. First for sawdust, the average transport distance was 44 km with a cost of transport per MWh of 18.7 SEK. Second for bark, the average transport distance was 59 km with a cost of transport per MWh of 26.7 SEK. Third for dry chips, the average transport distance was 62,8 km with a cost of transport per MWh of 24 SEK. Fourth for shavings, the average transport distance was 29.8 km with a cost of transport per MWh of 14.5 SEK.

4. Discussion

4.1. Sawmill

4.1.1. Production of sawn wood

The production of sawn wood at sawmills in this study was in total 4737 km^3sw in 2019 (Table 4). These results corroborate the findings from previous work, in comparison Björklund & Persson (2020) reported for 2019 a total of 4888 km^3sw for Region 1. These results were rather encouraging as they closely match the result from this study. Although Björklund & Persson´s (2020) results match the results from this study, there is still a difference of 151 km^3sw. There are two likely factors contributing to the difference in results. The first one being, that between years the production of sawn wood fluctuates. This has been further corroborated with Björklund & Persson (2020) where they reported the same numbers from 2015-2018. Starting from 2015 the data reported was, 4591 km^3sw, 4613 km^3sw, 4793 km^3sw, and 4780 km^3sw for 2018. The second being in sawmills with less than 1 km3sw produced has been fixed since the last inventory in 2000. These sawmills account for 60 km^3sub (Björklund & Persson 2020). For this study there is no sawmill with less than 1 km^3sub included. The differences are minor and thus, for this study it can be determined that the production of sawn wood is a relatively accurate result.

4.2. By-product production at sawmills

This study collected data and presented results from seven sawmills, regarding the production of by-products BIU and AIU. One of the surprising findings were that for both BIU and AIU there was a large discrepancy of MWh/m^3sw between the sawmills.

The latest sawmill inventory (Navrén et al. 2001), showed that the average lumber yield in Sweden was 47% for sawmills with a production over 5000 m^3sw/year.

Beyond the lumber yield of 47% the remaining percentages were: chips 34.3%, shavings 10.4%, and a rest of 8.3%. It has been suggested that the lumber yield can be higher. Gullmark & Zeneli (2018) reported a lumber yield of 52% on average. Beyond lumber yield, chips were 23%, dry chips 5%, shavings 15% and a rest of 5%. Overall, these two examples could account for a maximum difference of 5% in by-products. However, since the rest of 8.3% and 5% include volume lost during the drying process the difference is most likely less than 5%. One important thing of note here is that bark is not accounted for when comparing this study to that of Gullmark & Zeneli (Gullmark & Zeneli 2018), and Navrén et al (2001). Thus, when recalculating the CV without bark BIU the result for total production increases to 12% in this study. This shows that when accounting for all sawmills in the data sample the variation is greater than what can be explained with lumber yield. This finding was unexpected and suggests that there are more factors at work than lumber yield. There are several factors that may affect the share of by-products produced BIU:

1. The taper of the timber affects the possible lumber yield. Timber with a larger taper leads to higher share of by-products (Hoflund 2013).
2. Different wood species have different quality measures that affect the yield of by-products. Two of the measures that may affect by-product share concerning wood species is the average taper and bark share of the lumber. Most sawmills in the study produce sawn wood from one or two wood species.
3. Average diameter may affect the by-product share since a larger diameter of the timber most likely leads to a higher lumber yield. Thus, in extension the average diameter in the catchment area affects the theoretical by-product production.
4. How the timber is in sawn. Depending on the value of certain sawn products it might be more economical to sacrifice additional lumber yield to increase the value of the timber log. Thus, increasing the by-product share.
5. The way the debarking process is preformed may affect share of bark and thus by-product share.

The amount of by-products available after internal use are affected by additional factors. This area is relatively unstudied, thus there has been no available literature to compare with. This study has showed that there is a range in total consumed by-products for internal use of 0.119 MWh (sawmill 3) to 0.499 MWh (sawmill 1). Thus, sawmill 1 consumed more than 400% more MWh of by-products compared to sawmill 3 (Table 5 and Table 6). The arithmetic average of consumption for this study was 0.308 MWh/m^3sw produced. The share of consumption on average was

45% sawdust, 41% bark, 8% dry chips, and 6% shavings. A note of caution is due here as the sawmills had consumed quite different assortment shares for their internal use. For instance, some sawmills consumed no sawdust (sawmill 6 and 7), sawmill 5 consumed 90% bark and 10% dry chips. Thus, as the sample is small the average consumption on assortment level needs to be studied further. List of some of the factors that may affect this result:

1. The grade of refining at the sawmill, in some cases this is done off site but for some there are integrated technologies. For instance, some sawmills have integrated planning mills that increase the by-product amounts.
2. Integration with district heating networks. Some sawmills have installed flue gas condensation to be able to deliver heat. Thus, in some cases the sawmill can consume additional by-products if the demand exists.
3. The efficiency of the boiler at the sawmill, the boiler is used for combustion of by-products at the sawmill. It was suggested from some providers for sawmill data that the efficiency could variate as some had more modern components.
4. Overall energy efficiency of the sawmill. As the heat from the boiler in most cases is used to power the drying phase of the lumber. Thus, the efficiency of the dryers can change the need for additional consumption.

4.3. Pulp mill

4.3.1. Roundwood consumption

In the study the data for total consumption of roundwood for pulp production in the study area was 16.75 milj m^3fub in 2019. This can be compared to the data reported in Björklund & Persson (2020) for Biometria i.e., 13.1 milj m^3fub in 2019. The presentation of the data is different in two ways. Firstly, Björklund & Persson (2020) included data for Sweden in four regions; the first region (Region 1) in their report closely matches the study area except for Jämtland county. Where Härjedalen municipality inside Jämtland county was excluded. In the present study the whole Jämtland county was included. Secondly, consumption for particle boards was included (Björklund & Persson 2020). This inconsistency in the amount of roundwood consumed for pulp mills does not seem to be as a cause of how the data was presented. In this study there has been no pulp mill active in the municipality of Härjedalen. In the study area for this study there has been no production of particle boards as they are in other parts of Sweden. Thus, consumption for particle boards should not affect the result. The inconsistency could instead be related to investments, for instance SCA Östrand doubled their production during 2019, thus increasing roundwood consumption with the same factor (SCA 2020a). This cannot fully explain the inconsistency, and it is possible that results in this study overestimated the roundwood consumption at pulp mills.

A note of caution is due here when it comes speculating on the future as the market is in an expansion phase with several large changes coming. The future investments and shutdowns will affect the consumption of roundwood in the study area. List of some expansion uncertainties:

1. SCA has declared its intention to close the printing paper line in Ortviken mill, and at the same time develop increased CTMP pulp production starting in 2023 (SCA 2020b).
2. When the investment in Ortviken mill is initiated the CTMP line in Östrand mill will be closed (SCA 2020b).
3. Investments in Metsä Boards pulp mill in Husum where Norra Skog became partners in two ways, partly owning the pulp mill production (30%), and partly a long-lasting roundwood supply contract. In the press release it was discussed that the roundwood supply contract may decrease dependency on imported wood and instead increase Swedish roundwood supplying (7 2020).

4.3.2. By-product production at pulp mills

This study found that for every m^3sub of roundwood the pulp mills on average produced 0.020 MWh of sawdust and 0.204 MWh of bark. The sold volume was 0.0007 MWh of sawdust and 0.0146 MWh of bark. This outcome is contrary to that of Staffas et al (2015) who found that pulp production produced only one assortment. That assortment was bark at around 10% of the volume roundwood used, however no sawdust production was mentioned. Petersson (2018) corroborated the sawdust and bark result of this study, she concluded that both sawdust and bark were produced at the pulp mills. Furthermore, Billerud Korsnäs pulp mill in Karlsborg was included in the study, Petersson found that the mill had a production of sawdust at around 25 700 MWh, compared to this report where applying the average production would yield 31 000 MWh. These findings were unexpected as Petersson (2018) and Staffas et al (2015) report different results to each other and there is little to no focus given to these numbers. There are two likely causes for the inconclusive results. First, the area is largely unstudied and is mainly processed in larger studies with regional or national circumference. Second, the variation in between pulp mills could be too large to give a descriptive average for every pulp mill.

These results need to be interpreted with caution because of the large variation in between pulp mills and the small sample size. This study has acquired the full data from one pulp mill on production of by-products where it was apparent that large amounts were sold. Some data providers communicated no sales of by-products and were net users of by-products. This discrepancy could be attributed to several factors.

1. The way the pulp mill separates the fibres, there are three main ways to do this. Mechanical, sulphite and sulphate separation.
2. Integration with district heating networks. Some pulp mills have integrated with district heating networks where they can burn excess by-products to deliver heat and power.
3. There are differences in how the pulp mills refine their pulp product. Some mills have integrated lines where they produce products such as, paper and cartons.
4. Technology at the mill. Depending on what year and quality the mill components held there are variations in efficiency on mill level. Thus, leading to variations in volume of by-products used and produced.

These factors mentioned above can in the future also increase as investments increase the mill size and technology moves forward. There are also further ideas to integrate other technologies at pulp mills such as a biorefinery or smaller scale biofuel production. Thus, increasing the differences on a mill-to-mill level.

4.4. Supply and demand in the study area

This study found that in the study area the production of by-products was sawdust 1822.5 GWh, bark 1165 GWh, 357.9 GWh dry chips, 135.1 GWh shavings, and 4485.6 GWh c-chips in 2019 (Table 8). The demand in the study area was 3022.2 GWh of sawdust and 1068.2 GWh of bark from two industry segments: heat and power (appendix 1) and pellets (appendix 2). C-chips supply was assumed to be sent directly to the pulp mills; thus, they were not available to supply the demand for pellet or heat and power production. In total this study pointed to that in the study area there was a deficit of 610.1 GWh.

There may have been an effect on the results from the sample. The comparison in Table 2 showed there being a difference in the distribution between the sample and population of sawmills. The sample production of sawn wood in this study was based on larger sawmills in comparison to the population. There was also a smaller distribution share of medium sawmills in the sample. Small sawmills in particular but also medium sawmills showed a tendency to produce a larger amount of by-products compared to large sawmills. For secrecy purposes the sawn wood production and production of by-products could not be shown together. However, it is likely that since the population skewed more towards medium sawmills compared to the sample this has limited effect on the results. Assuming that the population would follow the same tendency, there would be an effect on the conversion rates towards more available by-products. At worst assuming all sawmills produce the same amount AIU as sawmill 1 the total would be 9733 GWh for the study area. In comparison to the results from this study that would be around 1767 GWh more or in total 122% of 7966 GWh. However, the real difference is probably much smaller as sawmill 1 was the sawmill with the largest amount of by-products produced per m^3sw out of the sample. The sample size would have to be increased to determine the effects of this aspect further.

There is one factor that has affected the accounted consumption of by-products for heat and powerplants and one factor that may affect the future demand of by-products. First there is a possibility that heat and powerplants accounted their consumption of by-products assortments incorrectly. There is some evidence for this as in Appendix 1 there is one category called UUWS (unspecified unrefined wood assortment) where the accounting might include the assortments in this study. The total consumption was around 456 GWh in the study area, since the assortment mix is unknown it is not possible to know to what degree the total is assortments included in the study. Secondly, the heat and powerplant consumption of peat that reached around 500 GWh in 2019 will eventually be phased out for fossil free assortments. One of the largest users in the study area Skellefteå kraft has the aim to phase out all their peat consumption by 2025 (Skellefteå Kraft 2019). The first factor suggest that the actual by-product consumption may be higher than what has been modelled in this study. The second factor suggests that in the future the demand for by-products may increase to replace peat consumption.

Björklund & Persson (2020) reported for Biometria a total sawmill by-product production for Sweden in 1000s m^3s, chips 11 408, sawdust 5 001, shavings 793, and bark 3613. When applying a flat conversion rate of 2 MWh/m^3 the total supply in GWh would be 41 630. In Björklund & Persson (2020) 26% of sawn wood production was in region 1. When applying 26% of 41 630 GWh the total comes to 10 882,3 GWh. This can be compared to this study where the total supply of by-products BIU was 8939 GWh and AIU was 7966 GWh. Björklund & Persson (2020) reported that the data for sawmill by-products was highly uncertain and their data had been converted several times before reporting. There are several possible explanations for this result.

1. The data in this study is built on a small sample size with seven sawmills, one pulp mill with full insight and thus, cannot be interpreted without some caution when comparing numbers from a study with larger sample size.
2. In this study the conversion rates have been the same for all sawmills and are accounted in Table 1. In Björklund & Persson (2020) the sawmills themselves reported numbers meaning the individual sawmills conversion rate was used.
3. For this study, the total supply of by-products was calculated for both BIU and AIU and this has not been separated in other studies.
4. When calculating the supply in this study the weighted average conversion rate was used as the data indicated that smaller sawmills produced on average more by-products than larger sawmills. The arithmetic average would have yielded more by-products.
5. In this study when recalculating the sawmill by-product data individual assortment conversion rates were used (Table 1). Björklund & Persson (2020) used a flat rate of 2 MWh/m^3s. This recalculation is to be considered uncertain as a flat rate of 2 MWh is not realistic for all assortments. Björklund & Persson also commented on that their data had in some cases not been separated by assortment while in this study the results were assortments specific.
6. It is possible that the share of by-products in region 1 could be higher or lower than 26% that was the share of sawn wood in region 1 for Björklund & Persson (2020). One factor that supports this is the catchment areas natural conditions that affect factors such as, share of tree species or growth zone. In turn that may affect the amounts of by-products produced. Thus, it can be suggested that on average some regions in Sweden could have more by-products than others per m^3sw.

However, the overall results for total by-products are encouraging as this study's result is comparable to Björklund & Persson (2020). These findings also suggest that the area has still many unanswered questions.

4.5. Supply and demand in county perspective

On county level this study has found that all counties had a deficit. The counties with a deficit were, Jämtland with 450 GWh, Norrbotten with 63.8 GWh, Västerbotten with 55.3 GWh and Västernorrland with 40.8 GWh. As the data for demand is actual numbers consumed there must be additional supply from somewhere else. A possible explanation for these results may be the lack of data from sources that make up the additional deficit.

1. Import from other regions outside the study area. Some data providers communicated observations of imports of by-product assortments from Norway to Jämtland, or from Finland into Norrbotten.
2. Lumber refinement offsite from the sawmill location. There are some industries that work on already sawn wood that can make up a part of the deficit.
3. Private persons/smaller companies that are not industry level but still produce significant amounts of by-products. Such as woodworking or smaller sawmills. These sources are hard to find data on, thus, it is difficult to estimate how large impact this segment has and if it is sold to the demand units used in this study.
4. Storages of by-product assortments. This study has not investigated the normal storage amounts and storage time of by-products. This could affect the results as it is possible that some consumption could be covered by production from another year than 2019.

These findings suggest that the dependence of additional by-products outside of the ones described in this study is largest in Jämtland county. The second largest dependence is in Norrbotten, this is also supported by the deficit being larger in comparison to the total by-product production in the county. Västernorrland and Västerbotten are both close to balanced. Västernorrland and Västerbotten are most likely not that affected by the marginal deficit considering the small size of the deficit in comparison to the production in the counties.

4.6. Linear optimization

In this study the results of the linear optimization indicate that the average cost of transportation ranged from 14.5 SEK (shavings) to 26.7 SEK per MWh (bark). The average transport distance range between 29.8 km (shavings) to 62.8 km (dry chips). Similar results were also reported by Steiner (2010) that suggested for 150km transport distance the cost of transport for by-products to be 95.24 SEK/ton. Recalculated with a flat 2 MWh/ton the cost of transport was 47.62 SEK/MWh. Another study by Friberg & Hansson (2012) looked at transporting branches and tops in a chips format for heat and powerplants. Their results showed an average cost of 37.82 SEK/MWh for a transport distance of 127 km. This is for another assortment; however, their load weight (22-38 tons) as well as a conversion rate of 2.8MWh/ton makes the studies comparable. Using this studies transport cost function assuming the load weight of 38 tonnes and conversion rate of 2.8MWh/ton the cost of transport for 127km would be 35.9 SEK/MWh. There are some factors that need to be considered that may have caused these differences in the results of the linear optimization.

1. The pellets production assortments (sawdust, shavings, and dry chips) have some bias in between themselves. The results of the optimization are biased towards lower cost of transport and lower distance for shavings. Dry chips are the opposite and is biased towards higher transport cost and distance. This is because of the number of MWh per truckload. Shavings have the lowest amount of 94.5 MWh/truckload in comparison to dry chips with the highest 96.75 MWh/truckload. Thus, it is more economical to fill sawdust demand with dry chips than shavings since all other factors are the same.

2. The prerequisites of the study were that demand was higher than the supply, this may have resulted in that some routes that are unrealistic proceeded as all supply had to be sent out. It is rather difficult to estimate just how much this has affected the results as further flow analysis would have to be done. However, it is likely that this aspect lowered the overall cost since the more available options in a model usually leads to higher fulfilment of the objective function.

3. Since the demand exceeded the supply and the model optimized to minimize transport cost the remaining demand is certainly the most expensive routes. With a margin of 650 GWh in deficit it is safe to assume that all the routes to the demand nodes with the highest cost would be left to send. This factor could be investigated by redoing the same optimization with artificial increased supply. This factor has certainly meant that the cost of transporting has been lower than if this factor was negated.

In summary it is likely that the actual cost of transporting and average distance of transporting by-products in the study area is higher than what has been reported in this study.

4.7. Strengths and weaknesses

This study has been limited by the lack of information given in some areas. First, the pulp mill round wood consumption and by-product production are almost unique to the specific mill. Thus, to fully describe this segment of the market more data would have been needed to limit the uncertainties for this study. Second, the sawmill data was collected from seven sawmills showed a variation in the delivered data. The delivered sawmill data has no indication of being incorrect, however, the data sample should be increased to limit uncertainties outside the data sample. Third, the linear optimization results are given under very specific constraints for the study area. Thus, the results need to be viewed under the prerequisites for the optimization. One source of weakness with the optimization is that the model had several possible unrealistic transport routes. Such as routes that are too long to transport by truck economically. Thus, if the optimization were to be redone those possibilities should be limited.

Despite the smaller data sample from pulp and sawmills this study does offer insight for the research questions of this study. The data for collected for the sawmills especially and where pulp mills delivered complete data is to be considered very certain. Thus, the strength of this study lies in the secure data for sawmills and pulp mills. The sawmill data is a larger sample size then for pulp mills and because of this can be more broadly used.

4.8. Conclusions

This study set out to contribute to the information state about the market for unrefined by-products in the four northern counties in Sweden. The aims of the study were to: map the present-day market for by-product users and suppliers. Describe the market surplus or deficit at county level. Identify the cost of transport and average transport distance for dry chips, sawdust, shavings, and bark. Discuss the future demand for industry by-products in the study area.

1. The investigation of the market has found that there are three large scale users of by-products in the study area, pellet, pulp and heat and power industry. The study is limited by the lack of information from users in within the pulp mill segment. The second major finding for this aim is that by-product suppliers were made up of sawmills and pulp mills.
2. Whilst this study could not confirm there being a deficit or surplus this study has indicated that in the study area there is a deficit of 610 GWh for by-products in total. The indicated deficit is largest in the county of Jämtland

with 450 GWh. Followed by Norrbotten with 63.8 GWh. The study suggested that Västerbotten with a deficit of 55.3 GWh and Västernorrland with a deficit of 40.8 GWh could balance themselves out considering the small deficit in comparison to the large production.

3. The present study has gone some way towards enhancing our understanding of what the cost of transporting and how long the average transport could be. This study found that shavings had the shortest average transport distance and lowest cost out of all by-product assortments with 29.8km and 14.5SEK/MWh. Bark was transported an average distance of 59 km with a cost of 26.7SEK/MWh. Sawdust was transported an average distance of 44 km with a cost of 18.7 SEK/MWh. Despite its limitations this study also offers some insights into transporting by-product assortments. It was determined that transporting dry chips were the most economical transport. Thus, suggesting that longer transports could be more suitable with dry chips.

4. This study lays the groundwork to describe the pre-conditions needed to fully understand the processes in play for future by-product supply and demand. This study has identified several factors that influences the future for by-products. Whilst this study did not confirm whether the demand would increase there are several factors that point towards an increase in demand.

4.9. Suggestions for future work

This study has showed that within sawmills and pulp mills there is a large variation of by-product production that previously has not been described in other works. This would be a fruitful area for further work, where opportunity lies in describing this more broadly. Work needs to be done to establish how much by-products are produced both BIU and AIU to fully describe the market. This study suggests a larger study where more samples can be collected to deepen the knowledge of conversion rates for the whole county. What is clear is that using older statistics for by-products production is no longer a viable option.

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Appendix 1

Table 9: District heating consumption of Bark, Sawdust, GROT (branches and tops), Peat, UUWS (unspecified unrefined wood assortments) in GWh divided by owner, county, and location for the year 2019.

Owner	County	District heating network	Bark GWh	Sawdust GWh	GROT GWh	Peat GWh	UUWS GWh
Adven Energilösningar AB	Västernorrland	Sollefteå	0.000	0.000	0.000	0.000	65.849
Adven Energilösningar AB	Västernorrland	Timrå	0.000	0.000	0.000	0.000	0.000
Adven Värme AB.	Västernorrland	Bollstabruk	0.000	0.000	0.000	0.000	6,953
Adven Värme AB.	Jämtland	Bräcke, Enycon	0.000	0.000	0.000	0.000	16,955
Adven Värme AB.	Jämtland	Funäsdalen	0.000	0.000	0.000	0.000	7,872
Adven Värme AB.	Jämtland	Hede	0.000	0.000	0.000	0.000	11.523
Adven Värme AB.	Västernorrland	Långsele	0.000	0.000	0.000	0.000	0.000
Adven Värme AB.	Västernorrland	Näsåker	0.000	0.000	0.000	0.000	0.000
Adven Värme AB.	Västernorrland	Ramsele	0.000	0.000	0.000	0.000	6.824
Arvidsjaurs Energi AB	Norrbotten	Arvidsjaur	0.000	0.000	0.000	6.400	32.000
Bodens Energi AB	Norrbotten	Boden	0.000	9.000	0.000	1.500	2.000
BTEA Energi AB	Jämtland	Berg	0.000	9.935	0.000	0.000	0.000

Gällivare Energi AB	Norrbotten	Gällivare-Malmberget	10.000	57.000	10.000	127.800	0.000
Haparanda Värmeverk AB	Norrbotten	Haparanda Miljö	0.000	0.000	0.000	0.000	0.000
Haparanda Värmeverk AB	Norrbotten	Haparanda Residual	0.000	0.000	0.000	58.997	0.000
Härnösand Energi & Miljö AB	Västernorrland	Härnösand	37.645	4.067	15.948	21.702	0.000
Jokkmokks Värmeverk AB	Norrbotten	Jokkmokk	0.800	0.000	0.000	0.000	0.000
Jämtkraft AB	Jämtland	Krokom	0.000	0.000	0.000	0.000	16.706
Jämtkraft AB	Jämtland	Åre	0.000	0.000	0.000	0.000	0.000
Jämtkraft AB	Jämtland	Östersund	185.400	119.000	37.200	35.300	0.000
Jämtkraft AB	Jämtland	Östersund Produktspecifik	0.000	0.000	0.000	0.000	0.000
Jämtlands Värme AB	Jämtland	Strömsund	0.000	18.500	0.000	0.000	27.800
Kiruna Kraft AB	Norrbotten	Kiruna C	0.000	0.000	0.000	0.000	0.000
Kiruna Kraft AB	Norrbotten	Vittangi	0.000	0.000	0.000	0.000	0.000
Luleå Energi AB	Norrbotten	Luleå	0.000	0.000	0.000	0.000	0.000
Luleå Energi AB	Norrbotten	Luleå Klimatneutral	0.000	0.000	0.000	0.000	0.000
Luleå Energi AB	Norrbotten	Råneå	0.000	0.000	1.000	0.000	0.000
Nevel AB	Västernorrland	Kramfors	0.000	0.000	0.000	9.235	0.000
Pajala Värmeverk AB	Norrbotten	Pajala	13.600	0.000	0.000	0.000	0.000
PiteEnergi AB	Norrbotten	Norrfjärden	0.000	0.000	0.000	0.000	0.000
PiteEnergi AB	Norrbotten	Piteå	0.000	0.000	0.000	0.000	0.000
PiteEnergi AB	Norrbotten	Rosvik	0.000	0.000	0.000	0.000	2.047
PiteEnergi AB	Norrbotten	Sjulnäs	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Boliden	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Bureå	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Burträsk	7.962	7.962	0.000	0.000	0.000

Skellefteå Kraft AB	Västerbotten	Byske	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Jörn	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Kåge	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Lidbacken	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Lycksele	56.085	48.807	16.727	42.277	36.168
Skellefteå Kraft AB	Västerbotten	Lövånger	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Malå	0.000	108.290	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Norsjö	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Robertsfors	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Skellefteå	118.203	130.632	69.941	63.605	89.751
Skellefteå Kraft AB	Västerbotten	Storuman	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Ursviken-Skelleftehamn	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Vindeln	0.000	0.000	0.000	0.000	0.000
Skellefteå Kraft AB	Västerbotten	Ånäset	0.000	0.000	0.000	0.000	0.000
Sundsvall Energi AB	Västernorrland	Kvissleby	0.000	20.599	0.000	0.000	0.000
Sundsvall Energi AB	Västernorrland	Matfors	0.000	0.000	0.000	0.000	0.000
Sundsvall Energi AB	Västernorrland	Sundsvall	0.000	0.000	0.000	0.000	1.732
Sundsvall Energi AB	Västernorrland	Tunadal	0.000	0.000	0.000	0.000	0.000
Sundsvall Energi AB	Västernorrland	Övriga nät Sundsvall energi	0.000	0.000	0.000	0.000	0.000
Umeå Energi AB	Västerbotten	Bjurholm	0.000	0.000	0.000	0.000	0.000
Umeå Energi AB	Västerbotten	Hörnefors	0.000	0.000	0.000	0.000	0.000
Umeå Energi AB	Västerbotten	Sävar	0.000	0.000	0.000	0.000	46.694
Umeå Energi AB	Västerbotten	Umeå	261.300	114.9	19.800	12.700	32.800
Vasa Värme Holding AB	Norrbotten	Kalix	14.216	0.000	3.105	0.000	49.467
Ånge Energi AB	Västernorrland	Fränsta	0.000	0.000	0.000	0.000	0.000
Ånge Energi AB	Västernorrland	Ånge	0.627	0.000	0.000	0.000	0.383
Övik Energi AB	Västernorrland	Bjästa	0.000	0.000	0.000	0.000	0.000
Övik Energi AB	Västernorrland	Bredbyn	0.000	0.000	0.000	0.000	0.000
Övik Energi AB	Västernorrland	Husum	0.000	0.000	0.000	0.000	2.423

Övik Energi AB	Västernorrland	Moliden	0.000	0.000	0.000	0.000	0.000
Övik Energi AB	Västernorrland	Processånga	224.713	87.736	15.611	65.398	0.000
Övik Energi AB	Västernorrland	Örnsköldsvik	137.654	56.831	13.934	55.839	0.000

Appendix 2

Table 10: Consumption of sawdust for the year 2019 in MWh divided by owner and county.

Owner	County	Sawdust usage MWh
Pajala Bioenergi	Norrbotten	28221.00
Bioenergi i Luleå (SCA energy)	Norrbotten	333948.50
Stenvalls trä. Sikfors	Norrbotten	211657.50
Glommers Miljöenergi. Glommersträsk	Norrbotten	11758.75
Baseco Golv. Sorsele	Västerbotten	7525.60
Skellefteå Kraft. Hendensbyn/Skellefteå	Västerbotten	174029.50
Klintpellets. Robertsfors	Västerbotten	117587.50
Bioendev. Holmsund	Västerbotten	0.00
Femett Pellets. Nordmaling	Västerbotten	18814.00
SCA Energy. Stugun	Jämtland	94070.00
Prima Pellets (Norrträ). Krokom	Jämtland	7055.25
Trä & Bygg i Lockne. Brunflo	Jämtland	1411.05
Härjeåns Energi. Sveg	Jämtland	376280.00
SCA Energy. Härnösand	Västernorrland	790188.00
SCA Energy. Tunadal	Västernorrland	56442.00