UNIVERSITÀ
DEGLI STUDI
DI PADOVA

DIPARTIMENTO TERRITORIO E SISTEMI AGRO-FORESTALI

SCUOLA DI DOTTORATO DI RICERCA

TERRITORIO, AMBIENTE, RISORSE E SALUTE

INDIRIZZO TECNOLOGIE MECCANICHE DEI PROCESSI AGRICOLI E FORESTALI

XXI CICLO

OPTIMIZATION OF WOOD ENERGY PLANTS SUPPLY

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31 gennaio 2010

RIASSUNTO

In questi anni il crescente interesse all'utilizzo di fonti energetiche rinnovabili in sostituzione a fonti energetiche fossili è stato determinato dalla consapevolezza della necessità di salvaguardare l'ambiente e di comportarsi in maniera sostenibile. Tra le varie fonti energetiche rinnovabili, le biomasse legnose svolgono un ruolo importante, grazie alla loro locale ed omogenea distribuzione. L'utilizzo di biomasse legnose permette la riduzione delle emissioni di gas serra, l'utilizzo di risorse locali disponibili e sostenibili, la riduzione della dipendenza riguardo alle importazioni di energia, la maggior sicurezza dell'approvvigionamento di combustibili, il rispetto degli impegni assunti nel corso della Conferenza Internazionale di Kyoto. Inoltre l'utilizzo delle biomasse legnose forestali favorisce l'incremento delle attività, introiti ed occupazione nelle aree rurali.

Per una corretta progettazione di un impianto è essenziale fare un'indagine sulla presenza di risorse disponibili sul territorio. La valutazione e la conoscenza della disponibilità di materia prima a livello locale e la logistica dell'approvvigionamento sono essenziali per evitare una competizione intrasettoriale e l'importazione di biocombustibili da altre regioni o stati. Quando si pianifica la posizione adatta per impianti o centri di stoccaggio è essenziale considerare l'uso attuale del territorio, la legislazione vigente e aspetti sociali ed economici.

Nella catena di approvvigionamento di biomasse legnose le operazioni di trasporto sono quelle che, a parità di tipologia di materia prima, maggiormente determinano la differenza di costo. Ottimizzare i trasporti significa utilizzare il minor sforzo di trasporto possibile per soddisfare una domanda di combustibile con le risorse disponibili. I trasporti possono essere minimizzati utilizzando in maniera ottimale la capacità di carico dei mezzi di trasporto e scegliendo la strada più corta verso la destinazione finale. Le alternative di approvvigionamento che minimizzano i trasporti privilegiando le risorse di combustibile locali sono maggiormente sostenibili anche da un punto di vista socio-economico.

Lo studio e l'ottimizzazione dell'approvvigionamento in piccole realtà locali, o anche a grande scala, può essere un valido strumento di supporto alle decisioni che il gestore di un impianto deve intraprendere per assicurare il funzionamento dell'impianto stesso e minimizzare i costi.

All'interno di questo lavoro di ricerca è stata realizzata una metodologia che combina l'utilizzo della programmazione lineare con i sistemi informativi geografici. Nello studio sono state prese in considerazione diverse modalità di approvvigionamento per le differenti tipologie di materiale disponibile sul territorio. Per il cippato forestale sono stati considerate tutte le fasi e relativi costi di approvvigionamento da bordo strada all'impianto. Per conoscere offerta e domanda di combustibile, sono state raccolte informazioni sulle fonti e sulla destinazione del combustibile attraverso interviste e attingendo a banche dati. Attraverso una elaborazione di "network analysis" effettuata con gli strumenti GIS, sono stati individuati i costi di trasporto da ogni fonte di biomassa (bosco o segherie) fino alle potenziali destinazioni. Nella programmazione lineare sono stati presi in considerazione le limitazioni di disponibilità di combustibile, i costi di approvvigionamento e le capacità massime delle varie fasi delle catene di approvvigionamento per soddisfare la domanda di energia degli impianti. Il risultato dell'elaborazione eseguita con il software "LINGO" evidenzia le destinazioni ottimali del combustibile, che vengono poi visualizzate su mappe in GIS.

La metodologia è stata applicata allo studio dell'ottimizzazione dell'approvvigionamento di due impianti termici a cippato situati in Val di Fiemme (Provincia di Trento). E' stato simulato l'approvvigionamento di biomassa nel corso di un decennio con materiale proveniente da scarti di imprese di prima lavorazione del legno e da residui delle utilizzazioni forestali. Un'altra simulazione ha riguardato lo studio dell'approvvigionamento di cippato, nel corso di un anno e

su scala bimestrale, in base alla domanda stagionale da parte degli impianti e alla disponibilità di residui nel corso dei periodi temporali considerati. In questo ultimo studio è stata considerata anche la possibilità di utilizzare un centro di stoccaggio del materiale. Sono state testate tre localizzazioni del centro di stoccaggio allo scopo di verificare la posizione più strategica, dal punto di vista economico. L'andamento dell'essicazione del materiale stoccato e dell'incremento della sua densità energetica è stato modellizzato dopo essere stato studiato con prove in campo. Alcune analisi di sensitività sono state realizzate allo scopo di verificare l'influenza dei diversi parametri considerati dal modello sul risultato finale. La metodologia applicata può essere utilizzata come strumento per decidere la localizzazione ottimale di impianti o centri di stoccaggio del materiale nel corso della loro progettazione.

Una metodologia simile, per studiare l'approvvigionamento di materiale su grande scala, è stata applicata nella regione della Finlandia Centrale in particolare per rifornire una centrale e una bioraffineria. I due impianti presi in esame hanno una domanda elevata di combustibile e quindi con una forte competizione per le materie prime. L'ottimizzazione dell'utilizzo delle risorse evidenzia le aree di destinazione delle varie forme di biomassa disponibile. Ponendo dei limiti di disponibilità a pagare da parte di un impianto, si vuole studiare l'effetto sull'area di approvvigionamento.

Nell'ottimizzazione dell'approvvigionamento nei dieci anni, la tipologia di approvvigionamento ottimale è la cippatura a bordo strada o in bosco ed il trasporto di materiale cippato all'impianto. Il cippato rimasto ad essiccare un anno è preferito, in quanto ha più elevato contenuto energetico. Per quanto riguarda lo studio dell'ottimale localizzazione di un centro di stoccaggio, tra le tre localizzazioni del terminal non si registrano differenze significative in termini di costo totale di approvvigionamento. Questo può essere dovuto alla piccola scala dell'area considerata. Inoltre ulteriori limitazioni sui volumi di trasporto dovrebbero essere prese in considerazione, magari adottando variabili binarie al posto di variabili continue. Per quanto riguarda le analisi di sensitività, la più utile anche dal punto di vista della logistica è quella del volume di trasporto di combustibile. Aumentando la capacità di trasporto dell'autocarro trasportante residui non cippati, questa modalità di approvvigionamento viene preferita. Diminuendo il contenuto idrico il cippato forestale è preferito a quello di segheria.

Ne caso finlandese preso in esame, la modalità di approvvigionamento ottimale risulta essere per entrambi gli impianti l'utilizzo di residui forestali trasportati tal quali fino a una distanza di 60 km e imballati per distanze maggiori. Ponendo limitazioni sulla disponibilità a pagare da parte di un impianto, l'altro ne trae vantaggio in quanto si approvvigiona da un'area più vicina.

Il modello matematico che è stato sviluppato, attraverso la programmazione lineare ed in particolare il "problema dei trasporti", ricalca la problematica di approvvigionamento da risolvere. Un modello così sviluppato può fornire soluzioni più flessibili rispetto alla semplice pianificazione manuale e allo stesso tempo permette di testare diverse strategie e diversi possibile scenari. Grazie all'utilizzo del GIS è possibile visualizzare chiaramente da un punto di vista geografico le soluzioni ottenute, altrimenti consultabili leggendo una lista di numeri difficilmente comprensibile. L'utilizzo della programmazione lineare assieme ai sistemi informativi geografici sono un utile metodo per determinare la migliore localizzazione di strutture o l'approvvigionamento ottimale di materie prime. Le diverse analisi di sensitività permettono di capire i fattori che maggiormente influenzano la logistica dell'approvvigionamento.

ABSTRACT

In the last years the growing interest to use renewable energies instead of fossil fuels has been originated by the awareness to protect the environment and to behave in a sustainable way. Between the renewable energies, the wood energy plays an important role since it is widely and homogenously distributed in the world. The use of wood biomass has a positive impact on the rural activities, development and employment.

Before starting any project of a new plant is necessary to survey the availability of resources at local level, their exploitation and supply chains involved. This is essential in order to avoid competition for resources and import from other regions or states. When planning the location of plants or storages it is necessary to consider the current land use, laws, social and economical aspects.

Transportation operations are the most costly operation of the supply chain. Optimizing transportation means to fulfil the demand with minimum effort and available resources. Preferable sustainable and socio-economical friendly solutions minimize transport by prioritizing local fuels. Transport can be minimized by optimal utilization of vehicle payload and choosing the shortest travel paths.

Studying the optimal supply both at small scale and large scale level is a valid decision support tool that helps decision makers to choose a good strategy to minimize costs and having supply efficiency. In this study a methodology that combines the use of linear programming and GIS has been developed. It considers different supply chains with all phases from stands to plants and relative costs. Surveys have been conducted with the purpose of knowing the location and demand of plants. A network analysis has been used to calculate transportation cost from sources (sawmills and stands) to destination. The linear programming considers the constraints of availability of wood fuel, supply costs and maximum capacities of supply phases. The optimization has been solved building a transportation model with the software LINGO and displaying results on GIS maps.

The developed methodology has been applied to optimize the fuel supply of two plants located in Fiemme Valley (Trento province, in north-eastern Italy). The plants supply with forest residues and sawmill byproducts has been modeled for a period of ten years.

The results show that chipping forest residues before being transported is cheaper than transportation of logging residues.

Another transportation model has been formulated considering the seasonal fluctuation of fuel demand and supply and considering the possibility of storing fuel at terminal. The optimal location of a new terminal has been evaluated. Sensitivity analyses were done to study the effects of some parameters in the whole system and its possible improvement.

Results of the test about the best terminal location show that terminal is used for only few volume of forest residues. As the formulation has been done, there are not significant differences in total costs comparing three terminal positions. This can be due also to the small scale area considered in the study. Observing results of sensitive analyses carried out during the study, the most useful is the one concerning the truck payload.

A transportation model has been built for the supply of two plants in the Central Finland region with the aim to identify the optimal allocation of forest fuel. Additionally a comparison of different plant's "paying ability" has been tested in order to see the effect on their supply areas.

In the Finnish case study both plants are optimally supplied with logging residues. When there are constraints on paying ability for one plant, the other one has advantages.

The wood energy plant supply analyzed in this study have been optimized using linear programming. The transportation model built in LINGO considers all cost factors along the supply chain, providing a global optimal solution. The decision variables are represented by fuel flows of different supply chains, while the objective function is to minimize costs of the whole system. Modeling produces more flexible solutions compared to manual planning, and allows easy testing of different strategies and scenarios. Using a GIS for modeling biomass supply allows to study the effect of variation of geographical factors on the supply and costs of biomass production.

1. INTRODUCTION

In Italy, as in many European countries, the interest in using biomass for energetic purposes is growing. Main reasons are the growing prices of fossil fuels, the consciousness of climate changes, the willingness to use local fuel sources and the willingness to produce energy in a sustainable way. Every European country has set ambitious objectives to increase the share of renewable energy sources, in order to struggle the climate changes and improve the security of supply. Using local fuel the target of employment in rural areas can be fulfilled. In European context, forest biomass offers a large and economic potential as a renewable fuel when managed on a sustainable way (Voivontas et al., 2001; Frombo et al., 2009).

Biofuels are often used by heating plants, which are usually operated by local communities to provide energy for villages or cities. The number of such heating plants is steadily increasing in Europe. The increased demand of biofuels has led to a growing demand for decision support tools. Since it is important to plan in a proper way, there is a need to integrate optimization models in the decision support tools to improve the efficiency of fuel supply.

Even if there has been a long tradition of woodfuel use in the North-eastern Italian Alps, the use of wood for heating was diminished to some extent in the second half of the last century because of the spreading of fossil fuels. Now use of wood is rising again, because of major awareness of the need to reduce fossil fuels use and to limit environmental impacts such as greenhouse gas emissions. Moreover, this growth is strengthened by political initiatives. For example, European and regional funds provide incentives and support for the development of District Heating (DH) and wood-fuelled boilers as sources of renewable thermal energy. Biofuel (e.g. wood chip) use in this context is mainly connected to grants.

This study considers the Veneto and Friuli Venezia Giulia regions as well as Trento province in North-eastern Italy (Figure 1), where 86 percent of the forests are located in mountainous areas (Cavalli, 2004).

Figure 1. Localization of the study area: Veneto and Friuli Venezia Giulia regions and Trento province. On the right Fiemme Valley

On the whole, the economic feasibility of logging operations in the Northeast Italian Alps is influenced by small private ownership structures, as well as the difficult terrain conditions (steepness and roughness), small harvested volumes driven by silvicultural requirements (Stampfer and Kanzian, 2006), and high transportation costs and long distances (Spinelli *et al.*, 2007). In the study area, forest operations are mainly carried out on steep terrain; this affects the operational methods, equipment, road network requirements, length of working period, and the availability of manpower (Cavalli, 2004).

Installed boilers and district heating (DH) usually require modest amount of fuel with short transportation distance, with a maximum of 40-50 km. Moreover most chips burned in DH are purchased sawmill byproducts.

Wood biomass availability from wood industry depends on sawmills presence and on the amount of processed volume per year. In this area sawmills are generally small and, especially on mountainous area, they are oriented to process coniferous timber. Sawmill byproducts supply concerns partly the local market and partly it leans on abroad market (Germany, Austria and Eastern countries) (Ciccarese *et al.*, 2004).

1.1SOURCES OF BIOFUEL FOR DH IN ALPINE AREA

Biofuels for DH in alpine Italian areas consist on forest residues, energy wood and sawmill byproducts. The difference between forest residues and energy wood is that the latter consists of trees planted in order to be used as fuel.

Thinning, coppice stand conversions and logging residues (tops, branches and un-merchantable wood) as byproduct of conventional timber harvesting are considered forest residues. Short rotation forests planted for fuel production are not common in alpine area.

In Italian flat areas (like Po Valley) fuel may be mainly provided by riverbanks and edges exploitation.

Forest area in North-eastern Italy covers the 24% of the total land (Cavalli, 2004). High forest stands are mainly located on mountainous area, while coppice stands are mainly located on foothill areas and in valleys. Some forest stands cannot be logged because of the terrain steepness and roughness or their low yield and thus economical restrictions. Difficult terrain conditions, small harvest volume driven by silvicultural requirements and small forest hodings result in high production costs (Stampfer and Kanzian, 2006).

Mountainous forest operation conditions, and especially steepness and a low forest road network density, influence the logging systems. The whole tree (WT) and whole tree combined with the cut to length (WT-CTL) logging systems are considered the most cost effective solution in alpine conditions. The feasibility of logging residues supply chain is possible when integrated with timber production. Integration of industrial roundwood harvesting and wood chip production makes costs savings and simplified operations possible (Asikainen, 2004; Spinelli *et al.*, 2006). Separate recovery of logging residues from the stump site is never profitable under mountainous conditions (Spinelli and Magagnotti, 2007). If trees are bucked (delimbed and cross-cut) in the forest, then it is better to leave the residues in the forest (Spinelli *et al.*, 2006). WT is the most suitable logging system in alpine coniferous stands and it allows the piling of tops, branches and un-merchantable logs at roadside (Spinelli *et al.*, 2001; Cavalli *et al.*, 2003). In alpine area residues from trees topped, delimbed and bunched at felling site are not used for chipping. For this reason to estimate logging residues availability for energy purposes, the shares of WT and WT-CTL system has to be taken into account.

In WT and WT-CTL systems felling operations are usually manually performed, trees extraction is carried out with cable crane or tractor and winch. When conditions allow it, extraction with tractor and winch or with skidder, or forwarder is more economical than cable yarding (Spinelli *et al.*, 2001). Processing is done at roadside with chainsaw or processor. Timber assortments and residues are collected in different piles. Residues as tops and branches are seldom bundled before being transported.

A wood chip production system is a series of various steps, including processing, transportation and decision making, with the goal of converting forestry woody biomass into fuel providing transport of this resource from the forest to the plant (Stampfer and Kanzian, 2006).

Forest residues supply chain includes collecting residues, chipping and transporting. Wood chip production systems are organized around the chipping operation. Position of the chipper within the whole system determines the type of biomass to be transported. Chipping can be done in the forest at roadside, at terminal or at the plant site. Chipping operations at roadside require the positioning of machines next to one another or in queue. In mountainous area, where there is no enough space, work process has to be separated and an additional machine for loading truck must be used. Biomass can be transported as harvesting residues, roundwood, pressed bundles or chips. The load density and the transportation distance are the factors that influence the choice of the supply chain (Stampfer and Kanzian, 2006).

Nowadays sawmill byproducts represent the most important source of wood chips for DH. Small and medium sawmills are widespread on northern Italy mountainous area. They are usually small, sawing less than 5000 m^3 round wood per year. There are only few bigger sawing up to 35 000 m^3 sawn timber. As an average, half of the sawn softwood is regionally supplied. Sawmill byproducts are sawdust, chips and slashes. The production of residues is often around 80-90 m^3_{loose} every second week.

DH usually draws up a contract with sawmills and forest enterprises in order to ensure its supply.

1.2 TYPES AND QUALITY OF SOLID WOOD-BASED FUEL IN ALPINE AREA

In the Italian alpine area forest fuel usually derives from:

- logging residues: tops and branches and un-merchantable logs
- thinning of trees with DBH less than 17.5 cm
- pastures clearing and cleaning from bushes and trees
- cleaning of riverbanks and urban parks

Wood fuels used in alpine area include residual forest biomass, energy forest fuel and industrial by-products. Energy forest fuel consists of trees planted in order to be used as fuel. Heating plants can use also other types of biofuels such as straw, waste paper and recycled wood.

Forest residues are un-merchantable trees, branches and tops left in the harvest areas or at roadside after the merchantable logs have been transported to sawmill, pulpmill or other destinations. Moreover in Northern Europe it is quite common to use also stumps from regeneration cuttings.

In Italy, wood residues from the industrial sector are mainly of two kinds (Cerullo and Pellegrini, 2002):

- non treated wood byproducts such as sawdust, chips, bark, wood shavings and slabs from sawmills, carpenters, wood-working factories, plywood factories, wood packing factories…
- treated wood byproducts deriving from the production of wood-based panels, veneer, furniture, and furnishings and made on wood with glue and paint.

Residues from the paper production are not mentioned here.

Wood from forestry and from wood industry is used in the form of firewood, wood chips, bark, shavings, briquettes, pellets and demolition wood for firing in, e.g., wood stoves, wood pellet-fired boilers, district heating plants and cogeneration plants (CHP). The technologies used at these plants specify various requirements in respect of the physical properties of the wood, i.e. size, size distribution, moisture content, ash content and pollutants (stones, soil and sand). Physical characterization of wood fuels is important when choosing fuels for various boiler systems and technologies. In addition, information on the physical properties of the wood fuel can be used when drafting contracts for the future deliveries, specifying the fuel in relation to certain types of boiler systems, and the drafting of quality description of wood fuel. Knowledge of these properties in relation to various types of wood fuels thus contributes to a promotion of an environmentally and economically optimal application of the fuel.

The European Technical Specification on solid biofuels terminology (UNI CEN/TS 14588) defines the forest fuel as wood fuel, where the raw material previously has had not another use. Only the not treated wood can be used for energy production in boilers and plants. Forest fuel is produced directly from forest wood by a mechanical process. To some extent forest fuel is a limited concept included in the wood fuel category, which means energy produced under sustainable forest management conditions direct from forest to power plants.

In the alpine area sawmill byproducts consist in sawdust, slabs and bark, deriving from logs sawing.

Biofuels can be divided into: firewood, sawdust and slabs, pellet and briquettes and wood chips. Here the attention is focused on wood chips.

FIREWOOD

Firewood is split, round or chopped wood from delimbed stems, cut-off root ends and top and branches of softwood or hardwood. Ready to use firewood is normally split to 15-35 cm. Chunks of 6-8 cm thickness are most suitable for the majority of wood-log stoves. Firewood consists in wood and bark.

SAWDUST AND SLABS

Sawdust and slabs are a byproduct or residue from wood industries. Sawdust has a dimension between 1 and 5 mm in diameter and length. Slabs have dimension varying with the logs, but they are usually sold transformed in other forms, such as chips or shavings. The moisture content varies with the drying time of the logs milled.

PELLET AND BRIQUETTES

Wood briquettes are square or cylindrical fuels in lengths of 10-30 cm and a diameter of 6-12 cm. Wood pellets are cylindrical in lengths of 5-40 mm and a diameter of 5-10 mm. Briquettes and pellets consist of dry, comminuted wood, primarily consisting of shavings and sawdust compressed at high pressure. The size distribution is very uniform which makes the fuel easy to handle. The moisture content is low, approximately 8-10% of the total weight.

WOOD CHIPS

Wood chips are comminuted pieces of wood in lengths of 5-50 mm in the fiber direction, longer twigs (slivers) and a fine fraction (fines). Whole-tree chips are chipped from whole trees including branches. Wood chips are also produced from top ends and other residues. All forest fuel must be chipped before they can be used as fuel by automatic feeding boilers or heating plants. Chipping can be made directly at the harvest area (in terrain), at roadside, at terminal or at plant according to the logistic of the supply.

The moisture content of wood chips produced from green trees is approximately 50-60% of total weight, but after summer drying of the trees for 3-6 months, the moisture content is reduced to approximately 35-45% of the total weight. Small chip-boiler can manage wood chips with a moisture content between 20 and 45% of the total weight, while district heating plants normally accept wood chips with a moisture content of 30-55%. Wood chips may be polluted with stones, soil and sand, which increase the ash content. The ash content in whole trees depends on the tree species, and the quantity of needles, branches and stemwood. The natural ash content in needles may exceed 5%, in bark and branches approximately 3% and in stemwood approximately 0.6%.

The standard and legal framework CEN TS 14961 and the ÖNORM M7133 define the requirements and test methods of chipped wood for energetic purposes.

The required type of wood chips depends on the type of heating system. A system for the quality description of wood chips based on size classification is specified in the Austrian norms ÖNORM M7133 and M7132 (Table 1.1). The same norms specify also classes for moisture, bulk density and ash content (Table 1.2).

Table 1.1. Percentage composition is intended in dry weight. The particle size is determined sieving samples of fuel

Class	**Share in composition and relative ranges for particle size, mm**				**Permissible extreme values for particle size**	
	Max 20%	60 - 100%	Max 20%	Max 4%	Max cross section, cm^2	Max length, cm
G30	> 16	16 - 2.8	2.8 - 1	< 1	3	8.5
G50	> 31.5	31.5 - 5.6	5.6 - 1	< 1	5	12
G100	> 63	63 - 11.2	11.2 - 1	< 1	10	25

Table 1.2. Classification of wood chips according to ÖNORM M7133

MOISTURE		
Class	Moisture content, %	Description
w20	< 20	Air-dry
w30	20-29	Long shelf life
w35	30-34	Limited shelf life
w40	35-39	Damp
w50	40-59	Freshly harvested

BULK DENSITY		
Class	Bulk density, kg m^{-3}	Description
S160	< 160	Low bulk density
S200	160-250	Medium bulk density
S250	>250	High bulk density

ASH CONTENT		
Class	Ash content, %	Description
A1	< 1	Small ash content
A2	1-5	Increased ash content

Also the norm UNI CEN/TS 14961 classifies solid biofuels according to origin and sources and according to fuel properties. The main fuel characteristics are dimensions, moisture, ash, particle density and chemical elements. The total moisture content is measured following the UNI CEN/TS 14774-1/-2/-3 and the particle size distribution following the 15149-1/-2. Ash content and particle density measures are done according to the UNI CEN/TS 14775 and UNI CEN/TS 15150 respectively. The UNI CEN/TS 14918, 15103 and 15104 give respectively instruction on determining the net calorific value, the bulk density and the chemical content of the sample. The determination of all those parameters is done on samples collected and stored according to UNI CEN/TS 14778-1/-2/-3, 14779 and 14780.

Wood fuel appraisal can be done in terms of quantity and quality. Quantity can be expressed weighting the material. When purchase price for wood fuel is based on weight or volume, weighting is needed. Determining the size is important also when the contract fees for wood fuel procurement are based on the produced amount. Knowing the quantity is possible also to compare costs of various fuels (Nurmi, 1992).

There are various factors that are influencing and affecting the quality of wood chips. Quality can be characterized in terms of moisture content, bulk density, particle size distribution, heating value, tree species (Nurmi, 1992). Sampling is necessary to evaluate those characteristics.

According to Zanuttini *et al.* (1998) the chip quality is defined by the moisture content, the particle size distribution, the tree species and the type of raw material (stems with or without bark, tops, branches…). Particle size distribution has a big influence also on the time and possibility to store chips and on the type of boiler that can use that chips (Spinelli *et al.*, 2004). Particle size distribution depends on the type of chipper and how it is adjusted (Spinelli *et al.*, 2004). Chips that are too large can create “bird nests” or block the feeders (Van Belle *et al.*, 2003).

The biomass moisture content (w) is the water amount content in the biomass and it can be expressed as a percentage of the dry or the green weight. This property has a great relevance on the energy production processes because it has a large influence on the biomass chemical characteristics, on its density (ρ) and on its heating value (ehv). Wood moisture content is extremely variable with species, size of the tree and drying time. The moisture content varies from one tree part to another. It is often the lowest in the stem and increases towards the roots and the crown. Seasons are also known to effect moisture content (Hakkila, 1962). The moisture content is considered to be an important quality parameter: low moisture contents increase the heating value of fuel, improve the boiler efficiency and reduce transportation costs of wood chips. In order to facilitate the drying process and thus ensure the availability of high quality fuel in short and long term, supply chains for wood chips should be designed to also account and promote natural drying of timber during the procurement process.

Moisture content has an influence not only on the ehv, but also on the logistic of energy wood supply. Moisture content, together with the physical characteristics of the woody biofuels are the main factors to be considered on the supply logistic in order to optimize harvesting, handling, processing, transportation and storage of wood solid biofuels (Allen *et al.*, 1996).

In Italy the maximum weight of a truck is 24 t and an average tare of 13 t. This means that the truck payload is about 11 t. Table 1.3 shows how the transported energy varies with moisture content considering a truck maximum volumetric capacity of 36 m^3_{loose} and a maximum payload of 11 t.

Table 1.3. Transported energy considering a limited volumetric capacity and payload - Calculation of data from literature (Hellrigl, 2006, Tsoumis, 1991)

	spruce		beech		willow	
w %	30	55	30	55	30	55
Wood density, kg m^{-3}	541.2	841.9	903.5	1405.5	550.9	857.0
ehv, MJ m^{-3}	6 923.3	6 189.6	1 0938.3	9 713.5	6 376.5	5 629.6
Chips weight, t	7.8	12.1	13.0	20.2	7.9	12.3
Payload, t	11	11	11	11	11	11
Chips loaded, t	7.8	11	11	11	7.9	11
Volumetric capacity used, %	100	91	85	54	100	89
Loaded energy, MJ	99 695	89 131	157 511	139 874	91 821	81 067

Energy content of wood can be considered the effective heating value of biomass with moisture (ehv_w). Biofuels always contain some moisture which has to be evaporated in the first stage of combustion. The heat energy for evaporation comes from the burning fuel. This lowers the amount of usable energy. The effective heating value of moist wood can be calculated with formula (1) (Hartmann *et al.*, 2000).

$$ehv_w = \frac{ehv_0(100 - w) - (2.44w)}{100} \qquad (1.a)$$

where

ehv_w	effective heating value of wood with a moisture content of w (MJ kg^{-1})
ehv_0	effective heating value of oven dry wood (MJ kg^{-1})
2.44	is the energy required to evaporate water at 25°C (MJ kg^{-1})
w	moisture content on total weight (%)

The main species considered in this study are Norway spruce (*Picea abies* ((L.) Karsten)), Scots pine (*Pinus sylvestris* (L.)), birch (*Betula* spp.) and other broadleaves. Their effective heating values of oven dry wood are in table 1.4. Values for tree species grown in Italy and in Finland are shown in Table 1.4..

Table 1.4. Energetic values of some species considered in the studies

Species	ehv_0	ρ_0	α_v
Norway spruce (Italy)	19.32[1]	430[2]	13.5[2]
Norway spruce (Finland)	19.30[3]	442[4]	16.3[4]
Scots pine (Finland)	19.70[3]	477[4]	13.6[4]
Birch (Finland)	18.60[3]	570[4]	16.3[4]
Other broadleaves (Finland)	18.71[3]	414[4]	14.9[4]

[1] from Kollmann (1951)
[2] from Trendelemburg and Mayer-Wegelin (1955)
[3] from Nurmi (1993) and Nurmi (1997)
[4] from Kärkkäinen (2007)

The volumetric mass or density (ρ_0) is defined by the ratio between the dry mass [kg] and the volume [m^3]. This value varies greatly both within and among species, although the density of most species ranges between 320 and 720 kg m^{-3}.

The heating value can be based on weight (kilogram of solid wood) or on volume of the wood. The heating value per volume unit ($ehvv_w$) can be calculated considering the low heating value (ehv_w) and the density (ρ) of the same sample with known moisture content (Hellrigl, 2006).

$$ehvv_w = ehv_w \cdot \rho_w \tag{1.b}$$

For moisture content on dry basis higher than 30%:

$$\rho_w = \rho_0 \frac{\left(1+\frac{u}{100}\right)}{\left(1+\frac{\alpha_v}{100}\right)} \tag{1.c}$$

For moisture content on dry basis lower than 30%:

$$\rho_w = \rho_0 \frac{\left(1+\frac{u}{100}\right)}{\left(1+\left(\frac{\alpha_v}{100}\cdot\frac{u}{30}\right)\right)} \tag{1.d}$$

where:

$ehvv_w$	heating value per volume unit (MJ m^{-3})
u	moisture content on dry basis (%)
ρ_0	density of oven dry wood (kg m^{-3})
ρ_w	density of wood with moisture content *w* (kg m^{-3})
α_v	swelling percent (%)

The solid volume of forest chips is determined by the loose volume of chip load and conversion factor (m^3_{solid}/m^3_{loose}). The heating values of spruce wood at several moisture content calculated with various conversional factors solid-bulky volumes is in Table 1.5.

Table 1.5. Effective heating value of spruce wood at different moisture content

w %	ehv MWh m^{-3}	ehv^1 MWh m^{-3}_{loose}	ehv^2 MWh m^{-3}_{loose}	ehv^3 MWh m^{-3}_{loose}
0	2.31	0.92	0.86	0.77
10	2.17	0.87	0.80	0.72
20	2.01	0.80	0.74	0.67
30	1.92	0.77	0.71	0.64
35	1.90	0.76	0.70	0.63
40	1.86	0.75	0.69	0.62
45	1.82	0.73	0.68	0.61
50	1.78	0.71	0.66	0.59
55	1.72	0.69	0.64	0.57

[1] using a conversional factor of 2.5 m^3 m^{-3}_{loose}

[2] using a conversional factor of 2.7 m^3 m^{-3}_{loose}

[3] using a conversional factor of 3.0 m^3 m^{-3}_{loose}

Measurement of bulk volume is easy if the nominal dimensions of the vehicle are known. Deficiency or excess of chips load height are the only measurement needed (Nurmi, 1992). Some heating plants determine the chip volume as equal to the nominal load volumes. This leads to an overestimation of the chip volume, even if the vehicle is fully loaded in the forest. This is due to the compaction of the chips by 2-14% during transportation. To have more accurate information, measure should be done at the delivery point of the chips (Nurmi, 1992).

Forest fuel has not been competitive with sawmill byproducts because of its high supply costs and varying quality. Additionally to cost and quality issues, a constant supply is required throughout the year.

The combustion behavior of the biomass fuels depends on the one hand on their chemical properties and on the other hand on the physical structure of the organic materials. The physical structure can be influenced by different processing techniques, like milling, cutting, compaction, baling, or pelleting (Strehler, 2000).
In plants smaller than 10 MW, the most appropriate technology for forest fuel is direct combustion in fixed-bed combustion system (grate furnace systems). Here the primary air passes through a fixed bed in which drying, gasification and charcoal combustion take place. In bigger plants fluidized bed boilers are better, because they tolerate larger quality variations. Grate furnaces are appropriate for wood fuel with high moisture content, varying particle size and high ash content (Van Loo and Koppejan, 2003). District heating units are usually built to meet the requirement of whole-tree chips, especially as regards the conveyor systems and combustion chamber (Strehler, 2000). However the driest is the fuel, the most energy it produces per unit.

1.3 STORAGE

Chip supply for district heating needs to be guaranteed around the year. Forest roads in mountainous regions are often inaccessible in winter time because of the snowy conditions. Therefore terminals for storing wood fuel can be an option to ensure supply. When plants are located in the vicinity of urban areas, chipping and crushing at the plant is sometimes a problem because of the noise and dust emissions. Thus, an intermediate storage terminal can provide a more acceptable place for chipping or crushing. In some situations plants do not have enough storage capacity.
According to Shapiro (2001) stocks are useful to hedge against the uncertainties of supply and demand or to take advantage of economies of scale associated with manufacturing or acquiring products in large batches. Wood fuel stocks are also essential to build up reserves for seasonal demands or promotional sales. Storing is an essential part of the logging residue production chain and logistic because it secures the availability of fuel throughout the year and improves its quality (Ranta, 2002). Wood fuel stocks are needed in order to balance the seasonal fluctuation in demand at the heating plants and in supply from forest (Gunnarsson *et al.*, 2004).
Organizing a storage terminal means both planning the storage site and duration, the form in which the material is stored and scheduling of storing in relation to other actions in the production chain. The storage area can be located in the forest, at the plant or at an intermediate site (Ranta, 2002). Centralized processing areas (storage) close to the forest can be useful in mountainous areas where there is small place for chipping operations at roadside. Concentration of residues derived from many small stands has positive effects on productivity and utilization of the chipper (Stampfer and Kanzian, 2006). Moreover storing the wood for some months positively affects the drying for some months increasing its energetic value.

Centralized collection of forest residues is important in mountainous areas in wintertime, when roads can be closed for the snow cover.
The disadvantages of storing wood fuels are dry matter losses, increased handling costs and capital costs. For seasonal storing there should be coordination between periods of production and use.

Natural drying is most suitable for stems and logging residues. Natural drying of chips is not so effective because the ambient air cannot penetrate into the chip pile and internal heating and microbial degradation may occur (Gigler *et al.*, 1999). Nurmi's studies (2000) on wood storage from conventional forestry operations show that if comminuting of wood by chipping, shredding or hammer-milling is followed by storage in piles, the dry matter losses can be significant, especially if the wood has not been dried before chipping.
Storage terminals can have a mobile chipper serving several customers (terminals or plants) or a stationary chipper. They can be furnished for storage both chipped and un-chipped forest residues. Chipped products require to be stored on hard surface and protected against rain. Un-chipped forest residues can be stored on any surface. Storage of forest residues (branches) deteriorates the energy value (Gunnarsson *et al.*, 2004). The storing of decay damaged wood, instead, improves the energy value (Brunberg *et al.*, 1998). Storages should be located in an easy accessible place and there must be enough place for chipper and vehicles. Trees and logs must be disposed in good order, facilitating chipping operations. Logistic for transportation is a key factor for a terminal.
During storage, the properties of forest fuel can change, due to physical, chemical and microbiological processes. Matter losses, presence of microfungi, drying and remoistening are the biggest problems mainly caused by weathering and that can be diminished covering unchipped residues and storing in a suitable storage location (Pettersson and Nordfjell, 2007; Thörnqvist, 1985; Nurmi and Hillebrand, 2007; Jiris, 1995; Nurmi, 1999).
According to Ranta (2002) storing costs are affected by the capital costs and the changes in energy content during storage due to solid material loss and heat value change. The costs of setting up a storage terminal and the costs linked with the covering of logging residue piles must also be included in the storing costs.
According to Gronalt and Rauch (2007), in designing the optimal system structure it is essential where the chipping and/or storage operations are located. In these storage terminals forest fuel is collected, stored, chipped and delivered to bioenergy plants. The spatial allocation and the chipping technology determine the whole forest fuel supply network. In their study Gronalt and Rauch (2007) presented an approach based on iso-cost curves. They affirm that for optimal supply network total costs of transportation and terminal must be considered.
In a study conducted in Austria, Kanzian *et al.* (2007) optimize the forest wood energy flow to several heating districts considering the option to use terminals for storage. They found out that if all residues are handled via terminals, the average supply costs inclusive of storage will increase by 28%.
The small and medium terminals have relatively modest annual fixed costs and generally also low average supply distances, of 10-17 km. The heating plants should, on average, not be further away than 50-55 km from these terminals (Kanzian *et al.*, 2008).

1.4 EVALUATION OF FOREST BIOMASS SOURCES

Knowledge about forest biomass resources is used in the strategic decision making as well as in planning of new heating plant investments and biomass harvesting at operational level. Therefore, reliable estimation methods of forest biomass availability are needed for different decision-making situations (Ranta, 2005).

According to Van Belle *et al.* (2003) in the short term, the supply of forest residues is not constant but fluctuates with the extent of harvesting activities. Annual harvested volume is depending on the forest resource, forest management types, climatic hazards, forest industry characteristics, economic conditions, etc.

Forest residues sources are present in many studies (Van Belle *et al.*, 2003; Malinen *et al.*, 2001; Nord-Larsen and Talbot, 2004; Masera *et al.*, 2006; Ghiraldi et al., 2007; Gronalt and Rauch, 2007; Kanzian *et al.*, 2009; Loeffler *et al.*, 2006) quantified according to the National Forest Inventory data. Other sources of data can be the remote sensing (Bååth *et al.*, 2002) or actual harvesting data from previous years (Ranta, 2002; Kinoshita *et al.*, 2009). In many studies geographical information systems (GIS) have been applied to map the availability of biomass fuel resources with respect to demand by facilities (Nord-Larsen and Talbot, 2004; Möller and Nielsen, 2007; Ranta, 2002; Noon and Daly, 1996; Graham *et al.*, 2000; Voivontas *et al.*, 2001; Kanzian *et al.*, 2007; Perpiñá *et al.*, 2009; Cavalli and Grigolato, 2007).

Forest biomass exploitation has to deal with the uses of wood and its environmental sustainability. Frombo *et al.* (2009) present an innovative GIS-based Environmental Decision Support System (EDSS) that can be used to propose and evaluate planning strategies that minimize the overall costs and take into account environmental impacts and technology options.

According to Voivontas *et al.* (2001), the analysis of biomass potential is set of four sequential step, in which the spatial distribution of fuel potential is identified, evaluated and therefore assessed considering the theoretical, available, technological and economically exploitable fuel sources. The *theoretical* biomass potential is defined as the total annual production of agricultural, forestry and other residues in a region. This potential is subjected to restriction such as alternative uses of residues and efficiency of residue collection procedures. The *available* biomass potential is defined as the energy content (or volume) of the biomass that can be technically and economically harvested and used for energy purposes. The *technological* biomass potential for a certain biomass source and a specific energy form is defined as the energy that can be produced and is bounded by technology. The *economical* potential is defined as the part of the energy that can economically exploited with respect to alternative energy sources.

1.4.1 Demand and supply of wood fuel

In order to design national or regional strategies for sustainable biomass energy use and exploitation, it is necessary to highlight spatial patterns of biomass demand and supply (Masera *et al.*, 2006). Knowing and matching demand of fuel and its availability is possible to show up deficit and surplus areas. Allocation model developed by Ranta (2005) was used for allocating the supply resources between demand sites from overlapped supply areas and for finding the optimal location according to supply resources. Allocating was based either on LP-optimization models or user-defined heuristic rules, using, e.g., plant-specific priorities (Ranta, 2005). Gronalt and Rauch (2007) design and calculated the costs of an optimal supply network for several medium and large scale energy plants through a stepwise heuristic approach.

Asikainen and Kuitto (2000) and Asikainen *et al.* (2001) showed that an important cost factor in wood fuel procurement is the scale of operation. Harvesting machinery is expensive and thus the annual output considerably affects the costs. Moreover, the greater the share of the potential fuel supply recovered, the higher the cost of procurement.

Nowadays, decision makers should plan the allocation of new bioenergy facilities in a sustainable way, considering the availability and the current usage of local resources.

Plant location and fuel supply problem has been in some studies approached with the location-allocation modeling (Noon and Daly, 1996; Graham *et al.*, 2000; Ranta, 2005; Panichelli and Gnansounou, 2008). Such model allows finding the optimal location of new facilities or supplying the existing one in a least cost manner (Chalmers et al., 2003). The overall objective is to minimize the total transportation cost, usually expressed as the product of demand and distance.

When the raw material in the region is scarce, the energy facilities have to compete for the biomass resources in order to meet their own demand. Collection areas may overlap and biomass amounts supplied to one plant will not be available for others (Panichelli and Gnansounou, 2008).

1.4.2 Transportation of wood fuel

In general, efficiency, productivity and cost of transportation depend on the following factors (Pottie and Guimier, 1986):

- form in which the material is transported: each form requires different hauling vehicle as well as different methods for loading and unloading;
- material solid volume content (SVF): is the ratio of the solid wood volume to the total bulk volume occupied by the material (Table 1.6);
- moisture content on a green weight basis;
- hauling vehicle used.

Table 1.6. Solid volume content (SVF) for various forms of forest biomass as transported (Pottie and Guimier, 1986)

Forest biomass form		SVF (%)
Roundwood	- Even length shortwood, piled crossways	65-75
	- Tree lengths	60-70
Firewood	- Stacked	55-70
	- Rough piled	30-45
Chips	- From roundwood	40-50
	- From whole tree or residue	35-45
Unprocessed residue	- Tops and branches	15-25
	- Logs and slabs	40-65
Hog fuel		35-45
Cross-cut residue (blocks, billets, bolts)		30-50
Full trees		30-45
Tree sections and small trees (loose)		25-40

Transportation costs are usually relevant on the wood fuel supply chain cost. If biomass is bulky piled and scattered on small stands, the transportation have an important contribution on the supply costs.

Transportation costs highly depend on travel time, which is a function of distance and road characteristics (Möller and Nielsen, 2007). Infrastructure and distribution of biomass resources have big influence on transportation costs. Heating plants need to be preferable located close to sources of fuel.

1.5 LOGISTIC AND SUPPLY CHAIN

Worrel (1959) states the problem of forestry: "The basic economic problem in forestry management is to achieve the most efficient use of productive resources. This problem exists because either some fixed amount of output is desired or only some fixed amount of one or more productive factors is available, which puts an upper limit on the extent to which the services of these factors can be used. In the first situation, economic efficiency requires that the fixed output be obtained at the least possible total cost. In the second situation, economic efficiency requires that the factors be used in such a way as to produce a maximum net return to the limited factor."

The traditional term "logistic chain" has been defined as covering the material flow from raw material to final customer, and flows of demand information and transfer of payments in the opposite direction (Lukka, 2004). The modern view is that "logistics" is a subside in the supply chain (Harrison and van Hoek, 2002; Ballou, 2004). Logistics management is the part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements (Council of Logistic Management, 2004). Thus logistics is concerned more as a company's internal process, whereas supply chain is a more holistic concept (Christopher, 1998; Tan, 2001).

Logistic chain modeling is very important in improving the overall performance of the total logistic chain (Slats *et al.*, 1995). When logistic models are designed, the planning problem is usually divided into three types of problems according to time horizons, namely: operative, tactical and strategic problems (e.g. Jang *et al.*, 2002; Chopra and Meindl, 2003; Ballou, 2004). The issues of production and allocation are usually regarded as operative planning (short-term) and capacity expansion as tactical level planning (mid-term), whereas the design of the distribution network is more strategic in nature (long-term) (Thomas and Griffin, 1996). These distinctions are not always clear because some supply chain problems may involve elements that overlap different decision levels (Min and Zhou, 2002).

According to Stock and Lambert (1987) the foundation of the integrated logistics management concept is *total cost analysis*, which they define as minimizing the cost of transportation, warehousing, inventory, order processing and information systems, and lot quantity cost, while achieving a desired customer service level.

According to Christopher (1998), the supply chain is "a network of organizations that are involved, through upstream and downstream linkages, in the different process and activities that produce value in the form of products and services in the hands of the ultimate customer". In a broad sense, a supply chain consists of two or more legally separated organizations, being linked by materials, information and financial flows (Stadtler and Kilger, 2000).

A considerable proportion of the total supply costs of forest fuel originates from the logistics activities: transportation, storing and handling. Energy density of forest fuels is typically low, therefore the transportation distance has significant effect on the procurement costs (Ranta, 2002).

STRATEGIC, TACTICAL AND OPERATIONAL PLANNING

According to Shapiro (2001) strategic planning involves resource acquisition decisions to be taken over long-term planning horizons, tactical planning involves resource allocation decisions over medium-term planning horizon, and operational planning involves decision affecting the short-term execution of the company's business.

In the forest industry field, at strategic level that ranges from about 1-25 years, the transportation is integrated with road building and upgrading. Inadequate standard of the road network reduces the possibilities to use roads for timber transportation (Eriksson and Rönnqvist, 2003). Strategic management deals with adjusting the capacity of the supply chain with respect to changes in industry production (Forsberg and Rönnqvist, 2003). In tactical planning, assets are balanced against demand. This type of planning is based on several-year-long harvesting plans. These decisions are often included in the models in forestry management and harvesting (Eriksson and Rönnqvist, 2003). Tactical management deals also, e.g., with seasonal restrictions or natural disturbances such a storm felling or plagues (Forsberg and Rönnqvist, 2003). Planning the work schedule for next week's deliveries of a truck driver is an example of operational management (Forsberg and Rönnqvist, 2003). Operational planning concentrates on the actual movement of logs, fuel wood or fuel chips from supply nodes to demand nodes in a transportation network. In general there are separate truck fleets for logs and wood chips. In European northern countries fuel wood can be chipped or packed together in the form of large bundles. In the latter case it is possible to integrate this transportation with the log transportation (Eriksson and Rönnqvist, 2003).

1.6 MANAGEMENT SCIENCE – OPERATIONS RESEARCH

The terms "management science" and "operation research" are often used synonymously. Some Authors refer to operational research as the collection of theoretical knowledge related to the study of complex operations and to management science as the application of this theory (Asikainen, 1995). According to Dykstra (1984) there is no clear distinction between the two. Taha (1992) affirms that OR seeks the determination of the best (optimum) course of action of decision problem under the restriction of limited resources.

Operations research (OR) was defined the first time during the Second World War as a method to solve problems and assist in military operations (U.S. Army, 1961). After the war, OR was successfully applied to handle the increasingly complex problems of forecasting, coordinating and controlling manufacturing operations (Skinner, 1985). The approach of OR is the one of the scientific method. The process begins observing and formulating the problem and constructing a scientific (usually mathematic) model that attempts to abstract the essence of the real problem. OR is usually applied to problems that concern how to conduct and coordinate the operations or activities within an organization (Hillier and Lieberman, 1974). The OR was firstly applied to forest management problems from the early 1960s (Buongiorno and Gilless, 2003; Heinimann, 2007). Several modern system models in forest resource management combine the methods of OR and those of economics. Economics remains an essential part of the forest resource management: even when the objectives of management are purely ecological, such as in designing a conservation program, economics are needed to compare the costs, if not the benefits, of alternative approaches (Buongiorno and Gilless, 2003).

Management science applies the scientific method to the management of organizations or systems. Scientific method is made of four steps: observe, hypothesize, experiment and verify.

In management science those steps are applied in such a way to provide information useful in management of organizations or systems (Dykstra, 1984). According to Render and Stair (1992), management science is the scientific approach to managerial decision making.

The management science is a discipline for guidance in making decisions. Dykstra (1984) considered the management science as a tool for natural resources management. Natural resources decision problems are studied by mathematical programming, a sub-discipline of management science.

According to Heinimann (2007) forest operations management (operations research) consists of analysis, design, control and continuous improvement of business processes, such as procurement, order fulfillment, distribution, monitoring and control within firms and business to business networks. It measures and analyses internal processes with emphasis on effectiveness, efficiency, and quality using quantitative models to map and solve related problems of scheduling, inventory, shipment routing, or facility location.

Management science involves study of solution methods and it is a science of modeling (Dykstra, 1984). A model is an abstraction or a simplification of the assumed real world system. It is a representation of a system that has been built to study a real world system. The assumed real system is abstracted from the real situation by identifying the dominant factors that control the behavior of the real system (Taha, 1992). Dykstra (1984) classified three types of models: iconic, analog and symbolic. Mathematical models are a subclass of symbolic models. When a mathematical model can be constructed to describe an organization or system with a satisfactory degree of accuracy, then it becomes a convenient powerful tool for analysis. Such models are easy to manipulate, they provide consistent and precise results and interactions among variables are readily apparent (Dykstra, 1984). Mathematical model suffer also from certain faults, such as the too far abstraction from reality (assumption that cannot be supported), the consideration of many details in order to mirror the reality that cause mathematical clutter. Moreover situation being modeled involved often relationships difficult to quantify, and end up to leave them out or to deal with them in a crude way. The dimensionality of mathematical models is often so great that it is difficult or impossible to visualize the complex interactions embedded in the model (Dykstra, 1984). According to some Authors, simulation models are a subclass of mathematical models (Law and Kelton, 1982; Banks and Carson, 1984), or they are similar to mathematical models (Render and Stairs, 1992; Taha, 1992). Compared to simulation, linear programming generates optimal solutions to problems (Render and Stairs, 1992). Optimization models seek the optimal combination of actions, while simulation models try to predict the outcomes of certain measures (Rantanen, 1987).

OR technique to be effective must focus on a well defined problem and all meaningful constraints must be identified. If constraints are missed or not correctly defined, the model cannot imitate the reality and its outputs are biased (Asikainen, 1995). Identification of the objectives is the most important phase of any OR project (Render and Stair, 1992; Thesen and Travis, 1992). This stage includes description of the goal of the study, identification of the decision alternatives of the system and recognition of the limitations, restrictions and requirements of the system.

An OR study can be divided into the following phases (Taha, 1992; Patrone, 1965):

- Definition of the problem
- Construction of the model
- Solution of the model
- Validation of the model
- Implementation of the results

Data used in the model can be readily available from previous studies or statistics. Estimates and educated guesses must be used if the data are neither available nor collectable. If such estimated are used, they must be clearly declared as assumptions (Asikainen, 1995).The modeller has to choose an appropriate tool for model building.

One of the most important problems facing a modeller is that of trying to determine whether a model is an accurate representation of the actual system being studied (Law and Kelton, 1982). In the verification mistakes are found and solved, results can be manually calculated and compared to the model output. The first step of validation is to attempt to develop a model with high face validity, a model that on the surface seems reasonable to people who are specialists on the system under study (Law and Kelton, 1982; Banks and Carson, 1984). To develop such a model, the modeller should make use of all existing knowledge. This means discussions with experts, finding out the existing theory or studies and observation of the system. Conversation with experts familiar with the system ensures that the model will not be developed into an abstraction that is far from the real world (Ojala, 1992).

Sensitivity analysis can help to test quantitatively the assumptions made during the initial stages of the model development (Asikainen, 1995). When possible, simulation model results can be compared with those from the real system.

Natural resources problems can be analyzed by management science if they have certain characteristics (Dykstra, 1984):

- decision to be made in a complex environment, therefore there are not intuitive or easy solutions. There must be a decision maker who can choose among alternative courses of action, one or more identifiable objectives to be achieved and some doubts as to which course of action is best in terms of the decision maker’s objective
- limited resources
- facts of the situation must be quantifiable.

1.7 OPTIMIZATION: LINEAR PROGRAMMING

1.7.1 Principles of linear programming

From the larger class of optimization techniques called mathematical programming, *linear programming* (LP) is so far the most widely used. According to McKinnon (1989), LP is an extensively used planning method also in distribution management. LP typically deals with the problem of allocating in a optimal way limited resources among competing activities (Hillier and Lieberman, 1974). In mathematical terms LP is concerned with the problem of optimizing, i.e. either minimizing or maximizing, a linear function of several variables subject to linear constraints (Simonnard, 1966). Mathematical programming is concerned with the optimal allocation of scarce resources among competing ends (Dykstra, 1984). The optimal solution to the mathematical problem can be obtained numerically by execution of an algorithm. The use of LP in mathematical programming is based on four assumptions: proportionality, additivity, divisibility and deterministic assumption which all must come true in the model formulation (Hillier and Lieberman, 1974).

According to Thomas and Griffing (1996), models with linear transportation costs might have limited application in practice because the application of linear models might be debatable in some cases. This is due to the fact that in LP a linear objective and constraint functions are used in the formulation as surrogates for actual functions, which in transportation problems are often intrinsically nonlinear because they involve both fixed and variable costs. The process of converting a non linear expression to a linear one is called linearization. The effect of linearization on solution of an LP model can be evaluated, for instance with integer programming (IP), by constructing an optimization model with more realistic objective and constraint functions. IP can be classified according to the types of variables. In *pure integer programming*, all variables are restricted to integer values. In *mixed integer programming* (MIP) formulation, certain variables are integers, whereas the rest are allowed to be continuous. Another classification criterion is the number of integer values allowed for single variables; binary (0/1) restrictions are used to indicate whether something happens or not, whereas general integer restrictions allow all integer values that are in a feasible solution area (Schrage, 1997). Binary variables are used to describe cost relationship, constraints, and logical conditions that cannot be captured by linear programming. Zero-one variables and associated constraints can be employed to model a wide range of supply chain planning problems as well as many problems arising in financial planning, engineering, logical functions, and several other fields (Shapiro, 2001).

LP is made on the following elements:

- *Decision variables*: things about which a decision is to be made
- *Objective function*: describes the objective of the LP, i.e. maximize or minimize something
- *Constraints*

The constraint is made on equation/inequality and the part on the left is called *technological coefficient* or *left hand side* and the number on the right is called *right hand side*. The technological coefficients are constants that represent the contribution to the constraint of a unit increase in the activity level associated with the variables (Dykstra, 1984). If the problem is referred to multi-period, the problem takes into account that the decision taken in one period partially determines which decisions are allowable in the future periods. The submodel used in each period may be a product mix problem, a blending problem, or some other type. These submodels are usually tied together by means of inventory variables that are carried from one period to the next (Lindo, 2006). Models that include a time factor are called by some Authors (Hillier and Lieberman, 1974; Dykstra, 1984; Rantala, 2005) “dynamic”. Models for planning over time represent the real world by partitioning time into a number of periods. Multi-period models are characterized by:

- link or inventory variable for each commodity and period. the linkage variable represents the amount of commodity transferred from one period to the next
- “material balance” or “source = uses” constraint for each commodity and period, i.e. *beginning inventory + production = ending inventory + goods sold*.

When obtained the problem solutions, there is nearly always a difference between mathematical programming solutions and the implementation of those solutions through management decisions. Decision makers want information on which to base decisions. A mathematical programming analysis can provide part of this information but equally important will be other considerations that cannot be quantified or for some other reasons cannot be incorporated into the mathematical model.

With sensitive analysis changes on optimal solutions induced by changes in problem conditions can be studied.

According to Shapiro (2001) a fundamental ingredient in the economic analysis of an LP model is the *shadow price* associated with each constraint, which is defined as the change in the optimal value of the objective function if the right-hand side of the constrain is increased (or decreased) by one unit. If constraint is binding upon the optimal solution, its shadow price will be positive, if the constraint is slack, its shadow price will be equal to zero. In economical language the shadow price is the marginal value. In economical theory the value of the marginal product of a resource is the price the firm should be willing to pay for additional amount of scarce resources.

A network is made up of nodes and directed arcs connection pairs of nodes. Linear programming models with a mathematical structure corresponding to networks are called network models (Shapiro, 2001).

The transportation model seeks the determination of a transportation plan of a commodity from a number of sources to a number of destinations. The data of the model include the level of supply at each source, the amount of demand at each destination and the unit transportation cost from each source to each destination. The objective of the model is to determine the amount to be shipped from each source to each destination such that the total transportation cost is minimized (Taha, 1992). The transportation problem can be defined a two-level network problem, where all the nodes at the first level are suppliers, all the node at the second level are users, and the only arcs are from suppliers to users (Lindo, 2006).

In general, the transportation problem is concerned with transporting goods or services from multiple supply centers to multiple demand centers in an optimal manner (Dykstra, 1984).

In order to solve a transportation problem in the fuel supply of a heating plant is necessary to construct a supply network. The supply network considers, beside the fuel availability and the plants needs, the following aspects: transport modes, storage locations and economically justifiable transportation distances.

1.7.2 Application of LP in biomass supply

In recent studies, several papers can be found about Decision Support Systems (DSS) for the optimization of biomass exploitation. Noon and Daly (1996) integrated a DSS with GIS analyzing the transportation networks and estimating distance and costs. Nagel (2000) presented a methodology to allow biomass management for energy supply at a regional level.

Diekema *et al.* (2005) developed a computer model for the optimization of the biomass-to-energy chain that accomplished six objective functions. Those functions can be optimized once per time or combined. The model takes into account effects that are typical for biomass, like: seasonal fluctuation in supply and demand, moisture losses during drying and dry matter losses during storage due to biological processes.

Hultqvist and Olsson (2003) developed an optimization model that integrated different aspects of the raw material supply chain from harvesting to industrial processing with dynamic information constraints.

LP has been used by-Epstein *et al.* (1999) to find a system for the design of short term harvesting strategy. A branch and bound scheme was designed to find the solution to the problem: which stands to harvest, what timber volume to cut, what bucking patterns to apply to logs in order to obtain products that satisfy demand, they designed.

Optimization of forest biomass supply can be implemented using geographic information system and build tools for decision support systems (Freppaz *et al.*, 2004; Ranta, 2005; Frombo *et al.*, 2009). According to Eriksson and Björheden (1989) optimizing forest fuel production essentially means minimizing transportation costs.

Eriksson and Björheden (1989) evaluated five supply chains of forest fuel to plant passing or not through a terminal. Computed results, obtained through a linear programming method, highlight that the most economic way is the direct supply to plant. Added cost of improved fuel quality and secure supply does not pay off terminal costs. The problem, solved for a sequence of years, shows that transportation cost constitutes the most essential part of the total cost.

The optimal solution often includes the use of flows with mobile chippers and direct transportation to the heating plants.

The optimization of plant supply has been solved with different procedures, using just GIS tools or applying also the LP.

Plant location and fuel supply problem has been in some studies approached with the location-allocation modeling (Noon and Daly, 1996; Graham *et al.*, 2000; Ranta, 2005; Panichelli and Gnansounou, 2008), that allows finding the optimal location of new facilities or supplying the existing one in a least cost manner. The objective is to minimize the total transportation cost, usually expressed as the product of demand and distance. Perpiñá *et al.* (2009) developed a methodology based on GIS for biomass and transport optimization. They used the “closest facility” analysis that considers the shortest time taken to travel a distance without using a LP software. Frombo *et al.* (2009) developed a strategic decision model using LP in order to minimize the supply cost of energy plants considering also benefits. Kanzian *et al.* (2009) constructed a procedural method that calculated optimal material flows and expected costs at plant level for different demand scenarios and supply options and demonstrated the differences between direct flow and flow via terminal. They divide the model into two sub models: one optimizes the transport from terminal to plant, the second optimize the flow from forest to terminal or plant. With a stepwise procedure they developed a optimum of sub-models.

In this study is developed a transportation model with LP that considers all cost factors along the supply chain, providing a global optimal solution. The decision variables are represented by fuel flows of different supply chains, while the objective function is to minimize costs of the whole system.

2. AIM

The study aims to develop a method to optimize the supply of woody biomass to plants and find out the optimal way to run the biomass supply in a region.
A case study in North-eastern Italy and a case study in Central Finland are considered in order to optimize the allocation of local wood fuel resources in the cost-efficient way. The Italian case study deals with a small scale supply chain, while the Finnish one concerns a large scale supply chain.

In an Italian study area the optimal position of a terminal from the logistic point of view is evaluated. The method aims to minimize the total cost of wood fuel supply from forest and sawmills for district heating in a local alpine area. Sensitivity analyses were done to study the effects of a parameter in the whole system and its possible improvement.
In the Central Finland case study the aim is to identify the optimal allocation of forest fuel that supply two large scale plants in the least-cost manner. A comparison of different plant's paying ability can highlight their supply areas of forest wood chips.

Innovative methods to produce high quality wood chips for a rapidly growing energy sector are becoming increasingly important. Small heating plants require wood chips of high quality to ensure trouble-free operations as well as low maintenance costs. Moisture content is considered to be an important quality parameter in dealing with wood based fuels. The objective of the study is to investigate methods to promote the natural drying of small diameter trees.

3. MATERIAL AND METHODS

3.1 PLANTS AND BOILER DISTRIBUTION IN NORTH-EASTERN ITALY

In North-eastern Italy the use of wood for heating in the years 2003-2006 was promoted with European structural funds, rural development plans, energy projects, regional and provincial funds. Subsidies applications are managed and evaluated by regional and provincial energy offices.

The first step for supply optimization is to find location of wood biomass sources and demands. In order to know the actual demand of fuel, a survey has been carried out. Data on boilers and district heating technical characteristics, fuel typology (firewood, chip or pellet) and localization were collected by visiting regional and provincial energy offices, analyzing funding demands and filling out specific questionnaires. All information pertains to boilers and DH granted and already working. Wherever data concerning chip consumption were not available, it was calculated using (3.a):

$$C = \frac{P \cdot h}{lhv \cdot \eta} \tag{3.a}$$

Where *C* is the annual fuel consumption (t $year^{-1}$), *P* the power of the boiler (MW), *h* the annual working hours (h $year^{-1}$), *lhv* the lower heating value of the fuel (MWh t^{-1}) and η the boiler performance (%). Boiler's annual working hours were estimated considering the number of degrees per day of the settlement and according to the building type.
The calculation of tons of oil equivalent (*toe*) allow to estimate the fossil fuel that can be saved using a renewable source in order to respect limits in carbon emissions (3.b).

$$toe = \frac{C \cdot lhv_{wf}}{lhv_{oil}} \tag{3.b}$$

Where *toe* are the tons of oil equivalent (toe $year^{-1}$), *C* is the annual fuel consumption (t $year^{-1}$), lhv_{wf} is the lower heating value of wood fuel at a moisture content of 50% (2.3 MWh t^{-1}) and lhv_{oil} is the lower heating value of oil (11.67 MWh t^{-1}).

For a deeper knowledge of the Italian northeastern circumstances, detailed data about boilers technical characteristics, fuel supply chain, plant management, supply problems and fuel consumption were collected with personal interviews directed to the boiler manager. The investigated DHs are located in Trentino, Friuli Venezia Giulia and Veneto.
District heating data, combined with the local availability of wood fuel are the starting point for the development of a tool to study the optimal supply.

3.2 QUALITY OF WOOD FUEL: DRYING TEST

Effects on the drying process such as covering of the piles, partial debarking of stems and different locations were tested in order to find new methods to stabilize the moisture content of the woody material in the storage. Drying trials were set up in Finland, Scotland and in Italy utilizing tree species typically used in the area (DryMe project). The description and results of the trial carried out in Italy are reported in this study.

3.2.1 Test in Italy

The drying trials were situated in Cappella Maggiore, North-eastern Italy, Veneto region, Treviso province (Figure 3.1). The village Cappella Maggiore is placed in the Prealps (hilly area before the Alps) at the altitude of 150 m above the sea level. This area has a continental degree calculated with the Gorczynsky index IC around 50, computed according to annual thermal excursion (difference between the maximum average temperature of the warmest month and the minimum average temperature of the coldest month) and to the latitude. Such index allows to represent the climate of an area in a range between 10 and 100, where 0 is a maritime climate and 100 is a really continental climate (Treviso Province, 2008). Rains are all over the year, but the winter is the driest season, in summertime there are often heavy showers. The average rain in the last years has been between 814 and 1212 mm.

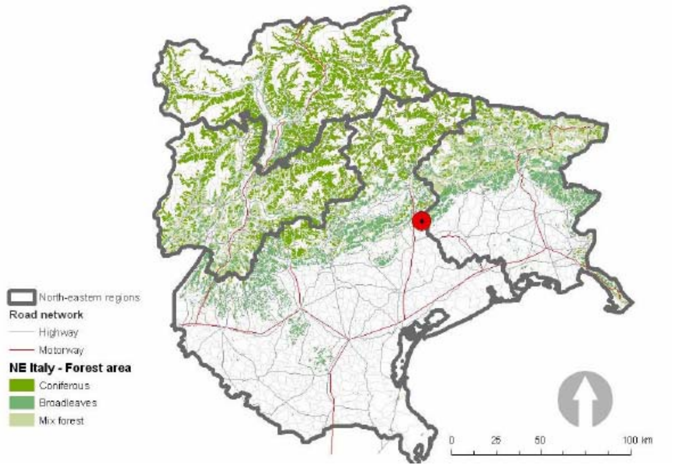
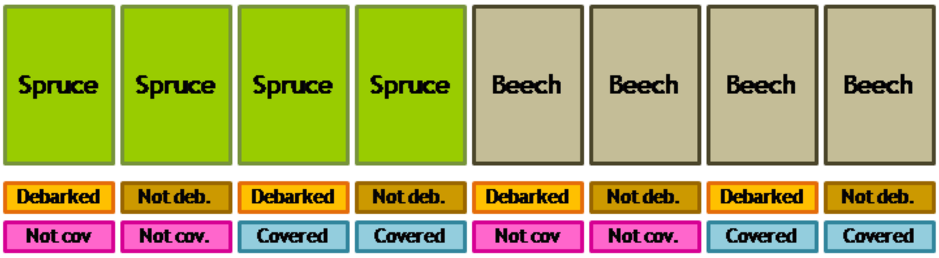


Figure 3.1. DryMe trials location

Trials were set up from December 22, 2007 to August 25, 2008. Piles were located in a open air place in a even area of the yard of a forest enterprise that harvests and sells firewood and produces forest chips to be sold to local small district heating or boilers. The chosen species for the test are spruce (*Picea abies*) and beech (*Fagus sylvatica*), corresponding to the dominant coniferous and broadleaved species of the region. Logs of 15-30 cm diameter derived from thinning from the neighbor forest were the raw material used for the test. The volume of piles was about 4-5 m^3 solid. Four piles of spruce and four piles of beech were prepared. Two piles of spruce and two of the beech were partially debarked with a processor (stroking stems forth and back 2-3 times through the processing system). One pile partially debarked and one control pile of spruce and beech were covered with a paper cover. Therefore the test was composed on 8 piles (Figure 3.2). Piles were collocate on a frame made of wood logs bearers. The effect of debarking and covering on the drying of wood was tested.

Piles were divided into 5-7 sample loads with maximum weight lower than the scale capacity (1500 kg). Sample loads were bundles of 7-10 stems tied up with iron strips (Figure 3.3).

The tool used for weighting was a load cell applied to the end of a crane. Weighting of piles was done measuring single bundles and repositioning them in the original place. Operationally two iron chains were attached to the scale and their end was fastened to the iron strips. When the crane was lifting the pile, the weight was displayed on the device (Figure 3.4). During the test piles were weighted seven times, almost once per month. The percentage of debarking was measured from photographs taken of the logs. Pictures were taken with a digital camera and analyzed with computer software in order to calculate the area of the bark losses.



Spruce	Spruce	Spruce	Spruce	Beech	Beech	Beech	Beech
Debarked	Not deb.	Debarked	Not deb.	Debarked	Not deb.	Debarked	Not deb.
Not cov	Not cov.	Covered	Covered	Not cov	Not cov.	Covered	Covered

Figure 3.2. Piles of the trials

Figure 3.3. Picture and representation of the piles

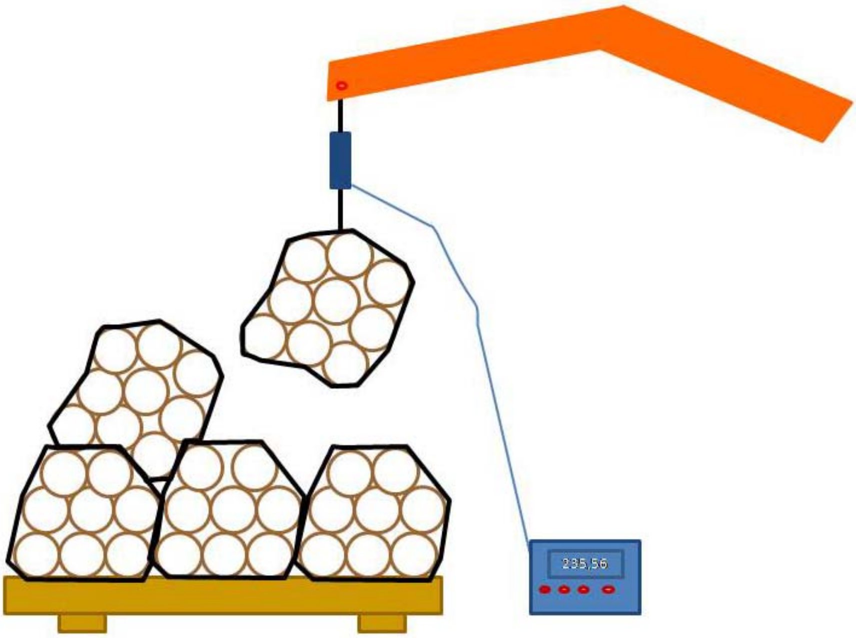


Figure 3.4. Representation of the weighting system

At the beginning and at the end of the trials (December 2007 and August 2008) moisture samples were taken from one log of every bundle. Samples disks were cut at least 30 cm from the log end and its moisture content measured in kiln laboratory according to the CEN/TS 14774. Changes in moisture content were calculated considering the initial moisture content at the beginning of the trial and the weighting measured data. Moisture content was measured also at the end of the trials (August 2008) in order to verify calculations. Dry weight has been calculated at the first measurement, therefore is possible to compute the moisture content every weighting time.

The trial was carried out in a larger context of drying tests in different European countries. The similar test was set up in Finland and Scotland. Here is reported only the methodology and results obtained in Italy. The objective of the study was to investigate natural drying of small diameter trees. Effects on the drying process of covering the piles, partial debarking of logs and different locations were tested in order to find the new methods to stabilize the moisture content of the woody material in the storage.

Natural drying depends on the local weather conditions. Temperature and relative humidity were recorded every hour using the weather station data logger positioned close to the piles. Rainfall precipitation data were collected by a official weather station located in the neighboring town.

Observing the precipitation data of the period in which the trial was set up compared to historical series, December 2007 has been the driest month and in January, April, May and June 2008 have been heavy rain months (Figure 3.5). Maximum temperature recorded in the studied period is in line with the past years (Figure 3.6).

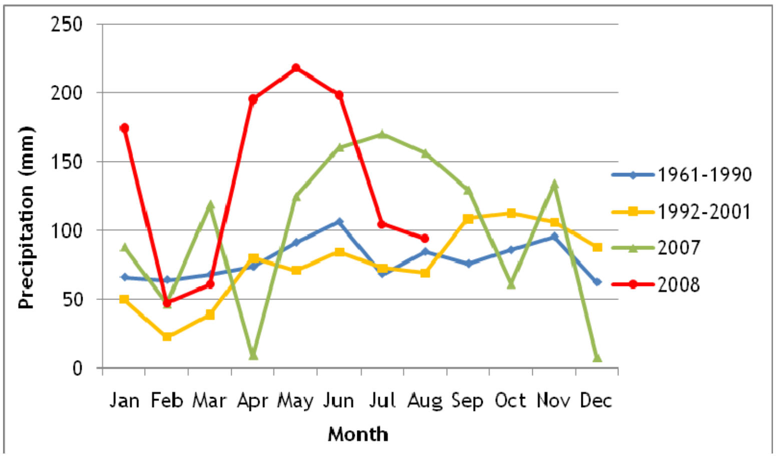


Figure 3.5. Precipitation in Treviso province during the previous decades and in years 2007-2008

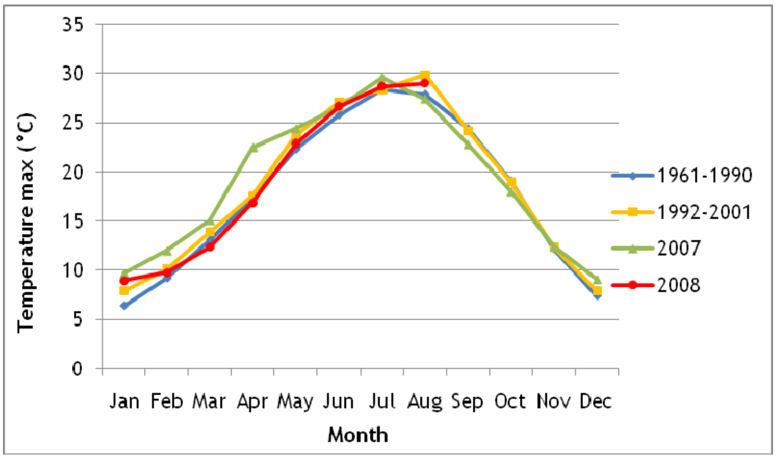


Figure 3.6. Maximum temperature in Treviso province during previous decades and years 2007-2008

3.3 WOOD FUEL SUPPLY CHAIN REGIONAL OPTIMIZATION: CASE STUDY IN NORTH-EASTERN ITALY

3.3.1 Area description

Fiemme Valley is the local area considered in the study. Fiemme Valley is located in the eastern part of Trento province and has an elevation ranging between 650 and 3300 m a.s.l. Area is mainly covered by coniferous high forest: assessed stands cover totally an area of about 40 000 ha as well coppice stands cover only 140 ha. Norway spruce (*Picea abies* Karst), fir (*Abies alba* Miller) and European larch (*Larix decidua* Mill.) are the prevailing tree species.

Forest stands have different uses and the prescribed yield is established in the management plan according to their vocation. Forest area property is mainly public.

Management plans referred to this area have mainly a validity of 10 years. The forest annual prescribed yield is about 108 000 m^3year^{-1}. The average growing stock is of 259,33 m^3/ha and the productive area is of 36 811 ha. Fiemme Valley forests have both even aged and uneven aged structures. Prescribed cuttings are usually selective, shelter-wood and sometimes strip, patch and group cuttings. Inside the productive forest area, forest road network density is estimated at 18 m/ha.

Magnifica Comunitá di Fiemme (MCF) is an administrative institution involving 10 villages of the Fiemme Valley. The area owned by the MCF is about 19 500 ha and forest area is about 12 500 ha. According to the management plans, MCF has a productive forest of 8 314 ha with an annual prescribed yield of 43 660 m^3.

Manager of the MCF was interviewed in order to obtain information concerning the supply chain of logging residues in the MCF stands. The lots yarded with cable crane are usually between 100 and 1000 m^3 and those yarded with tractor and winch are usually 50-400 m^3. Spring and autumn are the best seasons for yearding; during those seasons 70-80% of the total operations are performed (Behman de l'Elmo, 2007).

Cutting operations are always carried out with motor-manual system (chainsaw) while extraction is performed with aerial transportation system (cable crane) in the 80% of the stands and with ground skidding system (tractor and winch) in 20% of the stands. Processing at

roadside with processor is carried out in 20% of the sites, in all the other sites it is performed with chainsaw. The 30% of forest residues are chipped at boiler site and 70% at roadside and then transported with truck (60%) and with truck and trailer (40%) (Behman de l'Elmo, 2007).
In MCF stands, spruce tops and branches represent usually 25% of the cut volume. The material available for fuel purposes represents the 10% of the volume processed at roadside. Collected material for chipping purposes are mainly tops, with a fair wood content compared to the green parts. According to the stand volume table (Trento Province, 1956), the tops and branches rate is between 10 and 20% of the stem volume specified in the management plan. In MCF available un-merchantable logs are 10-12 m^3 every 100 m^3 spruce timber forwarded at roadside.

In Fiemme Valley there are a lot of woodworkers and sawmills. Many of those are small, processing less than 5000 m^3 yr^{-1}, and produce an amount of byproducts too small to guarantee a continuous supply for boilers. For this study it has been supposed that seven sawmills located in the valley could provide a good supply service for DH.
According to the census carried out in 2007 referred to boilers funded with European and local funds between 2003 and 2006, in Fiemme Valley there are 11 boilers. Only two of them are DH with a power bigger than 1 MW and they usually burn both sawmill byproducts and forest residues.

3.3.2 Forest chips supply chains

In Fiemme Valley forest it is possible to obtain fuel only when the FT or FT-CTL extraction system and roadside processing are carried out. Information gathered during interview to the technical manager of MCF can be generalized to all Fiemme forest.
Nowadays it is possible to use tractor and winch for a maximum distance from roadside of 100 m and with a steepness of 35% uphill and 25% downhill. With cable crane extraction system is possible to reach a distance of 1000 m from roadside in every kind of terrain conditions. Harvester and forwarder are not commonly used in this area because of difficult terrain conditions.
Felling, extraction and processing operation costs are charged on timber assortments supply costs. Forest residues are byproducts of timber harvesting, therefore costs are fully covered by logging costs.
Selection and shelterwood fellings are usually carried out in Alpine high forest and those cutting systems do not allow chipping on terrain. Forest residues for heating purposes need to be extracted from the forest at the same time as timber since the extraction after timber utilization is not economically sustainable. Chipping is usually done at roadside and sometimes residues are transported to heating plant and chipped there. Transportation of un-chipped material is possible only when bales of branches or tree sections (Spinelli and Magagnotti, 2007) or stems are used. It is possible to transport also loose residues, but the great part of the load must be wood with only few branches.
Chipping directly in the forest at the landing and transportation of chips has been found to be the most effective solution (Spinelli *et al.*, 2006; Spinelli and Magagnotti, 2007).
In Fiemme Valley at the moment there are no terminals for storing biomass.

3.3.3 Data for optimization

Fuel supply optimization at regional level needs to know the fuel availability and the demand. Such information were collected from management plans and from interviews and surveys. Data are then elaborated with the formulation of a transportation problem (LP) with LINGO software.

Transportation times, routes and costs are evaluated using the road network to transport the biomass from the original location to the heating plant. Hence a network analysis is performed using “network analyst” in GIS. This tool provides a network based spatial analysis that includes the optimal route, travel directions, shortest path, closest facility, service area analysis, drive-time analysis and origin-destination (OD) cost matrix analysis. Realistic network conditions can be modeled including turn restrictions, connectivity, traffic conditions and speed limits according to the real situation. In this study tool input data is the digital road network consisting in two classes: public and forest roads (see paragraph 3.3.3.4). The output of the OD cost matrix analysis is the time needed by an empty truck to reach the biomass source location and the time needed by the fully-load truck to travel to the heating plant (Figure 3.7).
Theoretical potential of forest biomass is estimated considering forest stand data from management plans and applying appropriate coefficients (see paragraph 3.3.3.3).

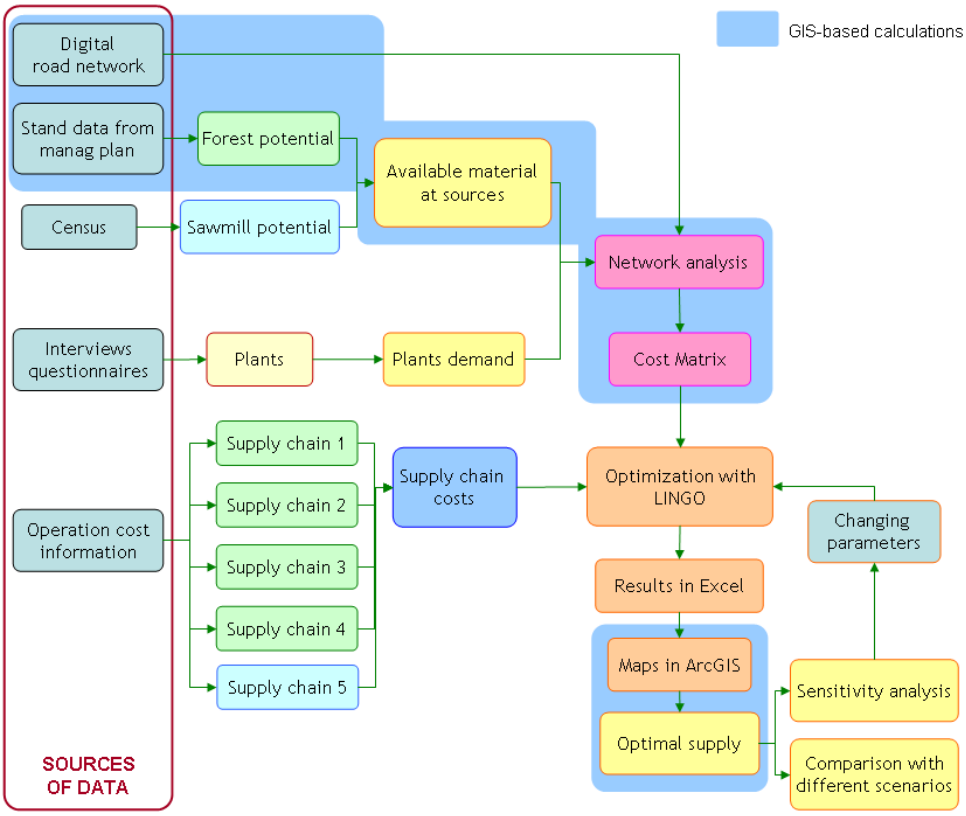


Figure 3.7. Flowchart of elements considered in the optimization

A standard method/model to decide how supply should be used to meet a specific demand is the **transportation model**.

The *decision variables* are flows of wood fuel from supply points (stands and sawmills) to demand points (plants) that are subjected to supply and demand *constraints*.
The *objective function* of the problem is to minimize the total plants supply cost.

3.3.3.1 DH demand

From the census (see chapter 3.1.1) comes out that in the year 2006 in Fiemme Valley there were 11 wood chips boilers: 9 with power lower than 1000 kW and two bigger that provide heating service to the villages of Cavalese and Predazzo (district heating, DH).
From interviews directed to plant managers comes out that Cavalese (K2) energy production is 33000 MWh yr^{-1}, 80% of which provided with wood biomass. Predazzo (K1) energy production from wood biomass is 60% of 7000 MWh yr^{-1}. Considering a boiler efficiency of 85%, energy content needed every year from wood is 31059 MWh yr^{-1} in Cavalese and 4941 MWh yr^{-1} in Predazzo.

3.3.3.2 Availability of sawmill byproducts

Questionnaires were sent to sawmill managers in order to know the availability of byproducts or chips for heating purposes. Only few answers were gathered, so this information was derived from a census updated in the year 2008 (Trento Province, 2008). Seven sawmills were considered providing chips for DH. Sawmill byproducts can be sawdust, bark and chips. Nowadays slabs are not any more commonly produced.

3.3.3.3 Forest residues availability

Estimation of potential wood fuel resources can be located where WT or CTL logging systems are carried out. Those systems can be applied where specific characteristics of road network quality and density, terrain characteristics and density and tree size of cut are accomplished (Sundberg and Silversides, 1988; Fabiano and Marchi, 2001).
Information for the residues availability estimation were collected with interviews and forest management plans database provided by Forest Service of Trento Province (Trento Province, 2007). In this study only productive stands with a prescribed yield within the validity of the management plan are considered. An index for logging residues that is possible to heap up at roadside when using cable crane extraction system was generalized to the cutting volume in spruce stands. As mentioned above, tops and branches usually collected represent 10% of the timber processed with processor (20% upon the whole forest area). Un-merchantable timber is 10% of the total harvested volume. Therefore logging residues index is here considered equal to 12%. Since data regarding cutting year and relative volume were not specified in management plans, it is assumed that the prescribed yield per stand is whole cut in one year. Moreover, cutting year was randomly assigned to every stand assuming to cut more or less the same amount every year during ten years (the average validity of a management plan). In this way it was supposed to cut and to make residues available in 81-93 stands every year.
In order to estimate more precisely the amount of residues that are technically available, a maximum extraction distance of 500 m from roadside is set. Cable crane or tractor and winch yarding systems were used in every terrain conditions and steepness indistinctly uphill and downhill. A Euclidean distance spatial analysis (buffer) with a distance of 500 m was built in ArcGIS on digital data of public and forest roads (Trento Province, 2004). The resulting area was then overlapped to stand data highlighting area technically extractable (Ai). Such area was then compared to the total area of the stand.

$$S_i = \frac{A_i}{A_{it}} \cdot V_i \cdot I \cdot P_i \tag{3.c}$$

Si	Logging residues of stand i (m^3)
Ai	Extractable area of stand i (ha)
Ait	Total area of stand i (ha)
Vi	Prescribed yield of stand i (m^3)
I	Logging residues index (%)
Pi	Percentage of spruce in the stand i (%)

Stand logging residues are then converted into energy content according to energy density (1.b).

Piling of timber and residues is not always done at roadside of every stand, but rather in larger places where is supposed to be possible to store residues for maximum one year. It is then assumed that timber and residues from 3-5 stands in an area radius of 600-800 m are forwarded and piled together at roadside in 190 places. Piling sites are collection areas where the forest biomass is temporarily collected before being transported to the plant. Piling sites are identified at roadside where 3-5 stands are faced to and can be a wood gathering point. Chipping operations are supposed to be done in those places at roadside.

Points with an amount of available residues lower than two truckloads (30 m^3) were not considered in the analysis because it is estimated to be not economical to move chipper and truck for too small amount of residues.

In this study the assumed conversion from solid mass into cubic meters is a factor of 2.5.

3.3.3.4 Road network

A digital road network was built according to public and forest roads shapefile provided by Trento Province (2004). Public and forest roads were classified.

Driving time (s_{ik}) from sources (sawmills and piling sites) to plant was calculated in ArcGIS with Network analyst tool building an OD Cost Matrix. Different average driving speeds for truck were assigned according to the road classification. Speed information were derived from literature: 39.4 km h^{-1} on public roads and 13.3 km h^{-1} on forest roads (Spinelli *et al.*, 2006; Spinelli and Magagnotti, 2005). Speed is estimated to be the same for all the means of transportation: a truck with loading capacity of 36 m^3_{loose} transporting forest residues and chips and a truck and trailer. Sawmill byproducts are supposed to be transported with a truck and trailer with loading capacity of 86 m^3_{loose}.

In the study it is assumed that truck can travel everywhere on public and forest roads, U-turns are allowed everywhere.

3.3.4 Costs calculation

Information of costs based on literature review (Spinelli et al., 2006a, 2006b, 2007) and according to interviews are presented in table 3.1. Their explanation is reported in the following sub-chapters. Operational costs have been calculated following Miyata (1980) approach.

Table 3.1. Costs considered in the supply chains

	Supply chains	Load capacity	Moisture content	Transportation	Load/unload	Chipping	Purchase value
		m^3 load^{-1}	%	€ load m^{-3} min^{-1}	€ m^{-3}	€ m^{-3}	€ m^{-3}
1	Chipping at roadside and transportation of chips	14.4	55	0.072	3.15	9.60	12.23
2	Transportation of un-chipped residues, chipping at plant	11.7	55	0.093	5.58	8.00	12.23
3	Transportation of un-chipped residues, chipping at plant	11.7	35	0.093	5.58	8.00	12.60
4	Chipping at roadside and transportation of chips	14.4	35	0.072	3.15	9.60	12.60
5	Transportation of chips from sawmill byproducts	34.4	45	0.033	0.67	-	30.00

3.3.4.1 *Transportation cost*

Transportation costs calculation is based on time for covering the path from source to plant (§ Road network paragraph). Such time was then multiplied for truck hourly cost.

Truck used for transporting residues is supposed to have a purchase value of 125000 € equipped with crane (20000 €) and tires (5000 €). Truck transporting forest chips is supposed have a purchasing value of 130000 € plus 5000 € for tires. Transportation of sawmill byproducts is supposed to be carried out by truck and trailer with a purchasing value of 150000 € plus 13000 € for tires. For all those means the annual utilization is estimated as 1600 h yr^{-1}.

The cost for forest chips transportation was estimated to be 62.50 € h^{-1} (including profit enterprise). Truck for forest residues cost is estimated as 65.20 € h^{-1}. Truck and trailer is supposed to have an hourly cost of 68.00 € h^{-1}.

Transportation cost includes both driving from the plant to the source of wood biomass (sawmills, wood gathering points, terminal) and back loaded to the plant. In this study truck driving cost with and without load is supposed to be the same.

Time for loading and unloading of forest residues and chips from sawmill byproducts is derived from literature (Grigolato, 2005). The time that truck has to wait to be loaded at roadside is estimated to be the time needed for chipping a volume of 36 m^3_{loose}, equal to 0.64 h. Truck transporting forest residues is considered to have a loading capacity of 15 m^3 solid equivalent, truck transporting forest chips has a capacity of 14.4 m^3 solid equivalents whereas the truck transporting sawmill chips has a capacity of 34.4 m^3 solid (Table 3.2). The hourly cost of the truck waiting during chipping operation is supposed to be the hourly cost of the truck without fuel. Additional 12.4 min are considered as weighting and dead time.

Table 3.2. Time for loading and unloading and capacity of truck

Transportation	Operation	Time	Load capacity	Cost
		min load^{-1}	m^3 load^{-1}	€ m^{-3}
Forest residues	Loading and unloading	59.9	15	1.09
Forest chips	Loading and unloading	58.8	14.4	0.77
Sawmill byproducts	Unloading	20.3	34.4	1.13

When calculating the transportation cost referred to the energy content of wood resources, the degree of moisture plays an important role (Noon and Daly, 1996).

3.3.4.2 Chipping cost

Chipping at roadside is usually carried out with a mobile chipper (truck mounted chipper).

Chipping at plant can be done with a mobile or stationary chipper. In this study a mobile chipper was modeled with working site productivity higher than at roadside operation, since it is not necessary to idle for trucks. Productivities at plant are greater than at roadside because of the better handiness of chipping at plant in a larger space (Table 3.3). This results in a lower chipping cost.

Truck mounted chipper here considered has a purchase price of 285000 €, equipped with crane (30000 €) and tires (5000 €). Estimated life time is 8 years and it is assumed to work 800 h yr^{-1}.

Productivity of the chipper at roadside is based on time studies carried out by the Author but such data are not yet published.

Table 3.3. Productivity and hourly cost of truck mounted chipper

	Productivity m^3_{loose} h^{-1}	Hourly cost € h^{-1}
Chipping at plant	60	192
Chipping at roadside	50	192

3.3.4.3 Purchase cost, storage and terminal costs

Purchase cost of chipped sawmill byproducts according to interviews is approximately 12 € m^{-3}_{loose}.

Logging residues cutting and extraction costs are covered by timber logging. Cost charged on forest residues is handling cost of raw material. Spinelli and Magagnotti (2005) refer a handling cost of 6.00-11.30 € t^{-1} on alpine condition for moving spruce energy wood material and piling at roadside. Considering the highest value, cost of forest raw material for chipping results to be 9.23 € m^{-3}. Organization cost of 3 € m^{-3} is also taken into account.

Storage cost of residues at roadside for one year is estimated with an interest rate of 3%. Dry matter losses (10%) are taken into account in the availability of residues in the following year.

Terminal is supposed to be built in an area between forest and villages. The cost, including the acquiring cost of 1 ha land and relative infrastructure, is considered to be depreciated over 40 years. The terminal is supposed to have a maximum capacity of 2500 m^3.

3.4 TEN YEARS OPTIMIZATION – SCENARIO I

The aim is to identify the optimal supply of district heating in order to highlight the best management of local resources.

The calculation is made year by year with fixed demand, fixed availability of sawmill byproducts and changing availability of residues at stands. Logging residues that are not used the previous year can be used in the current year.

3.4.1 Supply chains

Fresh forest residues heaped up at piling site can be transported directly to the plant as un-chipped material or as chips (Figure 3.8). In case of material is not used during the year, it can be left seasoning at roadside for the following year. When left drying at roadside, it is supposed that the moisture content of residues decreases down to 35%. Moisture content of fresh material is estimated to be 55%.

Sawmills byproducts are considered all already chipped and with an average moisture content of 45%.

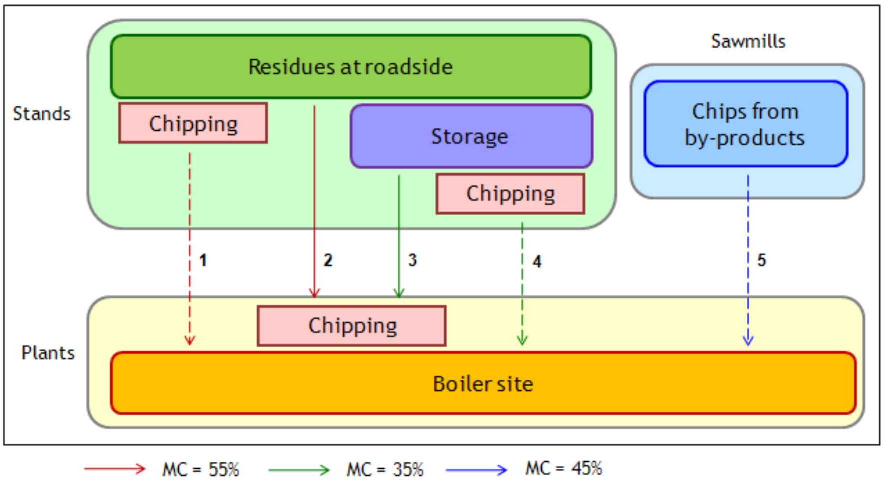


Figure 3.8. Forest chips supply chain. In green: transportation of material stored for one year, with a moisture content of 35%; in red: fresh material transported (moisture content of 55%). Dashed lines indicate transportation of chipped material, while full lines represent transportation of residues.

3.4.2 Transportation model formulation for scenario I

Optimizing the DH supply over a period of ten years, year by year, allow to use the most convenient sources and the most adapted supply chain with lowest cost.

The calculation was solved according to the linear programming formulation of the classic transportation problem (Dykstra, 1984).

The case study is hypothetical with some relationship with the real world. In order to represent the situation with a linear programming, simplifications of the reality were made.

The model has been formulated and solved with LINGO (Lindo System) linked with an excel spreadsheet. Results are therefore imported and displayed in Excel and in ArcGIS.

Assumptions:

- Possibility of chipping at plant and at roadside
- Sawmill byproduct supply and DH demand are supposed to be constant during ten years
- No capacity restriction of cutting and yarding stands
- No capacity restriction of chipping residues at stand or plant
- Residues can be stored at roadside for one year and used in the following year
- Purchasing costs are supposed to be constant every year
- Chipping and transportation costs are supposes to be the same every year

- Storage of residues can be done at roadside; maximum storage time is one year because of the problem of bark-beetle and fungi
- Sawmill byproducts are available only as chips
- Stands with an amount of available residues lower than a payload of two trucks transporting chips (totally 30 m^3) are not considered in the analysis
- Costs of transportation, chipping and purchasing are considered constant through the time

Location of chipping and types of transported material are the alternatives in the supply chains. Supply chains considered in this study are:

- chipping at roadside (stand), transportation of chips with a moisture content of 55% (SC 1)
- transportation of fresh (55%) un-chipped material from stand to plant, chipping at plant (SC 2)
- storing material for one year, transportation of dry (35%) un-chipped material to plant, chipping at plant (SC 3)
- storing material for one year, chipping and transportation of chips with a moisture content of 35% (SC 4)
- transportation of sawmill byproducts to plant as chips (45%) (SC5)

Variables

x^{NF}_{ikt}	un-chipped fresh material transported from stand *i* to the plant *k* in time period *t* (m^3)
x^{ND}_{ikt}	un-chipped dry material transported from stand *i* to the plant *k* in time period *t* (m^3)
x^{CF}_{ikt}	chipped fresh material transported from source *i* (stand or sawmill) to the plant *k* in time period *t* (m^3)
x^{CD}_{ikt}	chipped dry material transported from stand *i* to the plant *k* in time period *t* (m^3)
x^{NF}_{ikt-1}	un-chipped fresh material transported from stand *i* to the plant *k* in time period *t-1* (m^3)
x^{CF}_{ikt-1}	chipped fresh material transported from source *i* (stand or sawmill) to the plant *k* in time period *t-1* (m^3)

Sets

I	set of sources: stands (I_{sta}) and sawmills (I_{saw})
T	set of time periods
K	set of heating plants

Constraints

a^F_{it}	available fresh material at source *i* in time period *t* (w=55% from stand and w=45% from sawmills) (m^3)
a^F_{it-1}	available fresh material at source *i* in time period *t-1* (w=55%) (m^3)
a^D_{it}	available dry material at source *i* from time period *t* (m^3)
m_{kt}	demand of heating plant *k* in the time period *t* (MWh)
c^C_{saw}	transportation cost of byproducts from supply sawmill *i* to plant *k* in time period *t* (€ MWh^{-1} min^{-1})
c^{NF}_{ikt}	transportation cost of un-chipped residues from supply stand *i* to plant *k* in time period *t* (€ MWh^{-1} min^{-1})
c^{CF}_{ikt}	transportation cost of a chipped residues from supply stand *i* to plant *k* in time period *t* (€ MWh^{-1} min^{-1})

c^{ND}_{ikt}	transportation cost of un-chipped residues from supply stand *i* to plant *k* in time period *t* (€ MWh^{-1} min^{-1})
c^{CD}_{ikt}	transportation cost of a chipped residues from supply stand *i* to plant *k* in time period *t* (€ MWh^{-1} min^{-1})
c^{HF}_{it}	chipping cost at forest stand *i* of fresh residues in time period *t* (€ MWh^{-1})including unloading of chips
c^{HD}_{it}	chipping cost at forest stand *i* of dry residues in time period *t* (€ MWh^{-1}) including unloading of chips
c^{HF}_{kt}	chipping cost at plant *k* of fresh residues in time period *t* (€ MWh^{-1}) including loading and unloading of residues
c^{HD}_{kt}	chipping cost at plant *k* of dry residues in time period *t* (€ MWh^{-1}) including loading and unloading of residues
$c^{PF}_{t,\ sta}$	purchasing cost of fresh residues at stand *i* in time period *t* (€ MWh^{-1}) (not chipped)
$c^{PD}_{t,\ sta}$	purchasing cost of dry residues at stand *i* in time period *t* (€ MWh^{-1}) (not chipped)
c^{P}_{saw}	purchasing cost of byproducts at sawmill *i* (chipped) (€ MWh^{-1})
c^{V}_{saw}	loading and unloading cost of byproducts at sawmill *i* (chipped) (€ MWh^{-1})
v_{35}	Energy of dry stand residues with moisture content of 35% (MWh)
v_{55}	Energy of fresh stand residues with moisture content of 55% (MWh)
v_{45}	Energy of sawmill residues with moisture content of 45% (MWh)
r	increment of cost for raw material if stored at roadside (%)
s_{ik}	driving time from source *i* to plant *k* and from plant to source (min)

Those constraints ensure that the amount of biomass transported from stands and sawmills to plant do not exceed the available volume at source *i*

$$\sum_{k\in K} x_{ikt}^{CF} + \sum_{k\in K} x_{ikt}^{NF} \le a_{it}^{F} \qquad \forall\, i \in I,\ \forall\, t \in T$$

$$\sum_{k\in K} x_{ikt}^{CD} + \sum_{k\in K} x_{ikt}^{ND} \le a_{it}^{D} \qquad \forall\, i \in I,\ \forall\, t \in T$$

$$a_{it}^{D} = a_{it-1}^{F} - \left(\sum_{k\in K} x_{ikt-1}^{CF} + \sum_{k\in K} x_{ikt-1}^{NF} \right) \qquad \forall\, i \in I,\ \forall\, t \in T$$

This constraint assures that a sufficient wood fuel is transported to plants to meet their demands

$$\sum_{i\in I_{saw}} x_{ikt}^{CF} \cdot v_{45} + \sum_{i\in I_{sta}} x_{ikt}^{CF} \cdot v_{55} + \sum_{i\in I} x_{ikt}^{NF} \cdot v_{55} + \sum_{i\in I} x_{ikt}^{CD} \cdot v_{35} + \sum_{i\in I} x_{ikt}^{ND} \cdot v_{35} = m_{kt}$$

$$\forall\, k \in K,\ \forall\, t \in T$$

The following constraint guards against violation of the assumption of non-negativity

$$x_{ikt} \ge 0 \qquad \forall\, i \in I,\ \forall\, t \in T,\ \forall\, k \in K$$

Objective function

The objective is to minimize the supply cost of the DH

$$C = C^{tran} + C^{chip} + C^{purc}$$

The following formula expresses the transportation cost

$$C^{tran} = \sum_{i \in I_{saw}} c^{C}_{saw} x^{CF}_{ikt} s_{ik} v_{45} + \sum_{i \in I_{sta}} c^{NF}_{ikt} x^{NF}_{ikt} s_{ik} v_{55} + \sum_{i \in I_{sta}} c^{CF}_{ikt} x^{CF}_{ikt} s_{ik} v_{55} + \sum_{i \in I_{sta}} c^{ND}_{ikt} x^{ND}_{ikt} s_{ik} v_{35} + \sum_{i \in I_{sta}} c^{CD}_{ikt} x^{CD}_{ikt} s_{ik} v_{35}$$
$$\forall\ k \in K,\ \forall\ t \in T$$

The first term expresses the chipping cost at supply source and the second the chipping cost at plant

$$C^{chip} = \sum_{i \in I_{sta}} c^{HF}_{it} x^{CF}_{ikt} v_{55} + \sum_{i \in I_{sta}} c^{HD}_{it} x^{CD}_{ikt} v_{35} + \sum_{i \in I_{sta}} c^{HF}_{kt} x^{NF}_{ikt} v_{55} + \sum_{i \in I_{sta}} c^{HD}_{kt} x^{ND}_{ikt} v_{35} + \sum_{i \in I_{saw}} c^{V}_{saw} x^{CF}_{ikt} v_{45}$$
$$\forall\ k \in K,\ \forall\ t \in T$$

Where the first term expresses the purchase cost of sawmill byproduct and the second term the purchase cost of forest residues

$$C^{purch} = \sum_{i \in I_{saw}} c^{P}_{saw} x^{CF}_{ikt} v_{45} + \sum_{i \in I_{sta}} c^{PF}_{t,sta} \left(x^{CF}_{ikt} + x^{NF}_{ikt} \right) v_{55} + \sum_{i \in I_{sta}} c^{PD}_{t,sta} \left(x^{CD}_{ikt} + x^{ND}_{ikt} \right) v_{35} \cdot (1 + r)$$
$$\forall\ k \in K,\ \forall\ t \in T$$

The matrix is set so that there are 190 sources as piling places (everyone refers to 10 cutting years) and seven sources as sawmills that offer the same volume every year.

3.5 MULTIPERIOD OPTIMIZATION AND TERMINAL LOCATION - SCENARIO II

The aim is to optimize the plants' supply for one year considering six time periods of two months.

This scenario uses one terminal to store forest residues, so that supply is guaranteed especially when there is a peak in demand and restrictions in fuel availability. Storage has also the function to dry the forest fuel, increasing its energy content. In this scenario three terminal locations are tested to find out the most economically convenient position according to the supply areas and destination points. Locations of the pre-selected terminals were according to closeness to road network, maintaining a necessary distance from villages in order to avoid noises and traffic. This is an example to show that it is possible to use linear programming to help the decision maker to choose the most economically convenient location. Managing inventories during several time periods is vital to supply chain depending on the availability of fuel. Current models are mostly developed not considering different time periods. Multi-period optimization problem grows in complexity, but helps to solve the problem of deciding when, where and how the forest biomasses are converted into biofuels and how biofuels are transported and stored.

In the short term, the supply of forest residues is not constant but fluctuates with the extent of harvesting activities. In this scenario, the forest residues availability has a drop in winter, due mainly to the bad accessibility of the forest due to the snowy condition of the forest roads (Figure 3.9). The heating season is considered starting in July and ending in June.

The peak in demand is usually from December to March (Figure 3.10) and the sawmill byproducts availability decreases in August and December (Figure 3.11) because of holidays.

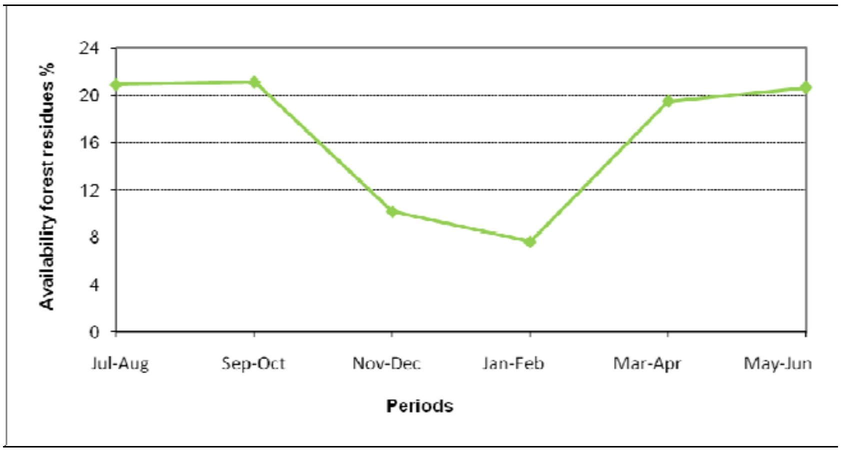


Figure 3.9. Relative availability of forest residues during the year

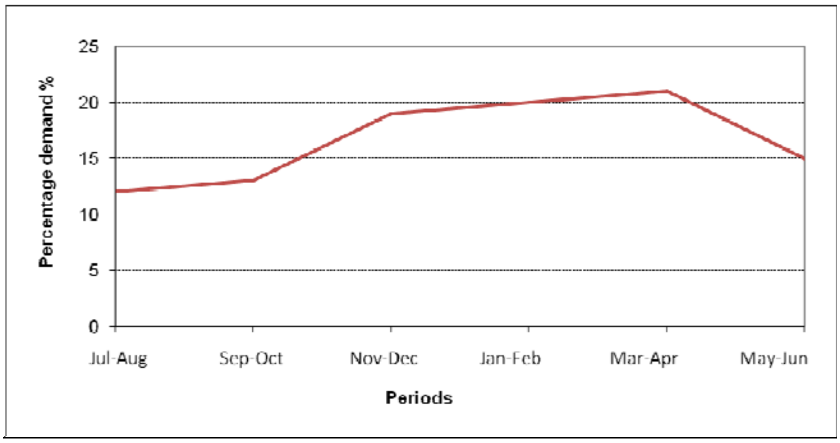


Figure 3.10. Relative percentage of demand throughout the year

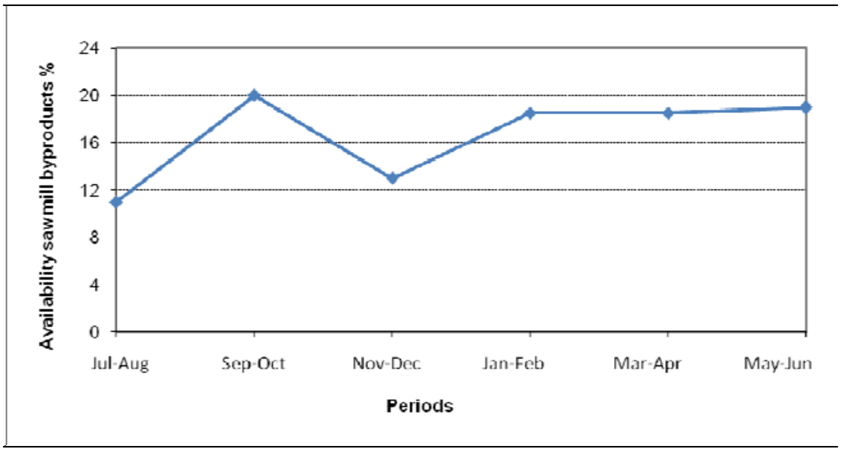


Figure 3.11. Relative availability of sawmill byproducts during the year

3.5.1 Supply chains

Three supply chains are considered in this scenario (Figure 3.12):

- SC1 - Supply of forest chips from stand to plant (x^C): chipping at roadside, transporting of chips from stand to plant and unloading the truck;
- SC2 - Supply of forest fuel from stand to plant, storing residues and chipping at terminal (x^N): transportation of forest residues from stand to terminal, unloading, storing and chipping them, transportation of chips from terminal to plant and unloading the truck;
- SC3 - Supply sawmill byproducts (x^B): loading of sawmill byproducts, transporting to the plant and unloading.

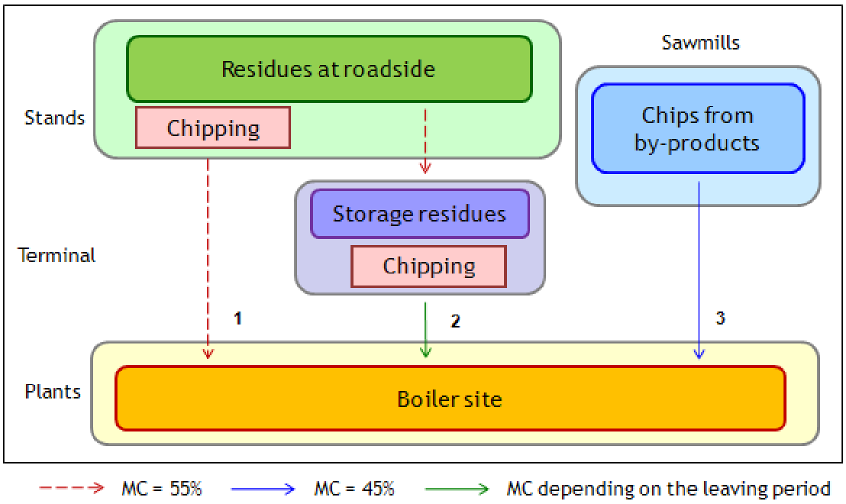


Figure 3.12. Supply chains considered in the optimization: red arrow: the forest fuel flow from forest to terminal or to plant with a moisture content of 55%; blue arrow: the sawmill byproducts flows with a moisture content of 45%; green arrow: the chips transported from terminal to plant that has a energy content that varies on the storing time.

Fuel flows from stands to plants (K1 and K2) passing through terminal (J), implies the use of additional variables (Figure 3.13): the x^N indicates the flows from stand to terminal, x^R the material stored at the beginning of a time period, x^F the material stored at the end of a time period and x^{SC} the material transported from terminal to plants in the time period. In the problem it is included the increasing of energy content storing the fuel.

The transportation model become more complicated due to the fact that more variables and constraints are involved.

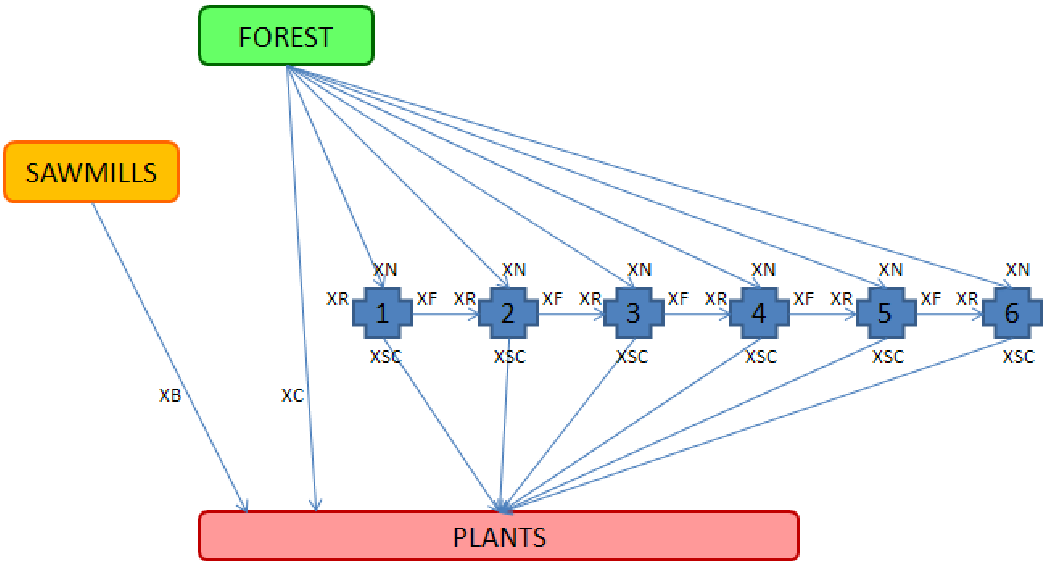


Figure 3.13. Scheme of the flows to plants and within the terminal during the time periods (1 to 6).

3.5.2 Transportation model formulation for scenario II

A transportation model has been formulated considering the seasonal fluctuation of fuel demand and supply and considering the possibility that the fuel can be stored at terminal. The transportation model has been run three times, changing each time the terminal location, with the aim to find out the most economically convenient position.
The effect of the added energy content from drying has been taken into consideration. The value (*g*) has been estimated according to the value obtained in the drying test on spruce covered and not processed. In the optimization calculations the increased periodic energy content is modeled by increasing the volume available at storage. Therefore volume available at terminal increases of 2.20% when biomass is stored one period. The transportation cost from terminal to plant considers a reduction coefficient of 97.80% that takes into account that the material has been stored for at least one period.
This scenario uses a moisture content of 45% for sawmill byproducts and 55% for forest residues.

The maximum capacity of storage (z^N_j) at the same time is here considered to be 2500 m^3. Once the fuel comes to terminal, it must be stored for at least one period.
It is supposed that the residues are chipped just before the transportation, this means that chipping is done the same time period that chips are transported to plants.
Here it is considered to optimize the plants supply chains during six time periods, corresponding to one year. The input data for the forest supply are related to year 6.

The size of the problem increases rapidly with the number of sources, plants and terminals, supply chains and time periods. In order to solve such problem, advanced operational research methods are needed. Possible combinations of transportation, routes and transported quantities are generated depending on their predicted contribution to the optimal solution.
The transportation model has been solved using LINGO linked with excel spreadsheet.

Variables

x^{N}_{ijt}	un-chipped material transported from stand *i* to the terminal *j* in time period *t* (m^3) -SC2-
x^{C}_{ikt}	chipped material transported from stand *i* to the plant *k* in time period *t* (m^3) -SC1-
x^{C}_{ykt}	chipped material transported from source *y* sawmill to the plant *k* in time period *t* (m^3) -SC3-
x^{C}_{jkt}	chipped material transported from terminal *j* to the plant *k* in time period *t* (m^3) -SC2-
x^{R}_{jt}	un-chipped material stored at terminal *j* at the beginning of time period *t* (m^3) -SC2-
x^{F}_{jt}	un-chipped material stored at terminal *j* at the end of period *t* (m^3) -SC2-

Sets

I	set of stands
Y	set of sawmills
T	set of time periods for first transportation
K	set of heating plants
J	set of terminals

Constraints

a_{it}	available material at stand *i* in time period *t* (w=55%) (m^3)
b_{yt}	available material at sawmill *i* in time period *t* (w=45%) (m^3)
m_{kt}	demand of heating plant *k* in the time period *t* (MWh)
c^{C}_{ik}	transportation cost of chipped residues from source *i* to plant *k* (€ m^{-3} min^{-1}) -SC1-
c^{N}_{ij}	transportation cost of un-chipped residues from source *i* to terminal *j* (€ m^{-3} min^{-1}) -SC2-
c^{C}_{yk}	transportation cost of sawmill byproducts from sawmill *y* to plant *k* (€ m^{-3} min^{-1}) -SC3-
c^{C}_{ik}	transportation cost of chipped residues from terminal *j* to plant *k* (€ m^{-3} min^{-1}) -SC2-
c^{H}_{i}	chipping cost at forest stand *i* (€ m^{-3}) including unloading of chips -SC1-
c^{H}_{j}	chipping cost at terminal *j* (€ m^{-3}) including unloading of chips -SC2-
c^{H}_{ij}	loading and unloading of un-chipped material and terminal costs (€ m^{-3}) -SC2-
c^{P}_{sta}	purchasing cost of residues at stand *i* (€ m^{-3}) -SC1, SC2-
c^{P}_{saw}	purchasing cost of byproducts at sawmill *y* including unloading of chips at plant (€ m^{-3}) -SC3-
v_{45}	energy content of sawmill byproducts (moisture content of 45%) (MWh m^{-3})
v_{55}	energy content of forest residues (moisture content of 55%) (MWh m^{-3})
s_{ik}	driving time from stand *i* to plant *k* and back (min)
u_{ij}	driving time from stand *i* to terminal *j* and back (min)
q_{jk}	driving time from terminal *j* to plant *k* and back (min)
o_{ij}	driving time from sawmill *i* to terminal *j* and back (min)
z^{N}_{j}	storage capacity at terminal *j* (m^3)
g	increased energy content during one period of two months

Those constraints ensure that the amount of biomass transported from sources to destinations do not exceed the available volume at source *I* in period *t*

$$\sum_{j \in J} x^{N}_{ijt} + \sum_{k \in K} x^{C}_{ikt} \leq a_{it} \qquad \forall\, i \in I,\ \forall\, t \in T$$

$$\sum_{k \in K} x^C_{ykt} \le b_{yt} \qquad \forall\, y \in Y,\ \forall\, t \in T$$

This constraint assures that a sufficient wood fuel is transported to plants to meet their demands

$$\sum_{i \in I} x^C_{ikt} v_{55} + \sum_{y \in Y} x^C_{ykt} v_{45} + \sum_{j \in J} x^C_{jkt} v_{55} = m_{kt} \qquad \forall\, k \in K,\ \forall\, t \in T$$

The following constraint guards against violation of the assumption of non-negativity

$$x_{ikt} \ge 0 \qquad \forall\, i \in I,\ \forall\, t \in T,\ \forall\, k \in K$$

Balance un-chipped material at terminal (mass conservation at terminal)

$$x^R_{jt} + \sum_{i \in I} x^N_{ijt} = x^F_{jt} + \sum_{k \in K} x^C_{jkt} \qquad \forall\, j \in J,\ \forall\, t \in T$$

$$x^R_{jt} = x^F_{jt-1} \cdot g \qquad \forall\, j \in J,\ \forall\, t \in T$$

The amount of material transported at plant must be lower than the available material at terminal at the beginning of the time period. It is considered that is not possible to deliver at plant the material arrived at terminal the same period

$$\sum_{k \in K} x^C_{jkt} \le x^R_{jt} \qquad \forall\, j \in J,\ \forall\, t \in T$$

The un-chipped material stored at terminal *j* at the beginning of the first period and at the end the last period will be equal to 0

$$\sum_{t=1} x^R_{jt} = 0$$

$$\sum_{t=6} x^F_{jt} = 0$$

Storage capacity at terminal: volume of un-chipped material stored at terminal at the end of the period t must be less than the terminal capacity

$$x^F_{jt} \le z^N_{jt} \qquad \forall\, j \in J,\ \forall\, t \in T$$

Objective function

The objective is to minimize the supply cost of the plants *K*

$$C = C^{tran} + C^{chip} + C^{purc} + C^{stor}$$

The following formula expresses the transportation cost

$$C^{tran} = \sum_{i \in I} \sum_{k \in K} c_{ik}^{C} x_{ikt}^{C} s_{ik} + \sum_{i \in I} \sum_{j \in J} c_{ij}^{N} x_{ijt}^{N} u_{ij} + \sum_{j \in J} \sum_{k \in K} c_{jk}^{C} x_{jkt}^{C} q_{jk} + \sum_{y \in Y} \sum_{k \in K} c_{yk}^{C} x_{ykt}^{C} o_{yk} \qquad \forall\, t \in T$$

The first term expresses the chipping cost at supply source and the second the chipping cost at plant

$$C^{chip} = \sum_{k \in K} \sum_{i \in I} c_{it}^{H} x_{ikt}^{C} + \sum_{k \in K} \sum_{j \in J} c_{jt}^{H} x_{jkt}^{C} \qquad \forall\, t \in T$$

$$C^{stor} = \sum_{k \in K} \sum_{j \in J} c_{jt}^{W} x_{jkt}^{C} \qquad \forall\, t \in T$$

Where the first term expresses the purchase cost of forest residues and the second term the purchase cost of sawmill byproduct

$$C^{purch} = \sum_{y \in Y} c_{saw}^{P} x_{ykt}^{C} + \sum_{j \in J} \sum_{i \in I} c_{sta}^{P} \left(x_{ikt}^{C} + x_{ijt}^{N} \right) \qquad \forall\, t \in T,\ \forall\, k \in K$$

3.6 ANNUAL OPTIMIZATION - SCENARIO III

The aim is to study the effects of restrictions in the whole supply. Sensitivity analyses are done to test the effect of changing some parameters on the whole system supply costs.

3.6.1 Supply chains

In this scenario the following supply chains are considered:

- chipping at roadside (stand), transportation of chips to plant with a moisture content of 55% (XC)
- transportation of fresh (55%) un-chipped material from stand to plant, chipping at plant (XN)
- transportation of sawmill byproducts to plant as chips (45%) (XS)

Location of chipping and types of transported material are the alternatives in the supply chains (Figure 3.14).

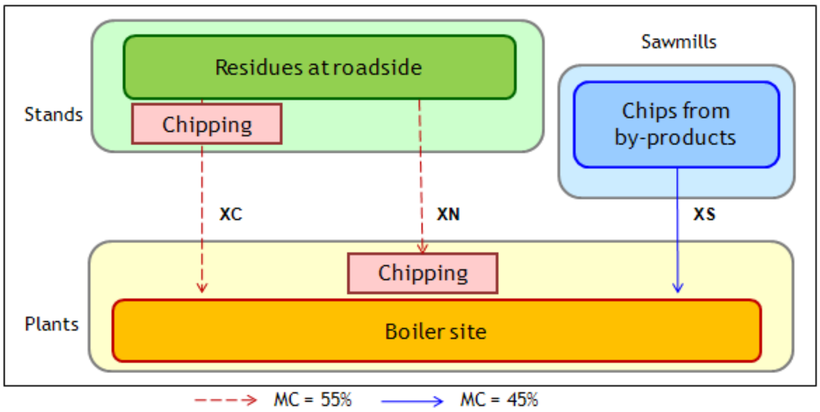


Figure 3.14. Supply chains considered in the scenario III

3.6.2 Transportation model formulation for scenario III

A simplified transportation model has been built considering data related to one year in order to carry out deeper analysis on some constraint factors. Sensitive analyses were done to illustrate impacts of changing:

- oil price
- truck payload
- demand
- moisture content.

Input forest residues data are related to the year 6. The time variable here is not considered. Also in this scenario the software LINGO interrelated with excel spreadsheet has been used to solve the transportation model.

Here is reported the general formulation, with sensitive analysis some constraints are changed.

Variables

x^N_{ik}	un-chipped fresh material transported from the stand *i* to the plant *k* (m^3)
x^C_{ik}	chipped fresh material transported from the stand *i* to the plant *k* (m^3)
x^B_{yk}	sawmill byproducts transported from the sawmill *y* to the plant *k* (m^3)

Sets

I	set of stands
K	set of sawmills
Y	set of heating plants

Constraints

a^F_i	available fresh material at source *i* (m^3)
m_k	demand of heating plant *k* (MWh)
c^S_{yk}	transportation cost of byproducts from supply sawmill *i* to plant *k* (€ MWh^{-1} min^{-1})
c^N_{ik}	transportation cost of un-chipped residues from stand *i* to plant *k* (€ MWh^{-1} min^{-1})
c^C_{ik}	transportation cost of chips from stand *i* to plant *k* (€ MWh^{-1} min^{-1})
c^H_i	residues chipping cost at stand *i* (€ MWh^{-1})including unloading of chips
c^H_k	residues chipping cost at plant *k* (€ MWh^{-1})including loading and unloading of residues
c^P_i	purchasing cost of residues at stand *i* (€ MWh^{-1}) (not chipped)
c^P_y	purchasing cost of byproducts at sawmill *y* (chipped) (€ MWh^{-1})
c^V_y	loading and unloading cost of byproducts at sawmill *y* (chipped) (€ MWh^{-1})
v_{55}	energy content of fresh stand residues with moisture content of 55%
v_{45}	energy content of sawmill residues with moisture content of 45%
s_{ik}	driving time from source *i* to plant *k* and from plant to source (min)
s_{yk}	driving time from source *y* to plant *k* and from plant to source (min)

Those constraints ensure that the amount of biomass transported from stands and sawmills to plant do not exceed the fuel available at source *i*

$$\sum_{k \in K} x^C_{ik} + \sum_{k \in K} x^N_{ik} \leq a_i \qquad \forall\, i \in I$$

$$\sum_{k \in K} x^B_{yk} \leq b_y \qquad \forall\, y \in Y$$

This constraint assures that a sufficient wood fuel is transported to plants to meet their demands

$$\sum_{y \in Y} x_{yk}^{B} \cdot v_{45} + \sum_{i \in I} x_{ik}^{C} \cdot v_{55} + \sum_{i \in I} x_{ik}^{N} \cdot v_{55} = m_k \qquad \forall\ k \in K$$

The following constraint guards against violation of the assumption of non-negativity

$$x_{ik} \geq 0 \qquad \forall\ i \in I,\ \forall\ k \in K$$

$$x_{yk} \geq 0 \qquad \forall\ y \in Y,\ \forall\ k \in K$$

Objective function

The objective is to minimize the supply cost of the DH

$$C = C^{tran} + C^{chip} + C^{purc}$$

The following formula expresses the transportation cost

$$C^{tran} = \sum_{y \in Y} c_{yk}^{S} x_{yk}^{B} s_{yk} v_{45} + \sum_{i \in I} c_{ik}^{N} x_{ik}^{N} s_{ik} v_{55} + \sum_{i \in I} c_{ik}^{C} x_{ik}^{C} s_{ik} v_{55} \qquad \forall\ k \in K$$

Here is expressed the chipping cost of forest residues at roadside or at plant and the loading costs for sawmill byproducts

$$C^{chip} = \sum_{i \in I} c_{i}^{H} x_{ik}^{C} v_{55} + \sum_{i \in I} c_{k}^{H} x_{ik}^{N} v_{55} + \sum_{y \in Y} c_{y}^{V} x_{yk}^{B} v_{45} \qquad \forall\ k \in K$$

Where the first term expresses the purchase cost of sawmill byproduct and the second term the purchase cost of forest residues

$$C^{purch} = \sum_{y \in Y} c_{y}^{P} x_{yk}^{B} v_{45} + \sum_{i \in I} c_{i}^{P} \left(x_{ik}^{C} + x_{ik}^{N} \right) v_{55} \qquad \forall\ k \in K$$

3.7 FOREST WOOD FUEL SUPPLY CHAIN OPTIMIZATION: CASE STUDY IN CENTRAL FINLAND

In Nordic countries bioenergy wood fuel is often used by heating plants, which are normally operated by local communities to provide energy for cities and village. A large number of new big wood-based heating plants and biorefineries are presently under consideration in Finland. Huge demand of fuel by biorefineries means intensive biofuels supply within a certain supply area. Forest fuel assortments, such as logging residues, stumps and small diameter whole trees, play a key role seeking to increase the utilization of local bioenergy sources (Ranta *et al.*, 2008). Recent studies and scenarios confirm that the annual use of forest fuels could be tripled without exceeding the limits of exploitation of forest as biomass reserves (Anonymous, 2007; Laitila *et al.*, 2008).

Establishment of new large scale CHP and biorefineries causes enlargement and overlapping of supply areas, which leads to increasing competition of fuel sources (Ranta *et al.*, 2008).

Over 80% of the annual domestic roundwood cuttings derive from private forests. This means that the option of collecting energy wood from the stand depends on individual forest owners' decisions (Ranta *et al.*, 2008).

Countrywide only one fifth of the potential forest fuel is being utilized, but locally there can be scarcity of resources. Therefore when planning such investment the competition for raw material can be a serious constraint. When planning the supply of a plant with high feedstock demand, fuel availability and supply chains design must be taken into consideration.

The aim of this study is to identify the optimal allocation of forest fuel that supply two large scale plants in the least-cost manner. Changing in demand and paying ability for the chips may affect the supply region of the two plants.

Fuel supply and demand are always the first thing to know before starting optimization studies.

3.7.1 Area description

The study area included municipalities that are within 200 km radius from Jyväskylä or Varkaus (Figure 3.3.15). Road network data were used as a basis for the cost calculations of truck transportation. The Finnish Road Administration maintains national road and street database called Digiroad (Anonymous, 2008). Digiroad describes the geometry and physical features of the roads including, e.g., the functional class of a road and turning restrictions. Corine (CLC2000) land use / land cover classification (CLC2000Finland. Final Report, 2005) and the boundaries of conservation and Natura 2000 areas were used to allocate the supply only to forest land available for wood supply.

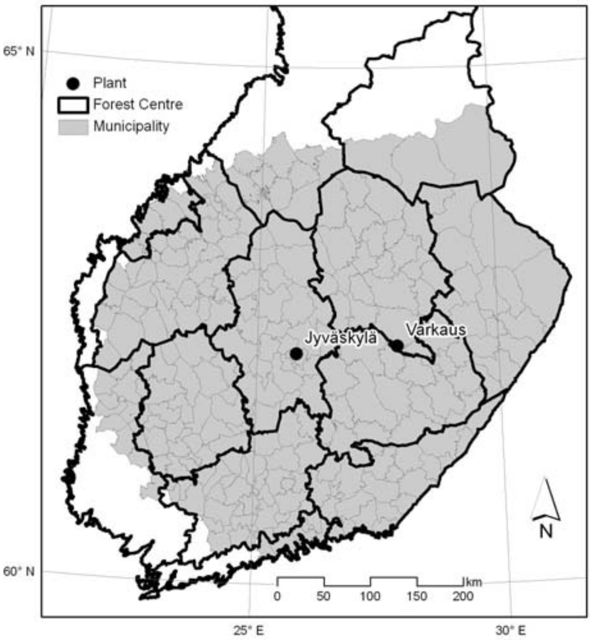


Figure 3.15. The study area. Boundaries: © National Land Survey of Finland, license MYY/179/06-V.

3.7.2 Energy wood resources

In Finland energy wood harvesting is strongly integrated into industrial timber harvesting. Forest wood fuel sources are logging residues from regeneration felling, small size trees from pre-commercial thinning and unproductive hardwood stands (Hakkila 2004; Ranta, 2005; Laitila et al., 2008) and spruce stumps from final felling.

Thinning is a standard silvicultural practice. In southern Finland, nearly all stands are thinned commercially twice or three times, and in northern Finland once or twice, during the rotation period. Commercial thinning is preceded by a pre-commercial thinning from which is possible to extract 15-50 m^3 ha^{-1} of biomass (Hakkila, 2003). Pre-commercial thinning is a challenge for forest owners because of its high harvesting cost and low yield. A subsidy of up to 11.25 € m^{-3} is provided if the material from early thinning is meant for chips production and the yield of the stand is lower than 25 m^3 ha^{-1} (Partanen, 2008).

In this case study energy wood resources at municipality level were estimated for the following raw material sources:

- logging residues from final felling of spruce stands
- logging residues from final felling of pine stands
- stumps from final felling of spruce stands
- whole trees (excluding stump and roots) from spruce, pine, birch and other broadleaves young stands

3.7.2.1 Logging residues and stumps

The availability of logging residues and stumps are affiliated to the regeneration cuttings and harvesting volumes of industrial roundwood. Therefore the biomass volumes from regeneration cuttings were based on annual commercial roundwood removals. The municipality specific data on commercial roundwood removals were gathered from the statistics of Finnish Forest Research Institute (Metinfo). The data were available from the year 2004 and contained both the cuttings of the private forests, company owned forests and state owned forests. In the statistics the roundwood volumes were classified, for instance, according to the tree species and timber assortments.

The availability of logging residues was based on the removal volumes of spruce and pine logs and the availability of stump and root wood was based on 65% removal volumes of spruce logs. The timber volumes were converted to biomass volumes by biomass factors which are detailed in the Table 3.4. The material and method was exactly the same which was used in the study of Laitila *et al.* (2008). The recovery rate of logging residues was 70% of total volume and 95% for stumps at the stand. Logging residues were composed of the crown mass, un-merchantable tops and oversize and rotten part of logs.

Table 3.4. Proportions of biomass components used in the availability estimation of logging residues and stumps (Hakkila, 1991; Asikainen *at al.*, 2001; Hakkila, 2004)

	Biomass component, %
Logging residues, Southern Finland, % per 1 m^3 of spruce logs	44
Logging residues, Northern Finland, % per 1 m^3 of spruce logs	68
Logging residues, Southern Finland, % per 1 m^3 of pine logs	21
Logging residues, Northern Finland, % per 1 m^3 of pine logs	28
Stump and root wood, % per 1 m^3 of spruce logs	28
Recovery rate of logging residues at the stand	70
Recovery rate of stump and root wood at the stand	95

3.7.2.2 Whole trees

The potential of forest chips of whole trees from advanced seedling stands and young thinning stands in Finland based on the 8th and 9th national forest inventories (NFIs) has been calculated by Ranta *et al.* (2007). In the 10th inventory, the inventory schema was changed from periodical to continuous inventory, where one fifth of the plots in the entire country is measured every year (Tomppo, 2006; Korhonen *et al.*, 2007). The field measurements of NFI10 started in 2004.

In this case study, the potential of forest chips from young forests was updated based on the NFI10 data. At first, removal of stem wood was calculated for each sample plot by simulating tending of a young stand or thinning according to silvicultural guidelines (Anonymous, 2006). Accumulation of industrial roundwood was based on bucking by cruising teams in the field. Only trees with diameter at breast height over 4 cm were considered.

Crown volume was calculated by using crown mass (Hakkila, 1991) and density factors (Hakkila, 1978). Accumulation of energy wood was obtained by summing removal of stem wood and crown volume. It was assumed that all the energy wood could be collected in the stand, i.e., recovery percentage was 100.

Sample plots suitable for energy wood harvesting were selected according to the following criteria:

- Stand development class is either advanced seedling stand or young thinning stand;
- Tending of advanced seedling stand or pre-commercial thinning had been proposed by the cruising team;
- The need for tending or thinning is urgent, i.e. within the first 5-year period;
- The accumulation of industrial roundwood is less than 25 m^3/ha;
- The accumulation of energy wood is more than 25 m^3/ha.

The proportion of suitable forests ($P_{dc,fc}$) was calculated by stand development class for each Forest Centre with NFI data as follows:

$$p_{dc,fc} = \frac{E_{dc,fc}}{A_{dc,fc}} \qquad (3.d)$$

$E_{dc,fc}$ area of the suitable plots of stand development class *dc* in Forest centre *fc*
$A_{dc,fc}$ total area of stand development class *dc* in Forest centre *fc*.

With Multi-Source National Forest Inventory (MSNFI) data, the areas of development classes can be estimated even at municipality level (Tomppo *et al.*, 1998).

New MSNFI data was utilized in order to calculate the area of forests suitable for harvesting energy wood in each municipality:

$$E_{dc,m} = p_{dc,fc} \cdot A_{dc,m} \qquad (3.e)$$

$A_{dc,m}$ is the total area of development class *dc* in municipality *m*.

The accumulation of energy wood from whole trees was estimated for each municipality:

$$V_m = \sum_{dc=3}^{4} E_{dc,m} \cdot \overline{V}_{dc,fc} \qquad (3.f)$$

$\overline{V}_{dc,fc}$ is the average accumulation of energy wood in development class *dc* in Forest Centre *fc*.

3.7.2.3 DH demand

In Finland the users of forest chips are mainly local DH or CHP. Only small scale heating plants can use forest fuel as main fuel, which are often high quality chips from delimbed small stems. The major share of forest fuel from regeneration felling is used in multi-fuel boilers applying advanced fluidized-bed combustion technology (Ranta, 2005).

In this case study two large scale heating plants are considered located in Central Finland: Jyväskylä and Varkaus. At this moment they are still under construction but their activity will start in the near future (Keljolanhden voimalaitos, 2009; Gust *et al.*, 2007).

Jyväskylä plant is located close to the city, so chipping at plant is not allowed (Ryymin *et al.*, 2008). Varkaus plant is instead located in the pulp, paper and saw mill integrate plant of Stora Enso Oyj (Gust *et al.*, 2007).

3.7.2.4 Available potential

Above-calculated energy wood potentials do not consider the use of wood chips by existing plants. In order to find out the free, available potential, the present use must be subtracted from the total potential. Since 2000, the usage of forest chips has been steadily rising in Finland, except in 2007 (Ylitalo, 2008). The reason for the exception was the low price of emission allowances for CO_2 in the end of emission trade period. From 2008 the prices and, therefore, the use of forest chips will increase again. That is reason why the figures of existing plants were taken from the statistics of 2006.

In 2006, the use of forest chips amounted to 3.4 million m^3 (Ylitalo, 2007). The origin of forest chips was specified by Forest Centre. On average, 57% originated from logging residues, 23% from whole trees from young forests, 15% from stumps and roots and 6% of large-diameters logs. As a rough approximation, the use in a Forest Centre was distributed to the municipalities proportional to the total potential of a municipality:

$$V'_{m,o} = \frac{V_{m,o}}{V_{fc,o}} \cdot (V_{fc,o} - U_{fc,o}) \qquad (3.g)$$

$V'_{m,o}$	available potential in municipality *m* from origin *o* (logging residues, whole trees or stumps)
$V_{m,o}$	total potential in municipality *m* from origin *o*
$V_{fc,o}$	total potential in Forest Centre *fc* from origin *o*
$U_{fc,o}$	present use of forest chips in Forest Centre *fc* from origin *o*.

3.7.2.5 Transportation distances

A point grid with 3 km interval was created and overlaid on the study area. Subsequently, the points falling on forest land available for wood supply (excluding not forest areas, conservation and Natura2000 areas) were selected for the analysis. From each point the transportation distance to the both plant locations was calculated along the road network in ArcGIS with *Network Analysis* tool. However, if the point was set further than 500 m from a road or there was no connection to the plant (e.g. on an island), the point was not located, i.e. the distance was not calculated. Restrictions given in Digiroad regarding road blocks or restrictions for truck size or truck traffic generally were treated as barriers in network analysis. There were altogether 11291 points in the analysis, of which 9900 were located.

3.7.2.6 Allocation of available potential

The potential for whole trees can be situated anywhere on the forest land available for wood supply. Consequently, the potential was distributed evenly for all the points within each municipality. Instead, potentials of logging residues and stumps were estimated based on realized cuttings and allocated, thus, only for located points within each municipality.

3.8 OPTIMIZATION OF LARGE SCALE PLANTS SUPPLY

Optimizing the supply of forest fuel to plants for heating or power production means evaluate the fuel supply chains available on the area and calculate their costs. Such data are then input into the linear programming model formulated with LINGO.
In the fuel supply optimization are considered steps reported in the flowchart in Figure 3.16.
Also in this scenario a transportation model has been formulated in order to minimize the total supply cost of plants.
The decision variables are flows of different wood fuel from supply points (stands) to demand points (plants) that are subjected to supply and demand constraints.

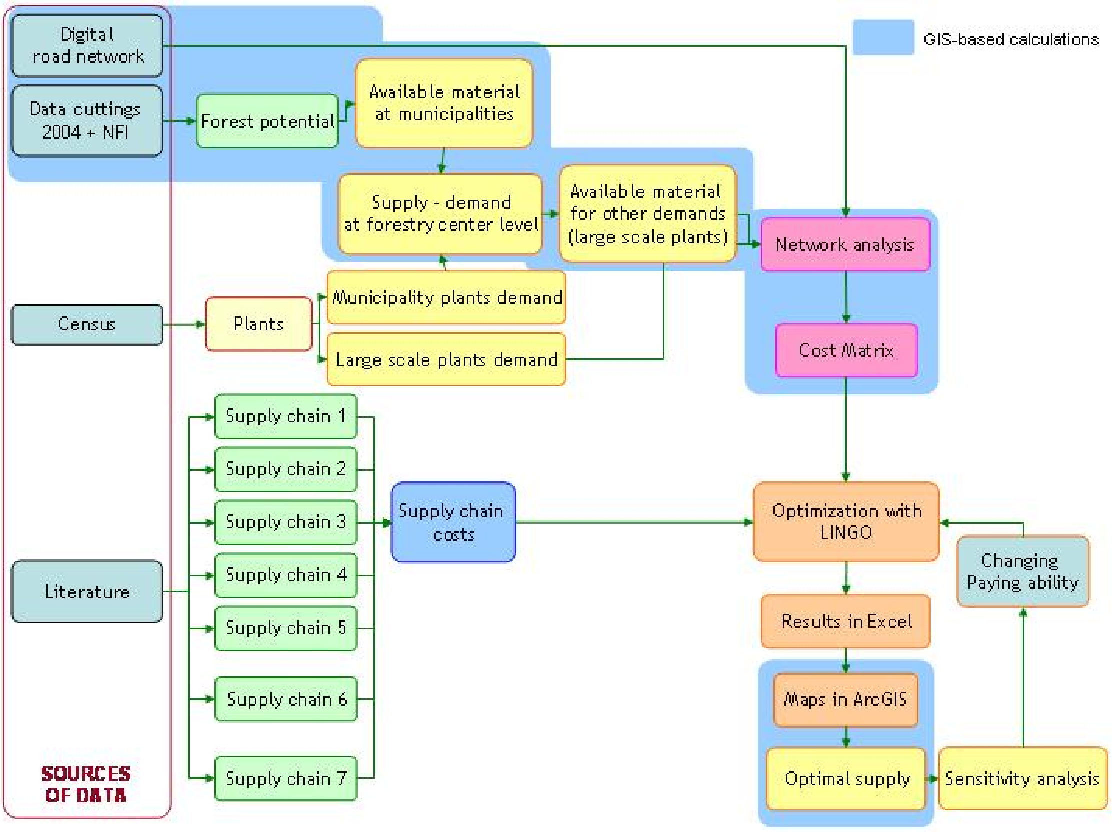


Figure 3.16. Flowchart of elements considered in the optimization

3.8.1 Supply chains

In Finland loose logging residues or small whole trees can be chipped on terrain or heaped up at roadside and chipped when dried. Another option is that the residues are yarded at roadside and transported as loose material to plant or terminal and chipped there. Logging residues from final felling can also be bundled and transported at plant or terminal and chipped there. Spruce stumps are uprooted, piled and left washing by the rain at stand. When dried they are transported with the biomass truck at terminal or at plant. Several supply chains can be adopted in Finland, but in this study area the most common are the following:

1. Chipping of loose logging residues at roadside storage and transportation of chips at plant
2. Transportation of loose logging residues and chipping at plant
3. Bundling of loose logging residues and transportation at plant
4. Transportation of loose whole trees and chipping at plant
5. Chipping of whole trees at roadside storage and transportation of chips at plant
6. Transportation of stumps at terminal, crushing of stumps at terminal and transportation of chips at plant
7. Transportation of stumps and crushing at plant

Energy wood in Finland is mainly transported with trucks (truck and trailer), there are only few large CHP installation which can use railway transportation of residue bundles, stumps or chips (Tahvanainen and Anttila, 2008).

In the forest chips supply chain, comminution is the main element affecting the whole system (Asikainen, 1995) because the location of the comminution determines the type of the material to be transported.

The supply chain for both bundles and stumps require a stationary crusher at the plant or at the intermediate terminal to prepare the fuel before combustion.

Jyväskylä plant is supposed to be supplied with the supply chains n. 1, 5 and 6 (Figure 3.18). The terminal is supposed to be located 10 km from the city (Ryymin et al., 2008). Chains n. 1-5 and 7 can supply the plant located in Varkaus (Laitila et al., 2008) (Figure 3.17). Chains 1 and 5 are the most common supply chains in Finland, where the energy wood is chipped at roadside storage into truck load and transported to the plant (Kärhä 2007).

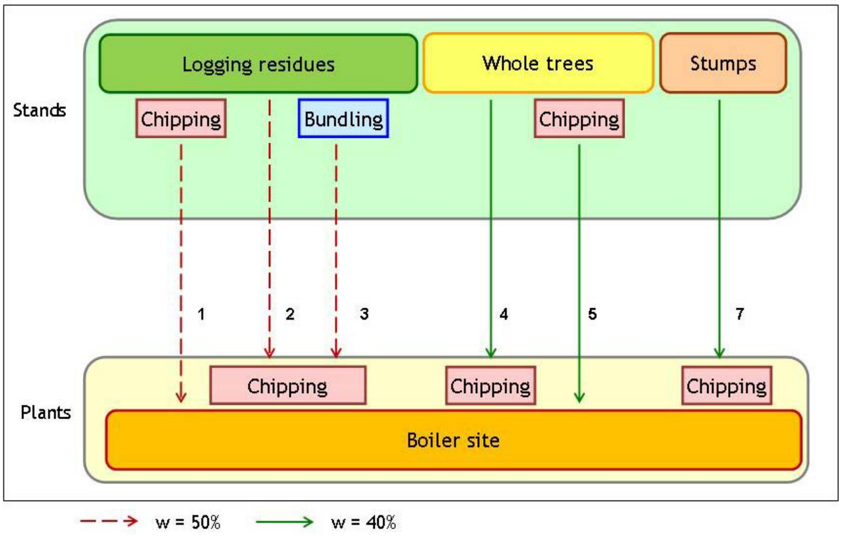


Figure 3.17. Forest fuel supply chains of Varkaus biorefinery

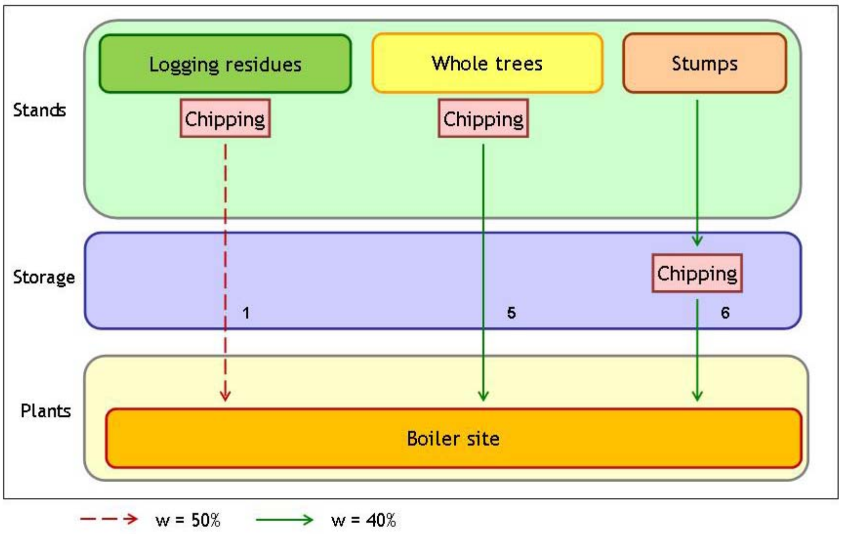


Figure 3.18. Forest fuel supply chains of Jyväskylä power plant

3.8.2 Cost calculation

All costs are calculated per volume and then converted in cost per energy content according to the average moisture content and to the average of species of the supply chain. The estimated moisture content of logging residues and stumps was 40 % and for logging residues and bundles 50 %.

3.8.2.1 Transportation cost

Transportation of loose logging residues, loose whole trees and stumps is supposed to be carried out with a biomass truck and trailer. Chips are usually transported with a chip truck and trailer. The bundling system is able to use standard timber trucks for transportation.

Parameter values used in the calculating the transportation costs (Table 3.5) were obtained from the studies of Ranta and Rinne (2006), Laitila (2008), Laitila *et al.* (2008), Ryymin *et al.* (2008) and parameter values were evaluated to be comparable.
Driving speeds are calculated according to Ranta's formulation 3.h and 3.i (2002):

$$spl_{ik} = 14.96 + 9.86 \cdot \ln(s) \tag{3.h}$$

$$spe_{ki} = 14.79 + 10.30 \cdot \ln(s) \tag{3.i}$$

spl_{ik} loaded truck speed from source *i* to plant *k* (km h^{-1})
spe_{ki} empty truck speed from plant *k* to source *i* (km h^{-1})
s one way distance from source to destination (km)

Truck is considered to have the same speed for transporting bales, loose residues, chips and stumps.

Parameters reported in Table 3.5 were used to calculate the transportation cost for every supply chain. Supply chain number 6 in particular includes loading of stumps at forest storage, unloading at terminal and furthermore loading of chips at terminal and unloading of chips at plant (Ryymin *et al.*, 2008). Loading the truck while chipping at roadside considers the waiting time of the truck (Laitila, 2008). The cost of stump chips loading at terminal, when using a wheel loader, was 0,9 € m-^{3} (Ala-Fossi, 2007).

Table 3.5. Parameters used in transportation cost calculation

Fuel type	Truck capacity	Loading time	Unloading and waiting time	Driving time cost	Terminal time cost
	m^3	H	h	€ h^{-1}	€ h^{-1}
Whole trees	30	1	0.8	77	51
Whole trees chips	44	1.3	0.8	72	47
Logging residues	30	1.4	0.8	77	51
Logging residues chips	44	1.7	0.8	72	47
Bales	45	0.8	0.6	75	48
Stumps	30	1.4	0.8	77	51
Stump chips	44	0.37	0.8	72	47

The calculated costs of supply chains utilized in the optimization are reported in Table 3.6.

Table 3.6. Transportation and terminal cost

	Supply chain	Terminal cost	Driving cost
		€ m^{-3}	€ h^{-1} m^{-3}
1	Loose residues, chipping at roadside	2.67	1.64
2	Loose residues, chipping at plant	3.74	2.57
3	Bundles, chipping at plant	1.49	1.67
4	Whole trees, chipping at plant	3.06	2.57
5	Whole trees, chipping at roadside	2.24	1.64
6	Stumps, chipping at terminal	4.99	2.57
7	Stumps, chipping at plant	3.74	2.57

3.8.2.2 Harvesting, baling, yarding, chipping and purchasing costs

Unit costs of cutting, yarding, bundling, stump extraction, roadside chipping and terminal or at plant crushing are calculated by the Excel-based procurement cost calculation models developed by the Finnish Forest Research Institute (Laitila, 2006), which combine the results of several research projects (Asikainen *et al.*, 2001, Laitila *et al.;* 2004, Heikkilä *et al.;* 2005, Laitila *et al.*, 2007). Organization cost was estimated to be 3.61 € m^{-3}, which corresponds to the average organization cost of industrial roundwood procurement cost in Finland (Kariniemi, 2006). Hourly costs of harvesting machines and transporting vehicles were obtained to the procurement calculators from the studies of Laitila (2008), Laitila *et al.* (2008) and Ryymin *et al.* (2008). The unit cost of each working stage is reported in Table 3.7. Cost of comminution at plant is considered to be the same for different raw materials (Laitila *et al.*, 2008).

Table 3.7. Values used in cost calculation (Laitila, 2006; Laitila *et al.*, 2007)

	Supply chain	cutting € m^{-3}	baling € m^{-3}	piling € m^{-3}	uprooting € m^{-3}	yarding € m^{-3}	organizing € m^{-3}	chipping € m^{-3}	Total € m^{-3}
1	Loose residues, chipping at roadside	-	-	0.3	-	6.2	3.61	5.9	16.01
2	Loose residues, chipping at plant	-	-	0.3	-	6.2	3.61	2.5	12.61
3	Bundles, chipping at plant	-	6.9	0.3	-	3.5	3.61	2.5	16.81
4	Whole trees, chipping at plant	13.5	-	-	-	6.1	3.61	2.5	25.71
5	Whole trees, chipping at roadside	13.5	-	-	-	6.1	3.61	4.5	27.71
6	Stumps, chipping at terminal	-	-	-	5.4	9.4	3.61	7.0	25.41
7	Stumps, chipping at plant	-	-	-	5.4	9.4	3.61	2.5	20.91

Costs are then converted according to the energy content of the fuel (Nurmi, 1992; Nurmi, 1993; Nurmi, 1997). Loose residues and bundlers are supposed to have a moisture content of 50%, whole trees and stumps are here considered to have a moisture content of 40%.

In this study incentives for harvesting whole trees are not considered.

Forest wood fuel purchase cost in Central Finland is supposed to be 2.00 € m^{-3} for whole trees, 0.67 € m^{-3} for logging residues and 0.30 € m^{-3} for stumps.

3.8.3 Transportation model formulation

Also in this case the aim to supply plants in the least-cost manner can be reached formulating a transportation problem. The decision variables are the transported fuel from sources to plants. The objective function is minimizing the total supply costs of the system. Constraints are the fuel demands of each plant, which must be fulfilled with the available fuel at sources. Variables are continuous.

The software used for optimization is LINGO (Lindo System) interrelated with an Excel spreadsheet. Results are displayed in Excel and with arcGIS.

Assumptions:

Sources of fuel are logging residues, pre-commercial thinning and stumps. Location of chipping operations and types of transported material determine the alternatives in the supply chains.

For Jyväskylä plant, supply chains considered in this study are:

- chipping of logging residues at roadside storage and transportation of chips (supply chain SC 1)
- chipping of whole trees at roadside storage and transportation of chips (SC 5)
- transportation of stumps to terminal and transportation of chips from terminal to plant (SC 6)

For Varkaus plant indeed the available fuel supply chains are:

- chipping of logging residues at roadside storage and transportation of chips (supply chain SC 1)
- transportation of loose residues and chipping at plant (SC 2)
- bundling logging residues, transportation of bales and chipping at plant (SC 3)
- transportation of loose whole trees and chipping at plant (SC 4)
- chipping of whole trees at roadside storage and transportation of chips (SC 5)
- transportation of stumps to plant and chipping at plant (SC 7)

Terminal of Jyväskylä plant is located near the city, in a place where it is not possible to crush stumps. Therefore supply chain n.6 has been taken into account in a simplified way considering the terminal as final destination of the stumps and adding the double loading and unloading costs (loading at forest roadside, loading and unloading at terminal and unloading at plant).

Variables

x^{CL}_{ik}	chipped logging residues transported from stand *i* to the plant *k* (MWh): SC 1
x^{NL}_{ik}	un-chipped loose logging residues transported from stand *i* to the plant *k* (MWh): SC 2
x^{NB}_{ik}	un-chipped bundles from logging residues transported from stand *i* to the plant *k* (MWh): SC 3
x^{NW}_{ik}	un-chipped loose whole trees transported from stand *i* to the plant *k* (MWh): SC 4
x^{CW}_{ik}	chipped whole trees transported from stand *i* to the plant *k* (MWh): SC 5
x^{NS}_{ik*}	un-chipped stumps transported from stand *i* to the plant *k** (MWh): SC 6
x^{NS}_{ik}	un-chipped stumps transported from stand *i* to the plant *k* (MWh): SC 7

Sets

I	set of sources: forest in every municipality
K	set of heating plants
K*	sub-set of plants that need terminal in the neighborhood for chipping facility

Constraints

a^{L}_{i}	available logging residues at source *i* (MWh): LR
a^{W}_{i}	available whole trees from thinnings at source *i* (MWh): WT
a^{S}_{i}	available stumps at source *i* (MWh): ST
m_k	demand of heating plant *k* (MWh)
c^{NL}_{ik}	transportation cost of un-chipped residues from forest *i* to plant *k* (€ MWh^{-1} h^{-1})
c^{CL}_{ik}	transportation cost of a chipped residues from forest *i* to plant *k* (€ MWh^{-1} h^{-1})
c^{NB}_{ik}	transportation cost of bundles from forest *i* to plant *k* (€ MWh^{-1} h^{-1})
c^{NW}_{ik}	transportation cost of un-chipped whole trees from forest *i* to plant *k* (€ MWh^{-1} h^{-1})
c^{CW}_{ik}	transportation cost of chipped whole trees from forest *i* to plant *k* (€ MWh^{-1} h^{-1})
c^{NS}_{ik*}	transportation cost of stumps from forest *i* to plant *k** (€ MWh^{-1} h^{-1})
c^{NS}_{ik}	transportation cost of stumps from forest *i* to plant *k* (€ MWh^{-1} h^{-1})
c^{HL}_{i}	costs: organization, yarding, piling, loading/unloading and chipping at roadside forest *i* of logging residues (€ MWh^{-1}) (SC 1)

c^{HL}_{k}	costs: organization, yarding, piling, loading/unloading and chipping at plant *k* of logging residues (€ MWh^{-1}) (SC 2)
c^{HB}_{k}	costs: organization, piling, baling, yarding, loading/unloading and chipping at plant *k* of bales (€ MWh^{-1}) (SC 3)
c^{HW}_{k}	costs: organization, cutting, yarding, loading/unloading and chipping at plant *k* of whole trees (€ MWh^{-1}) (SC 4)
c^{HW}_{i}	costs: organization, cutting, yarding, loading/unloading and chipping at roadside forest *i* of whole trees (€ MWh^{-1}) (SC 5)
c^{HS}_{k*}	costs: organization, uprooting, yarding, loading/unloading and crushing at plant *k** of stumps (€ MWh^{-1}) (SC 6)
c^{HS}_{k}	costs: organization, uprooting, yarding, loading/unloading and chipping at plant *k* of stumps (€ MWh^{-1}) (SC 7)
c^{PL}_{i}	stumpage price of logging residues at stand *i* (€ MWh^{-1})
c^{PW}_{i}	stumpage price of whole trees at stand *i* (€ MWh^{-1})
c^{PS}_{i}	stumpage price of stumps at stand *i* (€ MWh^{-1})
s	driving distance from source *i* to plant *k* (km)
spl_{ik}	driving speed of loaded truck from source *i* to plant *k* (km h^{-1})
spe_{ki}	driving speed of empty truck from plant *k* to source *i* (km h^{-1})

These constraints ensure that the amount of biomass transported from stands to plant do not exceed the available volume at source *i*. Equations refer respectively to logging residues, whole trees and stumps.

$$\sum_{k\in K} x_{ik}^{CL} + \sum_{k\in K} x_{ik}^{NL} + \sum_{k\in K} x_{ik}^{NB} \le a_i^{L} \qquad \forall\ i \in I$$

$$\sum_{k\in K} x_{ik}^{CW} + \sum_{k\in K} x_{ik}^{NW} \le a_i^{W} \qquad \forall\ i \in I$$

$$\sum_{k\in K} x_{ik}^{NS} + \sum_{k\in K*} x_{ik*}^{NS} \le a_i^{S} \qquad \forall\ i \in I$$

This constraint assures that a sufficient wood fuel is transported to plants to meet their demands

$$\sum_{i\in I} x_{ik}^{CL} + \sum_{i\in I} x_{ik}^{NL} + \sum_{i\in I} x_{ik}^{NB} + \sum_{i\in I} x_{ik}^{CW} + \sum_{i\in I} x_{ik}^{NW} + \sum_{i\in I} x_{ik}^{NS} + \sum_{i\in I} x_{ik*}^{NS} = m_k \qquad \forall\ k \in K$$

In particular considering the possible fuel supply chain, equations become:

$$\sum_{i\in I} x_{ik}^{CL} + \sum_{i\in I} x_{ik}^{CW} + \sum_{i\in I} x_{ik*}^{NS} = m_J \qquad \forall\ k = \mathrm{J}$$

$$\sum_{i\in I} x_{ik}^{CL} + \sum_{i\in I} x_{ik}^{NL} + \sum_{i\in I} x_{ik}^{NB} + \sum_{i\in I} x_{ik}^{CW} + \sum_{i\in I} x_{ik}^{NW} + \sum_{i\in I} x_{ik}^{NS} = m_V \quad \forall\ k = \mathrm{V}$$

The following constraint guards against violation of the assumption of non-negativity

$$x_{ik} \ge 0 \qquad \forall\ i \in I,\ \forall\ k \in K$$

Objective function
The objective is to minimize the supply cost of the DH (C)

$$C = C^{tran} + C^{other} + C^{purc}$$

Where C^{tran} is the transportation cost from plant to source by truck with empty load space and loaded from source to plant, C^{chip} is the other costs (organization, yarding, piling, loading/unloading and chipping costs) and C^{purc} is the purchasing cost of raw material.
The following formula expresses the transportation cost

$$\begin{aligned}
C^{tran} &= \sum c_{ik}^{CL} x_{ik}^{CL} \left[\left(s \cdot spl_{ik} \right) + \left(s \cdot spe_{ki} \right) \right] + \sum c_{ik}^{NL} x_{ik}^{NL} \left[\left(s \cdot spl_{ik} \right) + \left(s \cdot spe_{ki} \right) \right] + \\
&\sum c_{ik}^{NB} x_{ik}^{NB} \left[\left(s \cdot spl_{ik} \right) + \left(s \cdot spe_{ki} \right) \right] + \sum c_{ik}^{CW} x_{ik}^{CW} \left[\left(s \cdot spl_{ik} \right) + \left(s \cdot spe_{ki} \right) \right] + \\
&\sum c_{ik}^{NW} x_{ik}^{NW} \left[\left(s \cdot spl_{ik} \right) + \left(s \cdot spe_{ki} \right) \right] + \sum c_{ik}^{NS} x_{ik}^{NS} \left[\left(s \cdot spl_{ik} \right) + \left(s \cdot spe_{ki} \right) \right] + \\
&\sum c_{ik*}^{NS} x_{ik*}^{NS} \left[\left(s \cdot spl_{ik} \right) + \left(s \cdot spe_{ki} \right) \right]
\end{aligned}$$

$$\forall\, i \in I,\ \forall\, k \in K$$

The equation expressed all other costs involved in the various supply chains

$$\begin{aligned}
C^{other} &= \sum c_{i}^{HL} x_{ik}^{CL} + \sum c_{k}^{HL} x_{ik}^{NL} + \sum c_{k}^{HB} x_{ik}^{NB} + \sum c_{i}^{HW} x_{ik}^{CW} + \sum c_{k}^{HW} x_{ik}^{NW} + \\
&\sum c_{k}^{HS} x_{ik}^{NS} + \sum c_{k*}^{HS} x_{ik*}^{NS}
\end{aligned}$$

$$\forall\, i \in I,\ \forall\, k \in K$$

Purchasing cost is here considered

$$C^{purch} = c_{i}^{PL} \left(\sum x_{ik}^{NL} + \sum x_{ik}^{CL} + \sum x_{ik}^{NB} \right) + c_{i}^{PW} \left(\sum x_{ik}^{NW} + \sum x_{ik}^{CW} \right) + c_{i}^{PS} \left(\sum x_{ik}^{NS} + \sum x_{ik*}^{NS} \right)$$

$$\forall\, i \in I,\ \forall\, k \in K$$

3.8.4 Paying ability effects on the supply chain

The effect of competition for resources and the energy wood supply cost for the plant are evaluated using the optimization model. The optimization is based on minimizing the total supply costs for both plants.
The paying ability (PA) for a good is the maximum monetary amount that an individual would pay to obtain a good.
In order to analyze the effect of Varkaus procurement on Jyväskylä supply area, the Varkaus PA was studied. The starting point for the optimization was an evaluation of PA for LR, ST and WT in an Excel spreadsheet.
The effect of the PA is tested on Varkaus plant, selecting in the spreadsheet all sources that can supply the plants for a unitary supply cost (€ MWh^{-1}) lower than the PA. Selected sources are therefore processed through LINGO in order to fulfill the plants' fuel demand considering the demand and availability constraints.
Changing the Varkaus PA of different wood fuels, the plant must supply with other supply chains, giving more space to Jyväskylä plant.

First, sensitivity analyses concerning the PA for Varkaus are tested, then simulations of two cases of sensitive analysis changing the PA for logging residues (LR) and then the PA for stumps (ST) and whole trees (WT) show how the Jyväskylä and Varkaus plants could be optimally supplied. Another sensitive analysis is carried out doubling the Jyväskylä fuel demand.

4. RESULTS

4.1 PLANTS AND BOILER DISTRIBUTION IN NORTH-EASTERN ITALY

The census of boilers funded between 2003 and 2006 shows that most boilers are in mountainous areas, with an additional 21 percent in hilly areas (between 300 and 600 m above the sea level) and 15 percent in flat areas. The total of installed boilers was 545, with five percent installed in public buildings. The average boiler power size in Trento province is 149 kW, in Veneto it is 89 kW, and in Friuli Venezia Giulia it is 126 kW. The majority of heating systems are fuelled with firewood, however boilers fuelled by wood chips present the highest installed power (Table 4.1).

Table 4.1. Number and power of boiler from census in North-eastern Italy

Power	Firewood		Pellet		Chip		Total	
	Number	Power	Number	Power	Number	Power	Number	Power
kW	n.	kW	n.	kW	n.	kW	n.	kW
≤ 100	395	13147	18	668	63	3472	466	17287
100-1000	3	689	4	1415	57	25428	64	27532
> 1000	-	-	-	-	5	27020	5	27020
Total	398	13836	22	2083	125	55920	545	71839

The fuel consumption calculation highlights that all boilers together require about 1.6 10^5 MWh year^{-1}, corresponding to about $7.1 \cdot 10^4$ t year^{-1} of fuel, with a moisture content of 50%. By using woodfuel as a replacement, about $1.4 \cdot 10^4$ t of fossil fuel can be saved annually.

Chip boilers have a total power of about 56 MW and require chips for about 1.3 10^5 MWh, corresponding to 4.2 10^4 t year^{-1} of fuel at a moisture content of 35%. Trento province makes up 80% of chip energy demand.

From the interviews (Table 4.2) to plant managers comes out that when buying chips the main aspects checked are:

- moisture content
- color (green or brown)
- chip size
- security and reliability of supply

The ten considered DH offer a heating service to few private houses or to public buildings or to a village. Public buildings, such as schools, municipality house, gymnasiums, etc. often require more heat than private houses.

Plant managers suggest for the future the installation of boilers providing energy for groups of houses. They all answered that they are pleased to buy more forest fuel if it has moisture content around 30%. Problems using forest fuel is mainly the high moisture content. Boilers managers give more value to sawmill byproducts because they are clean, homogeneous and with a good moisture content. Wood chips from harvesting residues are recommended mainly to plants with moving grate furnace.

Boilers with fixed bed furnace require fuel with lower moisture content than the boilers with the moving grate. The presence of leaves and bark influences the ash production and the boiler needs to have more maintenance. Particle size does not cause problem for the interviewed DH.

The fuel price varies with quality and in two situations out of ten varies also according to the bought quantity and buying season. DH managers do not have problems in finding fuel at provincial or regional level. Fuel price varies with quality, but in some situation there is not clear distinction between quality classes. DH managers feel the need to create a proper fuel classification related to prices.

All DH managers that are now supplying mostly with sawmill byproducts would be favorable to use forest chips if having low moisture content and not too much green particles. This would mean to have a place to store and dry forest fuel. In none of those situations exist an intermediate storage, between forest and plant. All plants provide heat at a lower price than gas or oil.

Table 4.2. DH data collected through personal interviews

	Boiler power	**Fuel demand**	**Furnace grate**	**Fuel source**	**Supply area**	**Storage problems**
	MW	**m^3_{loose}**		**%**		
Plant 1	9	40000	moving	10 % forest, 90% sawmill	85% from local area	Rotten fuel
Plant 2	6	25000	moving	100% sawmill	80% from local area	-
Plant 3	8	37000	moving	10 % forest, 90% sawmill	55% from local area	Mouldy fuel
Plant 4	2.8	7000	fixed	25 % forest, 75% sawmill	55% from local area	Rotten and mouldy fuel
Plant 5	0.5	1000	fixed	70 % forest, 30% sawmill	100% from local area	-
Plant 6	1	3000	moving	30 % forest and agriculture, 70% sawmill	100% from local area	-
Plant 7	0.3	500	moving	100% forest association (forest)	100% from local area	-
Plant 8	0.7	530	moving	100% forest association (forest)	100% from local area	Powder and rotten fuel
Plant 9	0.4	900	fixed	100% forest	100% from local area	-
Plant 10	0.5	800	fixed	100% forest	100% from local area	-

4.2 DRYME RESULTS

Debarking with processor head was efficient for beech, it took away 15-35% of the bark. For spruce the debarking was about 12% of the bark area. As shown in Figure 4.1 and 4.2, the debarking intensity does not play a significant role for moisture loss in beech. The test has shown that beech and spruce not covered loose bark naturally due to wear and tear effect of weather factors and most probably due to their sunny position.

In Figure 4.3 and 4.4 it is represented the moisture content changes of spruce and beech considering covering and processing options. The weight loss corresponds to water loss and therefore decreasing of moisture content. The moisture content of spruce was decreasing most vigorously when trunks were debarked and piles covered (Figure 4.5). Comparing different procedures with beech, there seems to be no significant difference in moisture content whether piles were covered or not or whether stems were debarked or not.

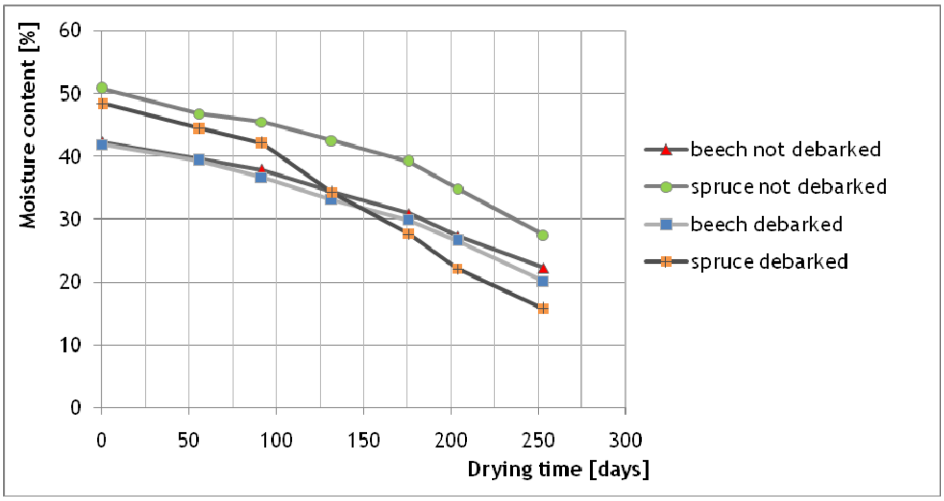


Figure 4.1. Change of moisture content of covered piles

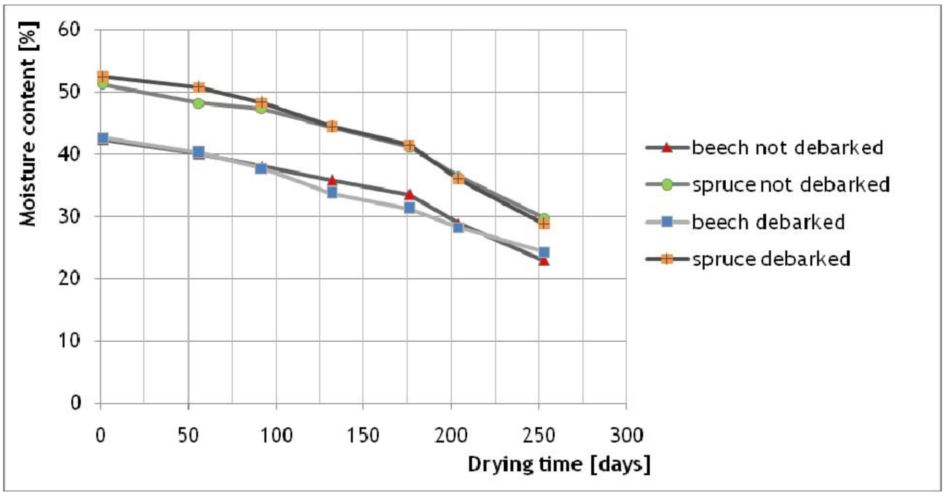


Figure 4.2. Change of moisture content of uncovered piles

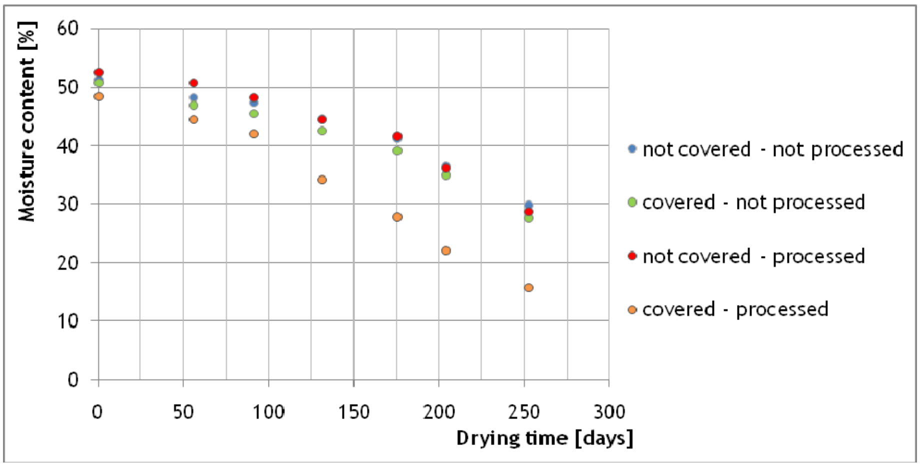


Figure 4.3. Moisture content of spruce piles according to the seasoning time, considering processing and covering options

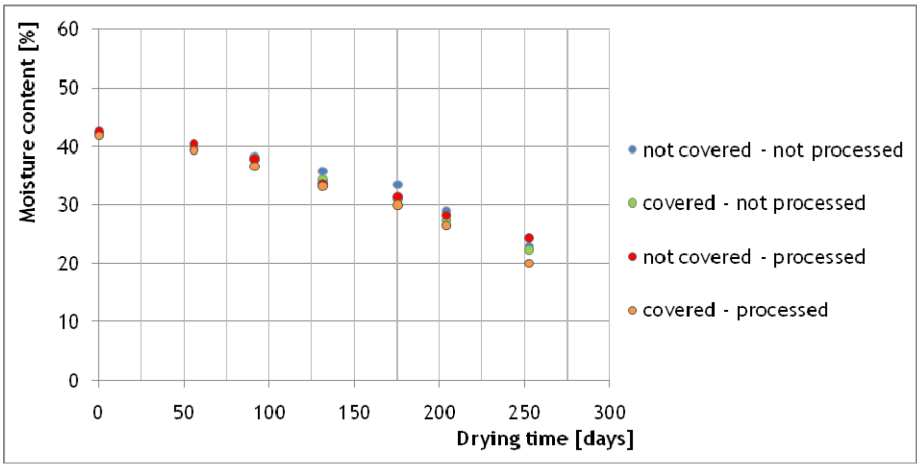


Figure 4.4. Moisture content of beech piles according to the seasoning time considering processing and covering options

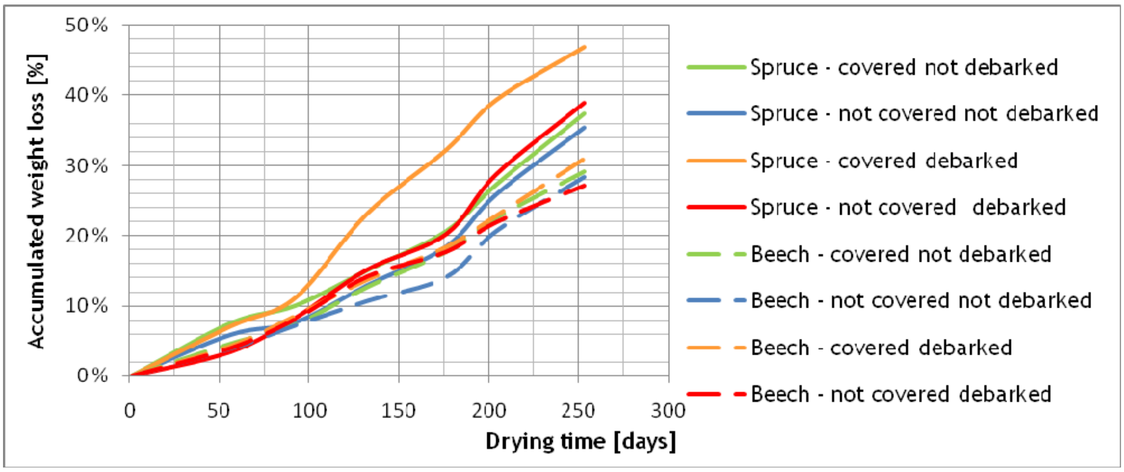


Figure 4.5. Accumulated weight loss of piles according to seasoning time

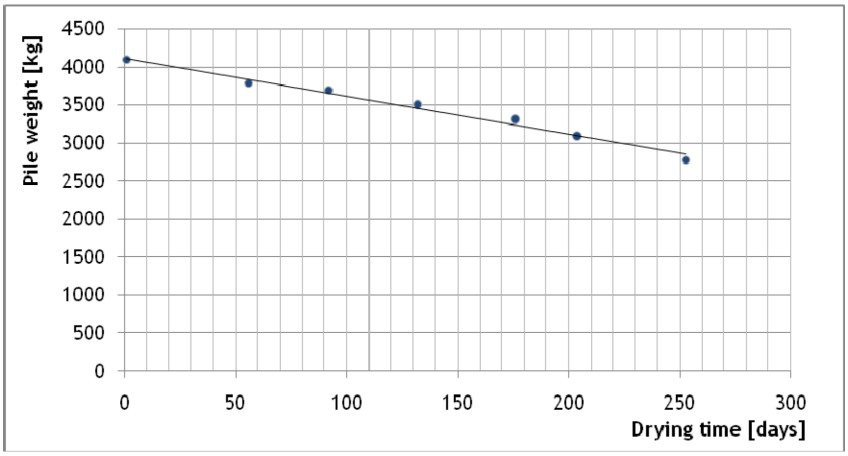


Figure 4.6. Weight loss of spruce pile, covered, not debarked

Results observed on spruce pile, covered and not debarked, have been taken into account in next paragraphs. A simplification of the drying behavior during seasoning with a linear function has been considered (Figure 4.6). The related function is $y = -5.0195x + 4\,114.6863$, with a $R^2 = 0.9853$. During eight months (four periods) there is a weight loss of 28.78%. During the same periods there is an increasing of 8.81% energy content.

Therefore in one period of 60 days there is an average increasing of energy content of 2.20%.

Observing the graphs of temperature and precipitations (Figure 3.5 and 3.6), temperatures of the trial site during the time of the test were similar to the average of past years. Precipitation in January and spring season were slightly more abundant than in past years. Therefore the test has been conducted during a time period that can be considered into the average, not exceptional.

Lowering the fuel moisture content the fuel quality improves. This means that fuel needs to be dried in a site possibly located in a dry, sunny and windy place. The floor must be compacted so that soil is not mixed with fuel when moved.

4.3 TEN YEARS OPTIMIZATION – SCENARIO I

Optimizing the supply of Fiemme Valley plants, fuel is delivered through supply chains 1 and 4 from forest (chipping at stand and transportation of chips) and supply chain 5 from sawmills. In maps (Figure 4.7 and 4.8) the sources (forest stands) and destination of forest fuel are represented.

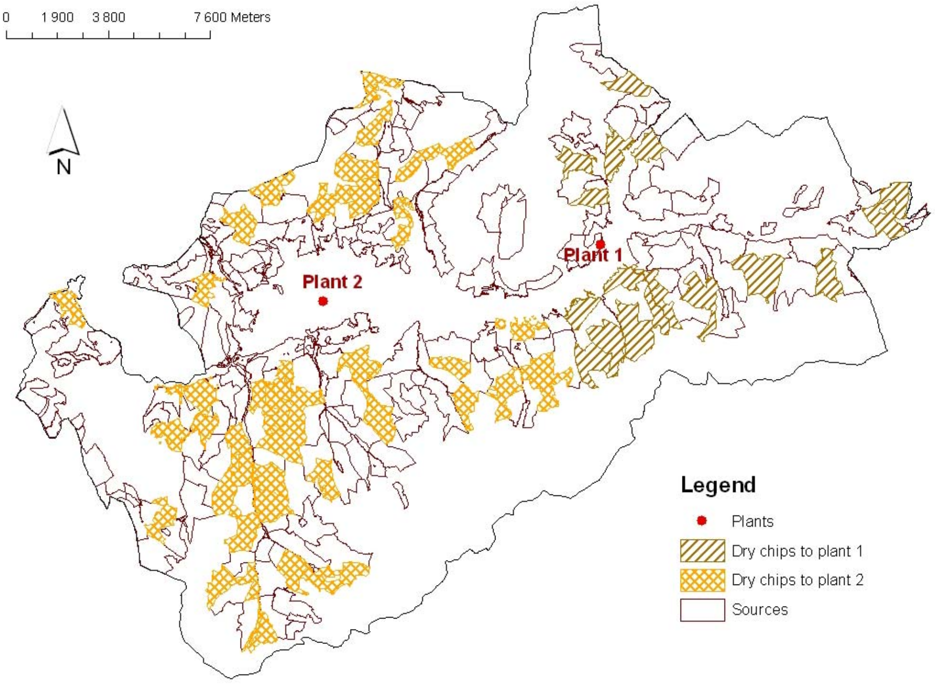


Figure 4.7. Map of the stands that should supply the two plants (results for year 6)

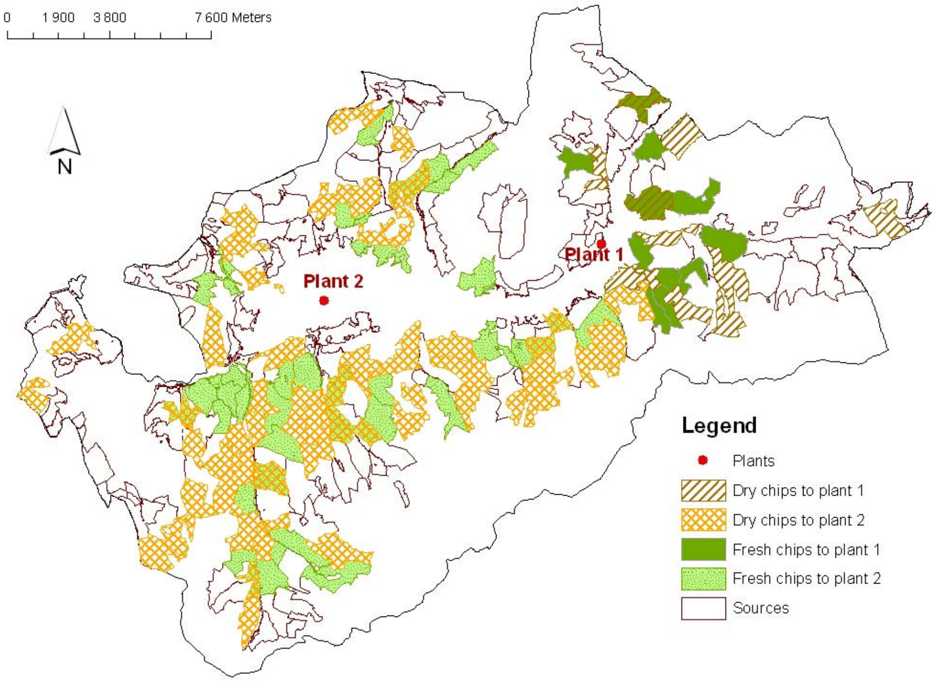


Figure 4.8. Map of the stands that should supply the plants (results for year 10)

In Table 4.3 and 4.4 the fuel transported by each supply chains is reported. Figure 4.9 represents the total and transportation costs of the scenario during the ten years. Taking away the first and the last year, the total costs during the ten years are approximately constant.
Supply chains that consider fuel chipping at plant are not selected by the optimization, because the supply cost of SC1, SC4 and SC5 are more economical than SC2 and SC3.

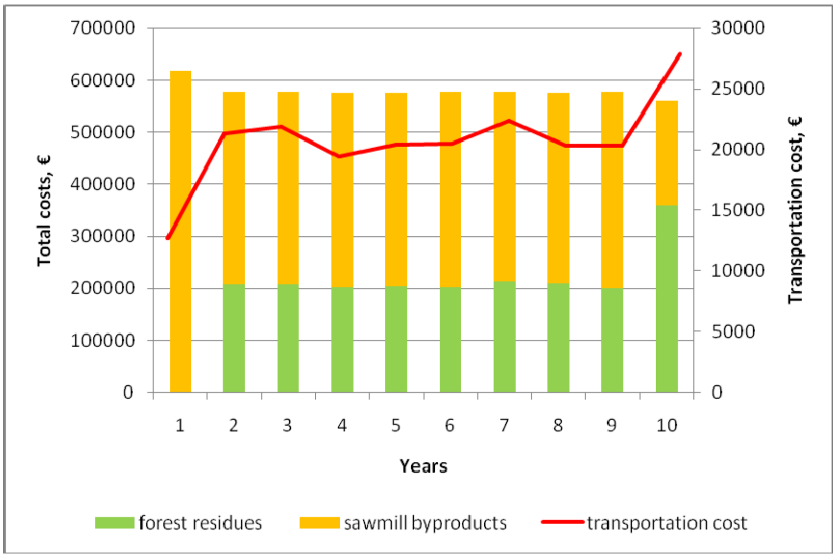


Figure 4.9. Total and transportation costs during the ten years

Table 4.3. Results considering original information. Fuel (MWh) transported to plant 1 (K1) with the different supply chains

	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10
SC1	0	0	0	0	0	0	0	0	0	1 920
SC2	0	0	0	0	0	0	0	0	0	0
SC3	0	0	0	0	0	0	0	0	0	0
SC4	0	4 941	4 941	4 919	4 941	4 941	4 941	4 930	4 933	3 021
SC5	4941	0	0	22	0	0	0	11	8	0
Total	4 941	4 941	4 941	4 941	4 941	4 941	4 941	4 941	4 941	4 941

Table 4.4. Results considering original information. Fuel (MWh) transported to plant 2 (K2) with the different supply chains

	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10
SC1	0	0	0	0	0	0	0	0	0	7 457
SC2	0	0	0	0	0	0	0	0	0	0
SC3	0	0	0	0	0	0	0	0	0	0
SC4	0	9 431	9 424	9 191	9 277	9 115	9 774	9 678	8 949	1 1807
SC5	31 059	21 628	21 635	21 867	21 782	21 944	21 285	21 381	22 109	11 795
Total	31 059	31 059	31 059	31 059	31 059	31 059	31 059	31 059	31 059	31 059

An additional optimization has been carried out considering to fulfill the procurement with maximum 70% of sawmill residues. This change has impact on the supply chains of the first three years, where SC1 is preferred (Tables 4.5 and 4.6).

Table 4.5. Results considering sawmill fuel procurement constraint of 70%. Fuel (MWh) transported to plant 1 (K1) with the different supply chains

	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10
SC1	1 482	1 482	658	0	0	0	0	0	0	1 920
SC2	0	0	0	0	0	0	0	0	0	0
SC3	0	0	0	0	0	0	0	0	0	0
SC4	0	0	825	2 330	4 941	4 941	4 941	4 930	4 933	3 021
SC5	3 459	3 459	3 459	2 612	0	0	0	11	8	0
Total	4 941	4 941	4 941	4 941	4 941	4 941	4 941	4 941	4 941	4 941

Table 4.6. Results considering sawmill fuel procurement constraint of 70%. Fuel (MWh) transported to plant 2 (K2) with the different supply chains

	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10
SC1	9 318	5 303	2 192	0	0	0	0	0	0	7 457
SC2	0	0	0	0	0	0	0	0	0	0
SC3	0	0	0	0	0	0	0	0	0	0
SC4	0	4 014	7 126	9 318	9 318	9 318	9 774	9 678	9 318	11 807
SC5	21 741	21 741	21 741	21 741	21 741	21 741	21 285	21 381	21 741	11 795
Total	31 059	31 059	31 059	31 059	31 059	31 059	31 059	31 059	31 059	31 059

4.4 MULTIPERIOD OPTIMIZATION AND TERMINAL LOCATION - SCENARIO II

Terminals considered in the study are located in the position represented in the map (Figure 4.10). Plants supply costs has not big difference comparing the three locations. In the first site the average supply cost is 17,3 € MWh^{-1}, in the second location is 17,4 € MWh^{-1} and in the third location is 17,5 € MWh^{-1}.

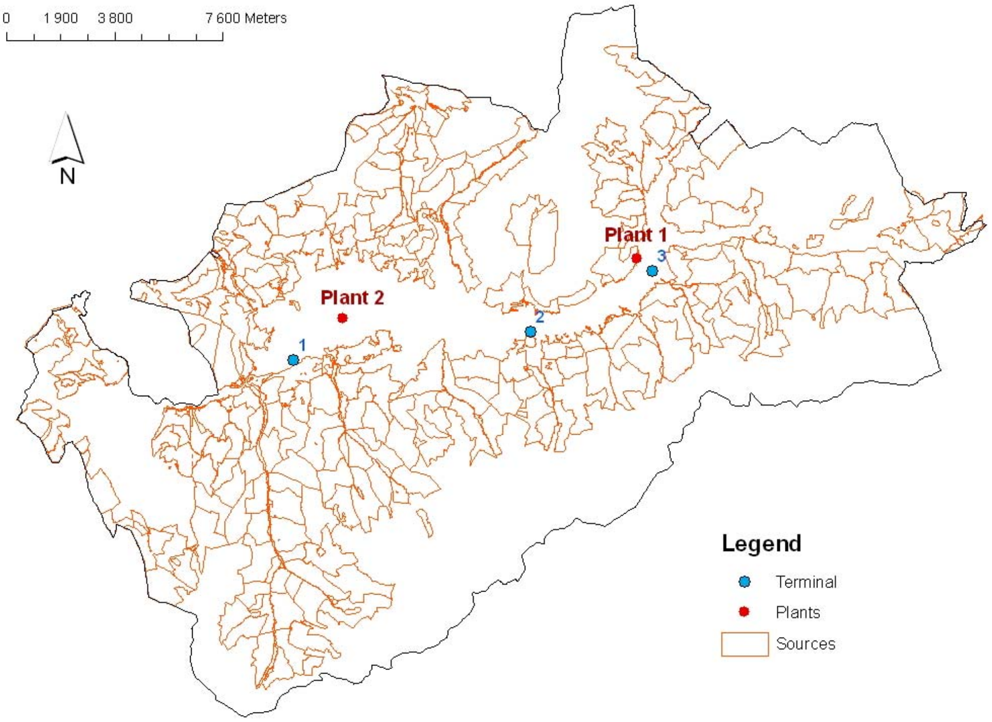


Figure 4.10. Location of terminals considered in the study

The linear programming objective was to minimize the total supply costs of the two plants. Total costs include chipping, loading and unloading, purchase, transport and terminal costs. Optimization results show that the terminal is used for only few cubic meters of forest residues (X^N and X^{SC} in Tables 4.7, 4.8, 4.9). Between terminal in position 1 (J1) and in position 2 (J2) there are differences only between periods and not on the cumulated flows during the year. Analyzing results comes out that the most costly terminal position is the third and the most economically convenient is the first one. Anyway, so as the formulation has been done, there are not significant differences in total costs comparing the three terminal positions.

Table 4.7. Wood fuel (m^3) transported with supply chains with terminal in position 1 (J1). K1 and K2 are respectively Plant 1 and Plant 2. X^C represents the chipped forest residues transported from stand to plant, X^N indicated flows from stand to terminal, X^{SC} is the material transported from terminal to plant and X^B is sawmill byproducts flow from industries to plant

Periods	X^C		X^N	X^{SC}		X^B	
	K1	K2	J1	K1	K2	K1	K2
1	229	362	286	0	0	109	1 701
2	238	1011	4	0	0	128	1 259
3	457	428	0	0	302	83	2 545
4	341	283	0	0	0	220	3 138
5	458	741	0	0	0	137	2 876
6	320	398	0	0	0	105	2 178
Total	2 042	3 224	290	0	302	782	13 697

Table 4.8. Wood fuel (m^3) transported with supply chains with terminal in position 2 (J2)

Periods	X^C		X^N	X^{SC}		X^B	
	K1	K2	J2	K1	K2	K1	K2
1	229	358	290	0	0	109	1 705
2	238	1015	0	0	0	128	1 256
3	457	428	0	0	302	83	2 545
4	341	283	0	0	0	220	3 138
5	458	741	0	0	0	137	2 876
6	320	398	0	0	0	105	2 178
Total	2 042	3 224	290	0	302	782	13 697

Table 4.9. Wood fuel (m^3) transported with supply chains with terminal in position 3 (J3)

Periods	X^C		X^N	X^{SC}		X^B	
	K1	K2	J3	K1	K2	K1	K2
1	0	648	290	0	0	325	1 432
2	238	1015	0	0	0	128	1 256
3	155	730	0	302	0	83	2 545
4	341	283	0	0	0	220	3 138
5	458	741	0	0	0	137	2 876
6	320	398	0	0	0	105	2 178
Total	1 511	3 816	290	302	0	998	13 424

4.5 ANNUAL OPTIMIZATION - SCENARIO III

In Figure 4.11 it is shown the average transportation cost that corresponds to a cumulated volume of forest fuel. The average transportation cost is higher when the available volume is increased because the distance from plant increases.

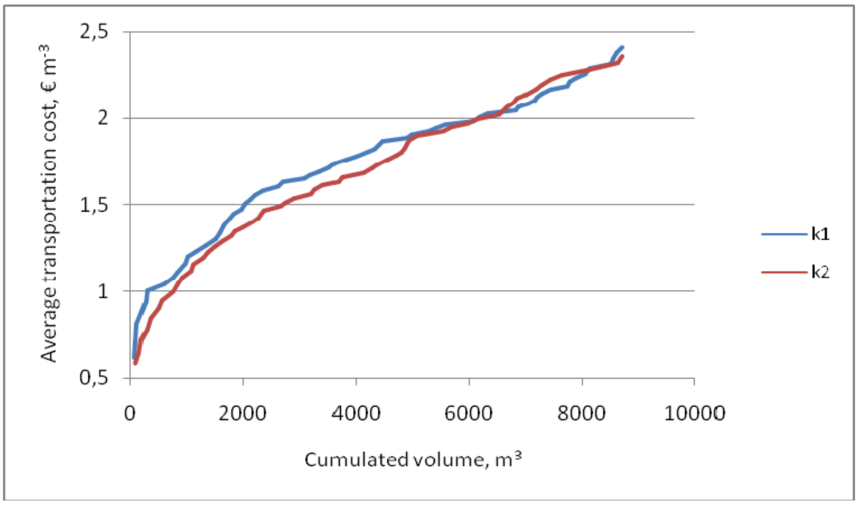


Figure 4.11. Average transportation cost from forest stands to plants

Changing the of oil price from 1 to 2 € l^{-1} (Figure 4.12), there are changes in prices of hourly cost of machines involved in the supply chains. Increasing the oil price, sawmill byproducts are preferred compared to forest chips. For Plant K1 there is a big change when oil costs 1,4 € l^{-1}.

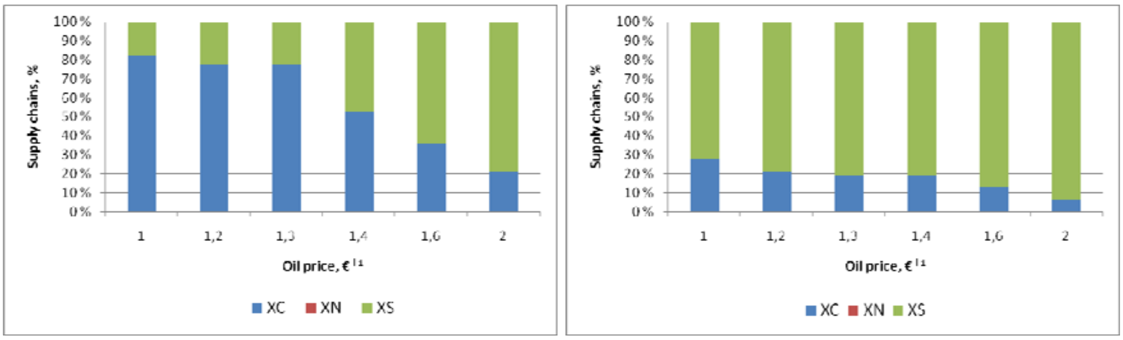


Figure 4.12. Variation of supply chains share changing the oil price at plant K1 (left) and plant K2 (right)

Sensitivity analysis changing the truck payload allows to see changes in chosen supply chains and in supply cost. Increasing the payload of truck used for forest residues, the supply chain X^N is preferred and there is a rapid decreasing of unitary supply cost. Increasing the loading capacity of forest residues (Figure 4.13) with a solid volume content of 32,5% from the original value of 11,7 m^3_{solid} (corresponding to 36 m^3_{loose}) to 17,4 m^3_{solid} (corresponding to 52 m^3_{loose}), a difference of 0,28 € MWh^{-1} can be shown and the X^N supply chain takes advantage on the X^C.

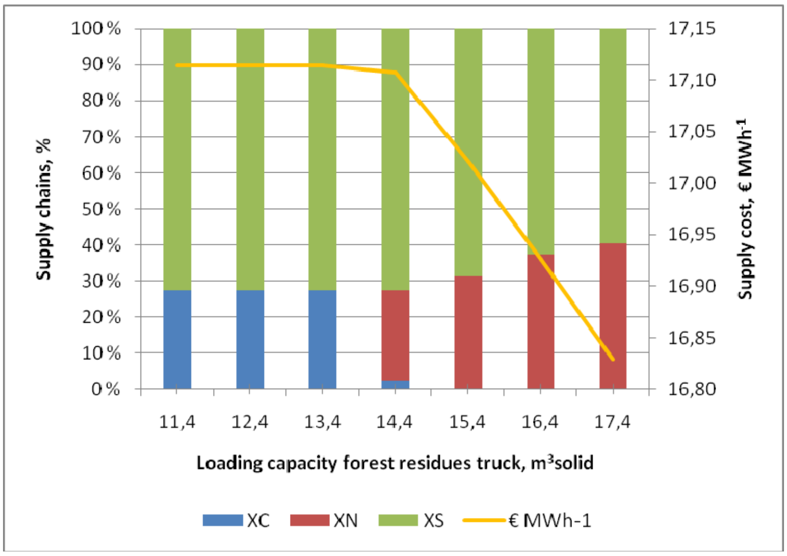


Figure 4.13. Variation of supply costs and supply chains changing the payload for forest residues truck

Also increasing the payload of truck for chips the supply cost decreases (Figure 4.14). Increasing the loading capacity, the preference for forest chips increases if compared to sawmill byproducts. When payload is higher than 17 m^3_{solid}, all available forest residues are exploited; therefore there is not increased share for X^N.

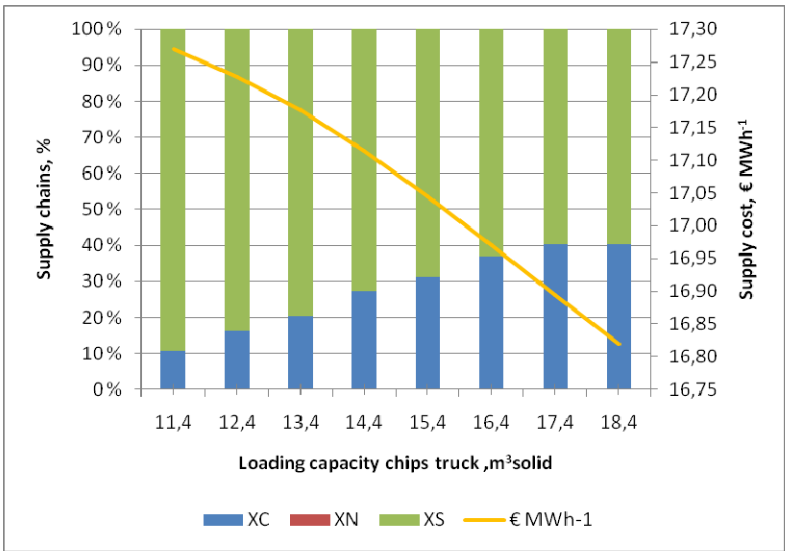


Figure 4.14. Variation of supply costs and supply chains changing the payload for chips truck

Comparing the two curve of unitary supply cost, changing the loading capacity, it is possible to see that the most influencing parameter is the loading capacity of truck used for forest residues (Figure 4.15).

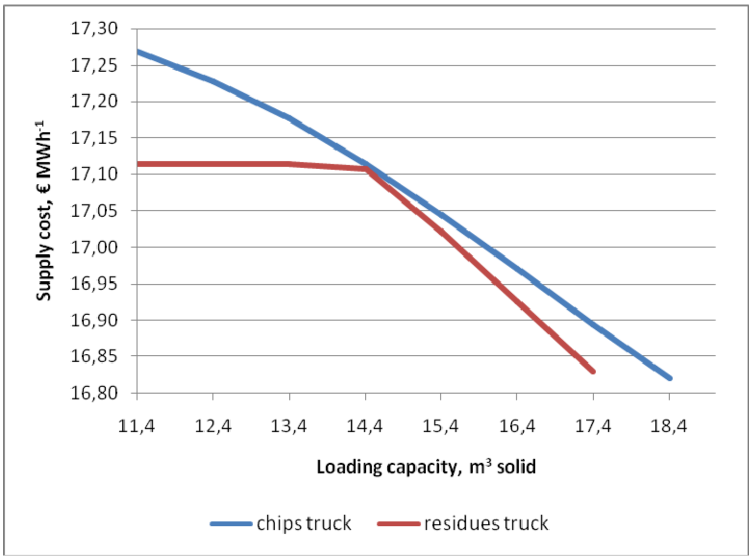


Figure 4.15. Variation of supply costs varying the loading capacity of forest residues and chip trucks

In Figure 4.16 share of supply chains and unitary supply cost of the scenario III changing moisture content of forest residues and forest chips are showed. Decreasing the moisture content, more forest fuel (X^C and X^N) is preferred and the unitary supply cost decreases.

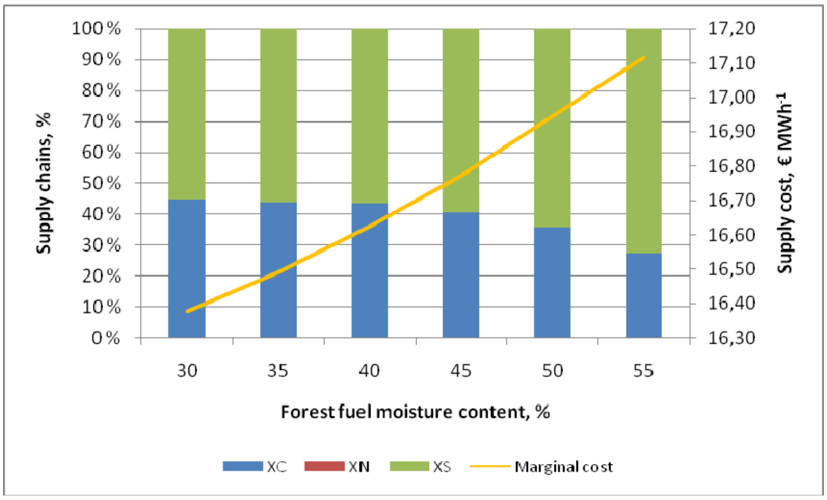


Figure 4.16. Share of supply chains and unitary supply costs changing the forest moisture content

A sensitivity analysis is carried out considering a plants' fuel demand factor ranging from a value of 0.7 to a value of 1.45 (Figure 4.17). The marginal cost increases rapidly when fuel demand is higher than 46800 MWh, so when demand is multiplied by a factor of 1.3. Amount of forest fuel transported to plant is constant when demand factor is greater than 1 and lower than 1.3. When plants demand is higher than a factor of 1.3, the amount of forest fuel increases. This is due to the fact that sawmill byproducts are used and the demand is fulfilled with forest fuel coming from long distance.

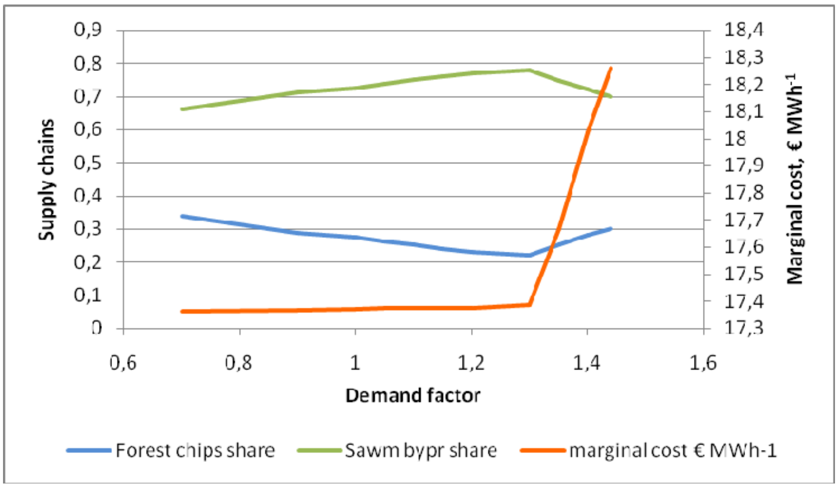


Figure 4.17. Variation of supply chains shares and marginal costs changing the demand

4.6 OPTIMIZATION OF LARGE SCALE PLANTS SUPPLY

Available fuel material, calculated according to Formula 3.16 related to the distance from Varkaus and Jyväskylä plants, is respectively reported in Figure 4.18 and 4.19.

The supply chain for logging residues transported with truck to plant and chipped there, offers the lowest total costs at a short transportation distance (Figure 4.20 and 4.21). For longer distances, the packing density becomes more important: additional work for baling residues is compensated by improving efficiency in yarding and transportation. The supply chain that considers the bundled residues is cheaper than chipping at roadside and transporting chips to plant. For whole trees raw material, the option that considers chipping at roadside is cheaper than chipping at plant only for short distances. Uprooting and transporting stumps to terminal, crushing them at terminal and transport chips to plant is certainly the most expensive option. Concerning logging residues, bundling supply chain increases the roadside costs of 2.3 € MWh^{-1}, but it has the lowest terminal costs.

Jyväskylä fuel demand is fulfilled from the supply chains number 1, 5 and 6; the first supply chain is the cheapest. Supply chains number 1, 2, 3, 4, 5, and 7 supply Varkaus (Figure 4.20). For Varkaus the most cost-competitive alternative for a distance up to 60 km is the supply chain 2, for longer distance the supply chain 3. Whole trees supplied with supply chain 5 are cheaper than stumps for distances longer than 109 km.

In Figure 4.21 the seven supply chains have been compared in their singular phases costs considering distances of 40 and 110 km.

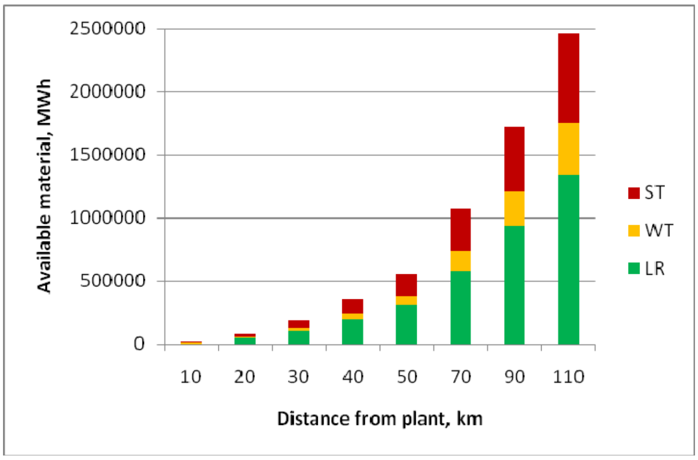


Figure 4.18. Available fuel types linked with the distance of sources from Varkaus plant

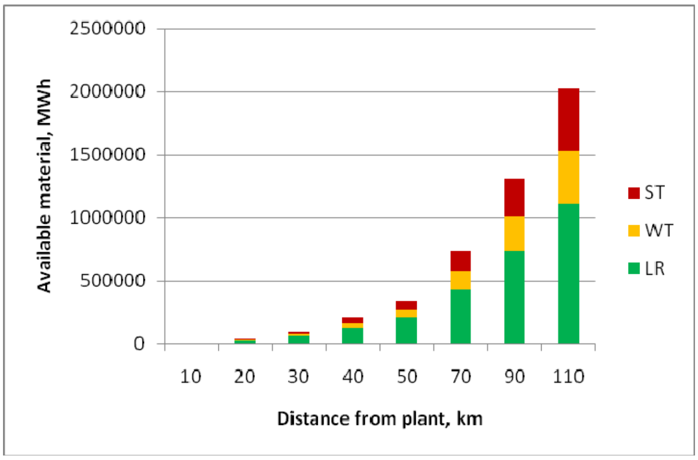


Figure 4.19. Available fuel types linked with the distance of sources from Jyväskylä plant

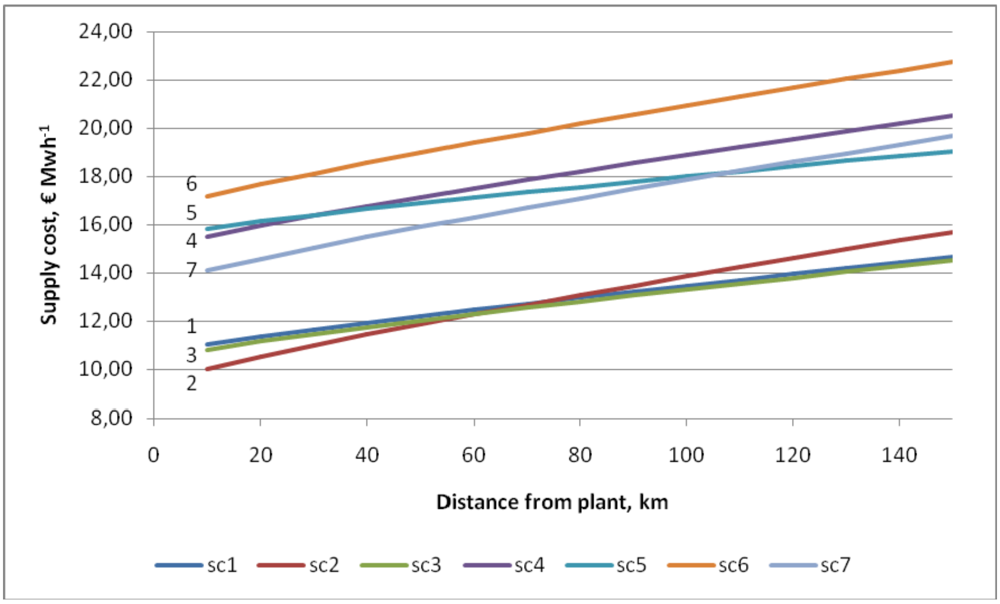


Figure 4.20. Supply chain costs according to distance from plants

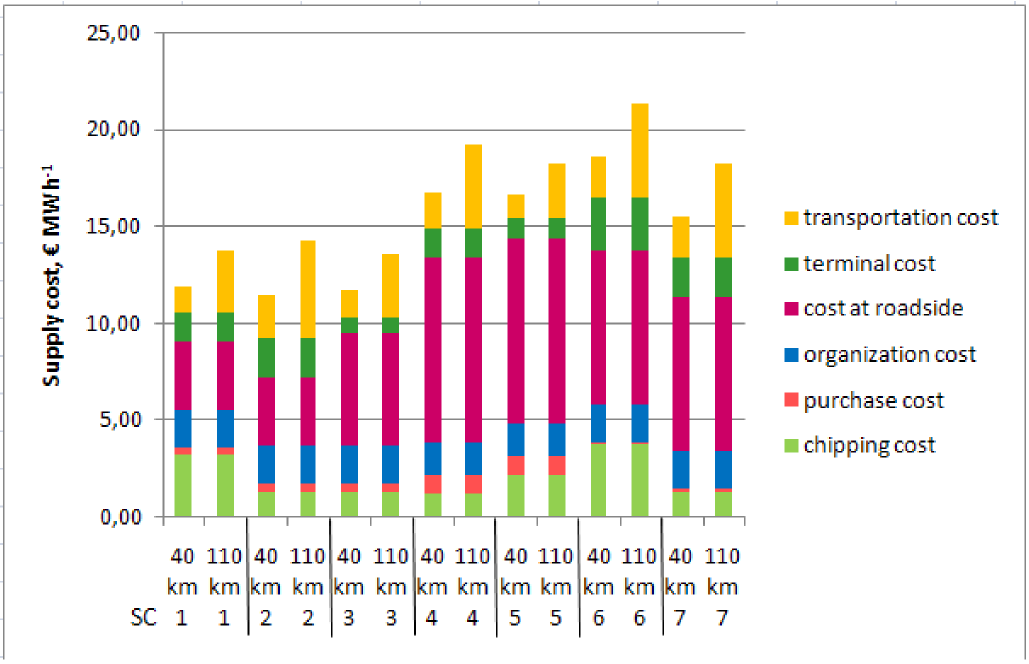


Figure 4.21. Supply cost components considering a distance of 40 and 110 km for the seven supply chains. Terminal cost includes loading, unloading phases. Cost at roadside includes phases according to the considered supply chain: cutting, uprooting, baling, piling and yarding.

Optimizing singularly the two plants' fuel supply, there is an overlapping area as shown in Figure 4.22. This means that there is competition for 196430 MWh. The competition for resources can be solved looking for fuel out of the optimal supply region of every plant. The objective of this case study is to minimize the whole system supply costs, therefore fuel will be globally supplied where it is cheaper (Figure 4.23). Optimizing the whole system, the cheapest material are the logging residues supplied with the supply chain 1 for Jyväskylä and with supply chain 2 and supply chain 3 for Varkaus. Varkaus supplies stumps for almost the 1% of the demand with supply chain 7. Supply chain 2 and 3 have a share respectively of 23% and 76%. Whole trees supply chains are not involved because too expensive.

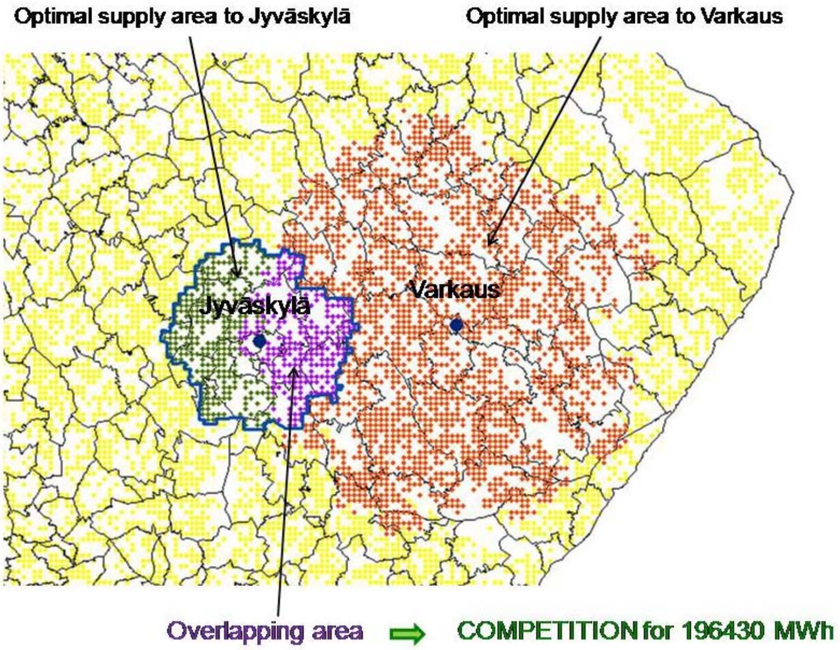


Figure 4.22. Optimal supply area for Varkaus and Jyväskylä singularly

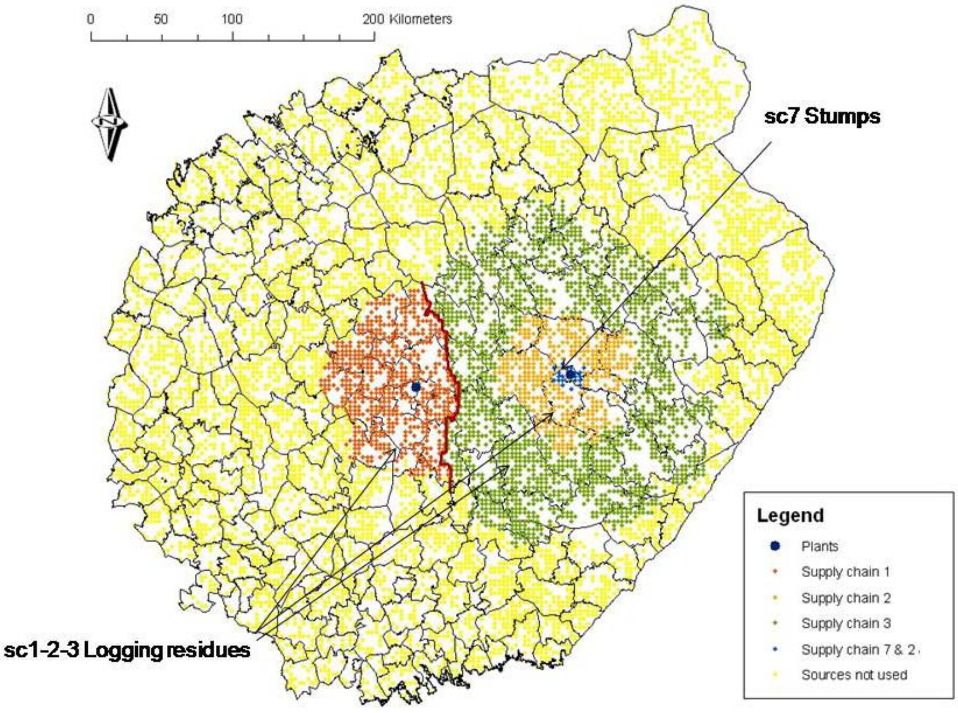


Figure 4.23. Optimal supply of the whole system

4.7 EFFECTS OF PAYING ABILITY

Sensitive analyses of the Varkaus paying ability (PA) for logging residues (LR), whole tree (WT) and stumps (ST) are carried out considering several options. Here are considered the original demand for fuel (2 000 000 MWh for Varkaus and 370 800 MWh for Jyväskylä plant).

The first test optimizes the plants supply considering a PA for LR supply costs decreasing from 17 to 11 € MWh^{-1}. Lowering the LR PA, more WT and ST are transported from the nearby forest stands. When the PA for LR is between 13 and 13,5 € MWh^{-1}, all sources are closer than 100 km to the destinations (Figure 4.24 and 4.25).

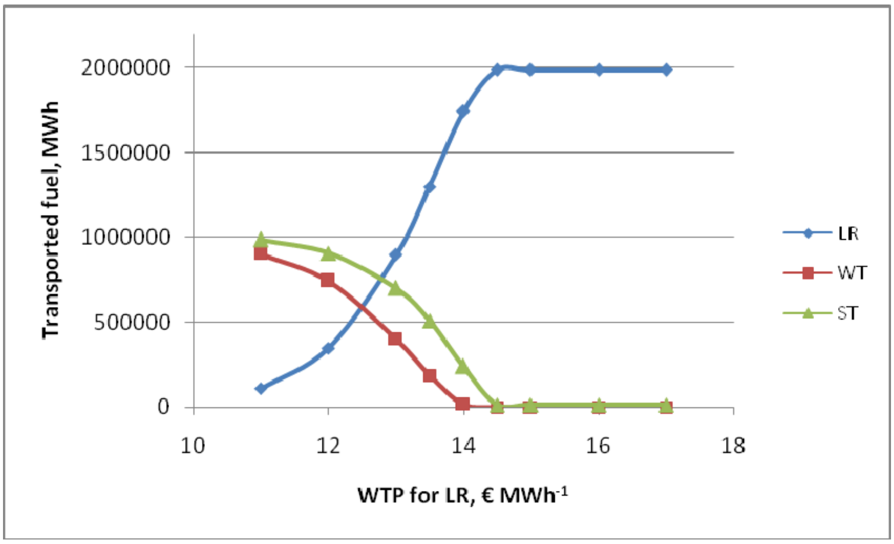


Figure 4.24. Transported fuel to Varkaus plant changing the PA for LR

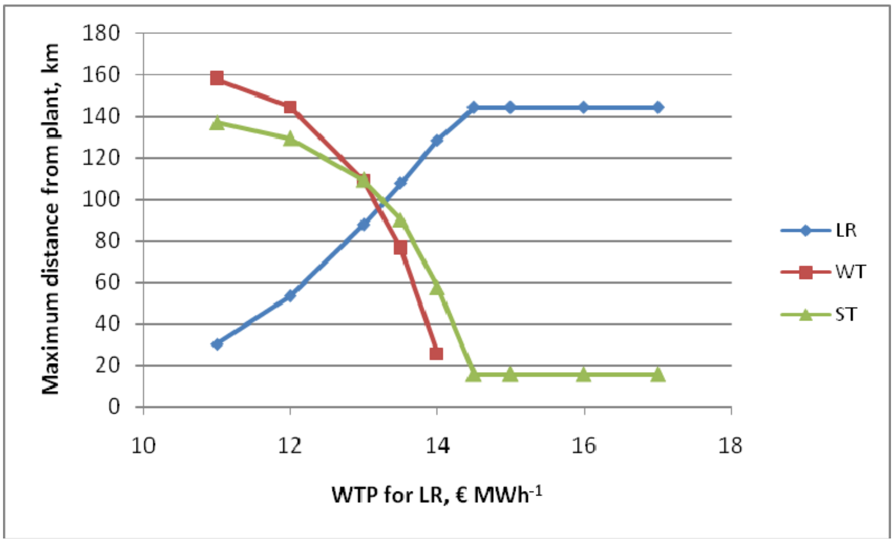


Figure 4.25. Maximum distance from Varkaus plant to fulfill the demand, considering the PA for LR

The second test considers more PA constraints. It keeps the PA for WT equal to 20 € MWh^{-1} and for ST equal to 17 € MWh^{-1}.

- Test A: LR 15 € MWh^{-1}, WT 20 € MWh^{-1}, ST 17 € MWh^{-1}
- Test B: LR 14 € MWh^{-1}, WT 20 € MWh^{-1}, ST 17 € MWh^{-1}
- Test C: LR 13.5 € MWh^{-1}, WT 20 € MWh^{-1}, ST 17 € MWh^{-1}
- Test D: LR 13 € MWh^{-1}, WT 20 € MWh^{-1}, ST 17 € MWh^{-1}

Figure 4.28 shows that, diminishing the PA for LR for Varkaus plant, stumps and whole trees are preferred. Interest for WT increases when the PA for LR goes down up to 13 € MWh^{-1} (Figure 4.26). This is due to the constraint of the PA for ST. To check the effect of the PA for stumps procurement, two more tests are considered:

- Test E: LR 13 € MWh^{-1}, WT 20 € MWh^{-1}, ST 16 € MWh^{-1}
- Test F: LR 13 € MWh^{-1}, WT 20 € MWh^{-1}, ST 15 € MWh^{-1}

Supply chain 5 is preferred to supply chain 4 because the first has lower supply costs up to a distance of about 30 km (Figure 4.20 and 4.27).

Observing Figures 4.31 and 4.32 and the test A-F results (Figure 4.27) it is clear that the two plants are in competition only for LR: Jyväskylä is supplied only with the supply chain 1. This is due to the high difference in supply prices between supply chain 1 and supply chain 5 and 6 and to the limited fuel demand.

The supply chain 1 in test A-F is never used to fulfill Varkaus demand because it is slightly more expensive than supply chain 3, which is preferred.

Figure 4.26. Share of transported fuel to Varkaus plant in the test A-D

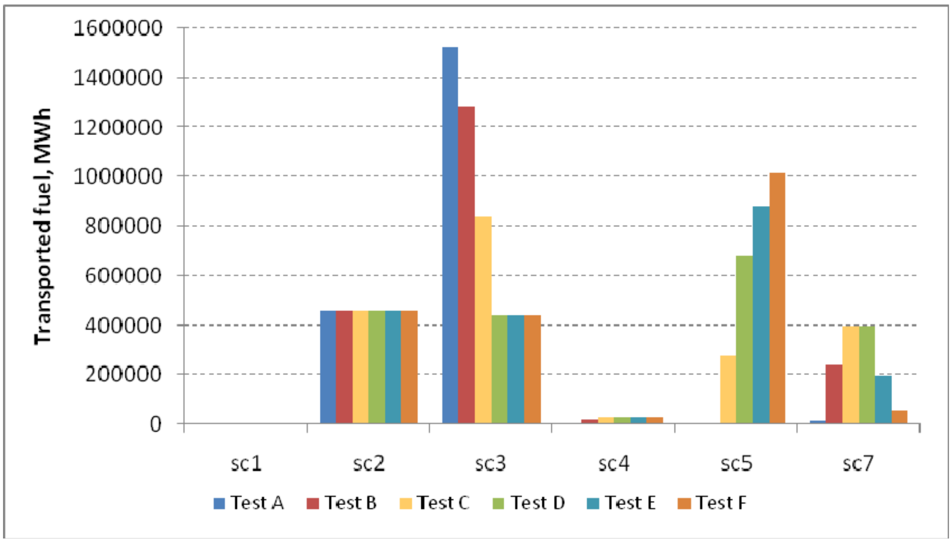


Figure 4.27. Transported fuel to Varkaus plant in tests A-F

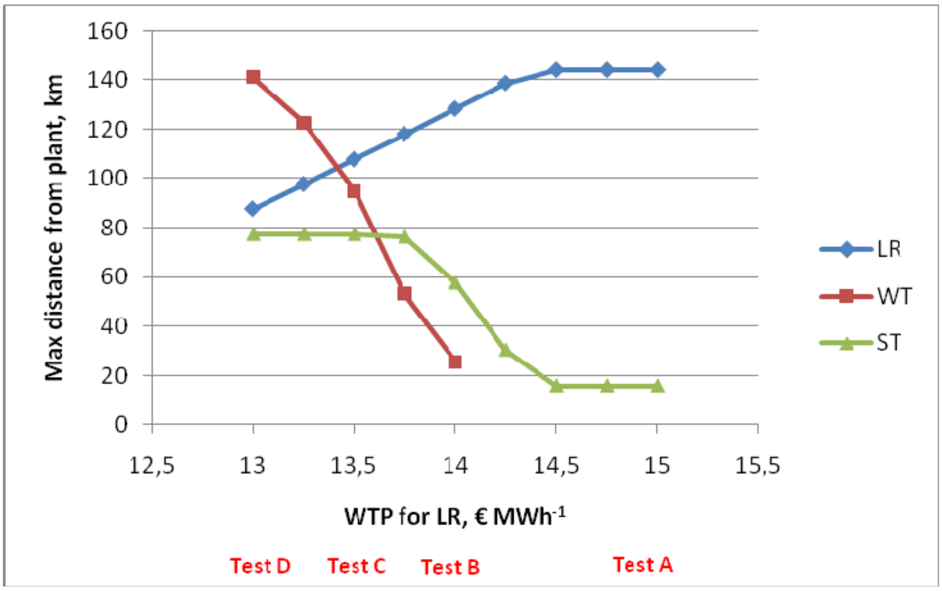


Figure 4.28. Maximum distance from Varkaus plant to fulfill the demand, considering the PA for fuels

In Figure 4.29 are reported the amount of LR, WT and ST transported to Varkaus plant with the tests A-D.

In Figure 4.30 the optimization of the two plants is mapped considering original information. Observing maps is possible to see the graphical difference in optimal supply between original data and sensitive analyses (Figure 4.31 and 4.32). When the PA for LR is diminished for Varkaus (test A-F), there is an advantage for Jyväskylä because there is less competition for LR, the preferred raw material, and there is only little economical advantage (0,8 %).

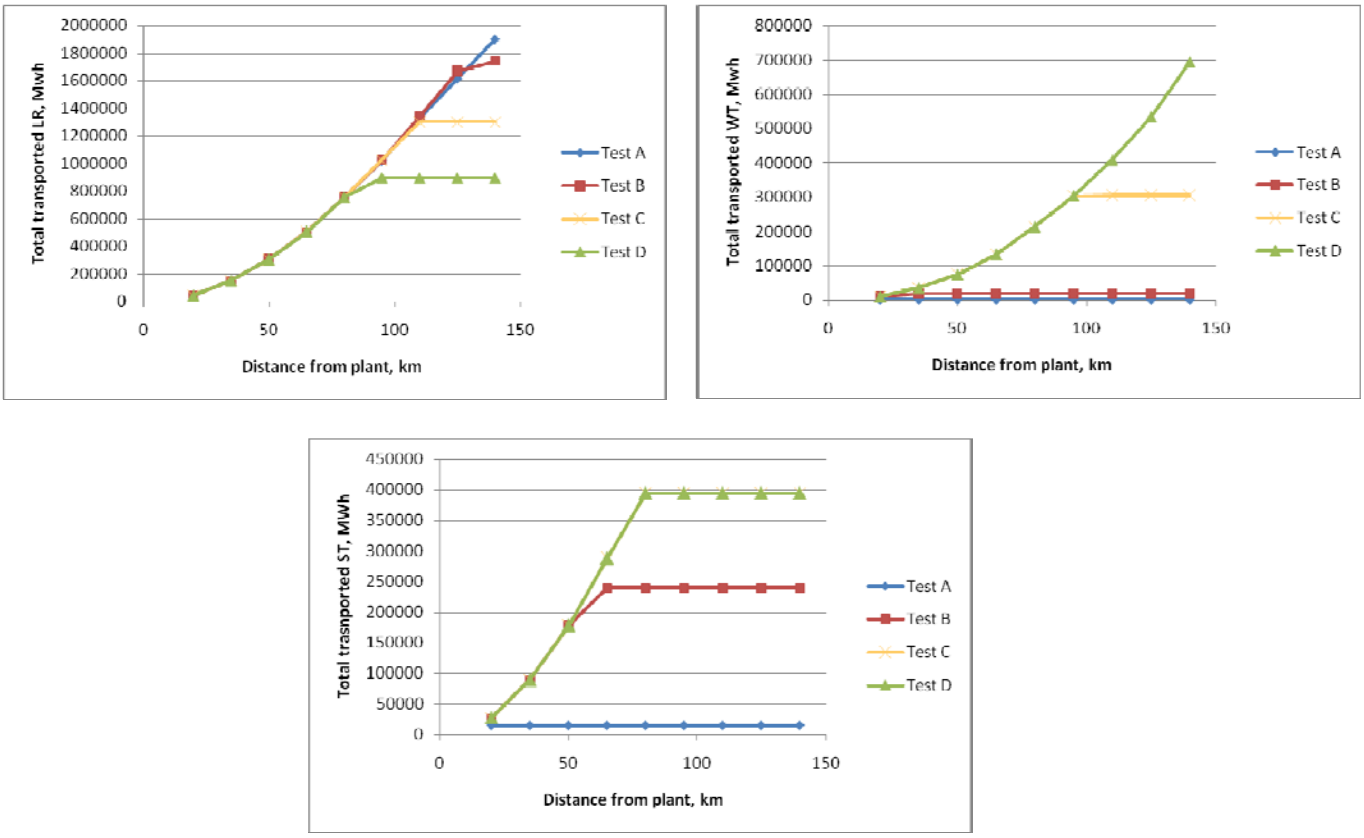


Figure 4.29. Transported LR, WT and ST to Varkaus plant in tests A-D

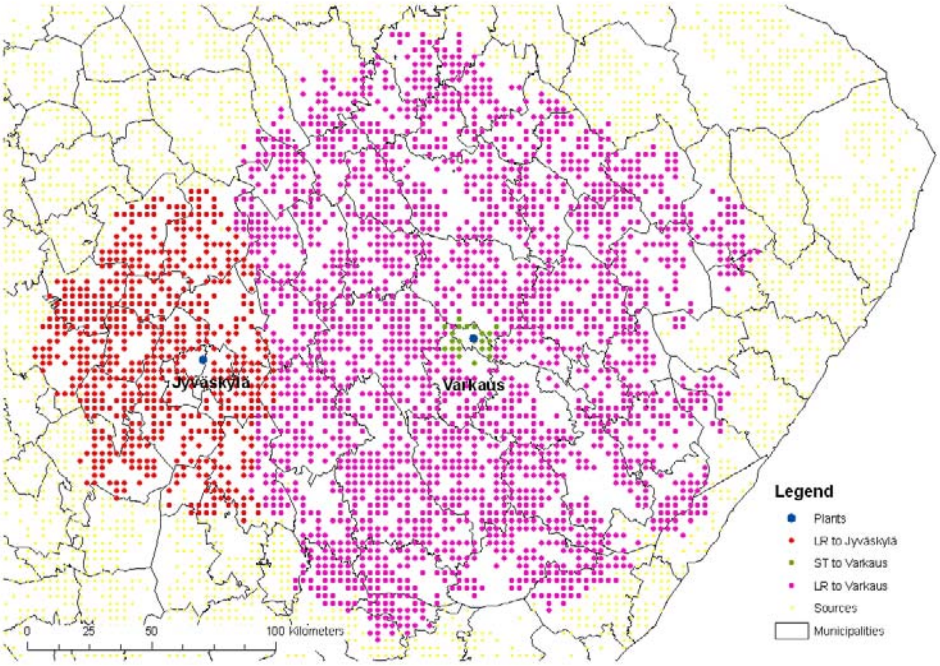


Figure 4.30. Map of the fuel supply optimizing considering original information data

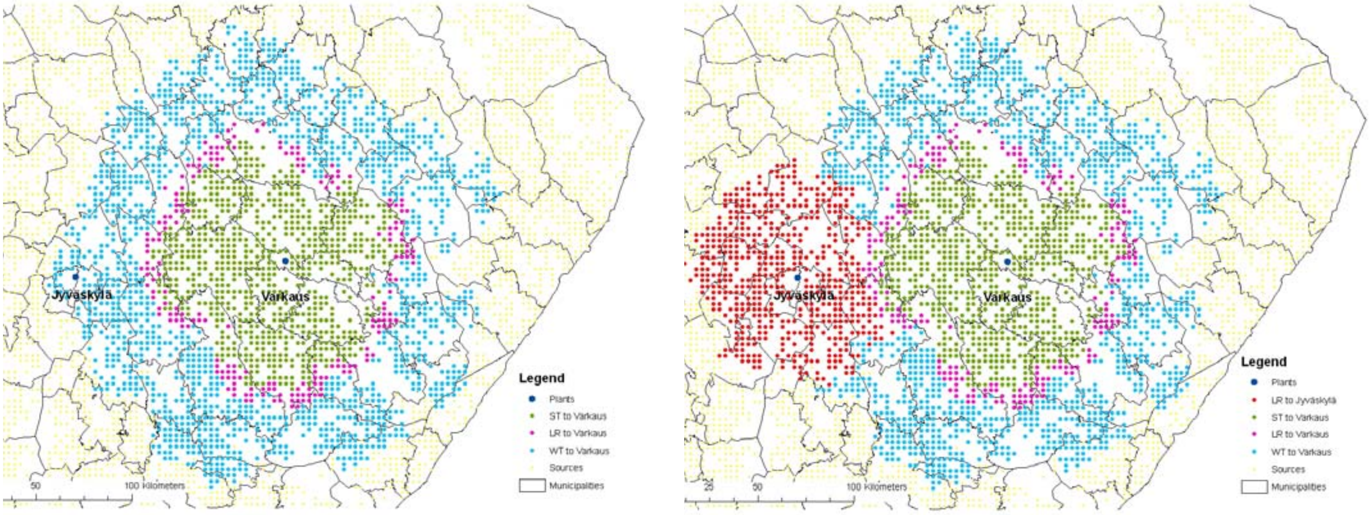


Figure 4.31. Representation of the transported fuel to Varkaus (left) and to both plants (right) in test D

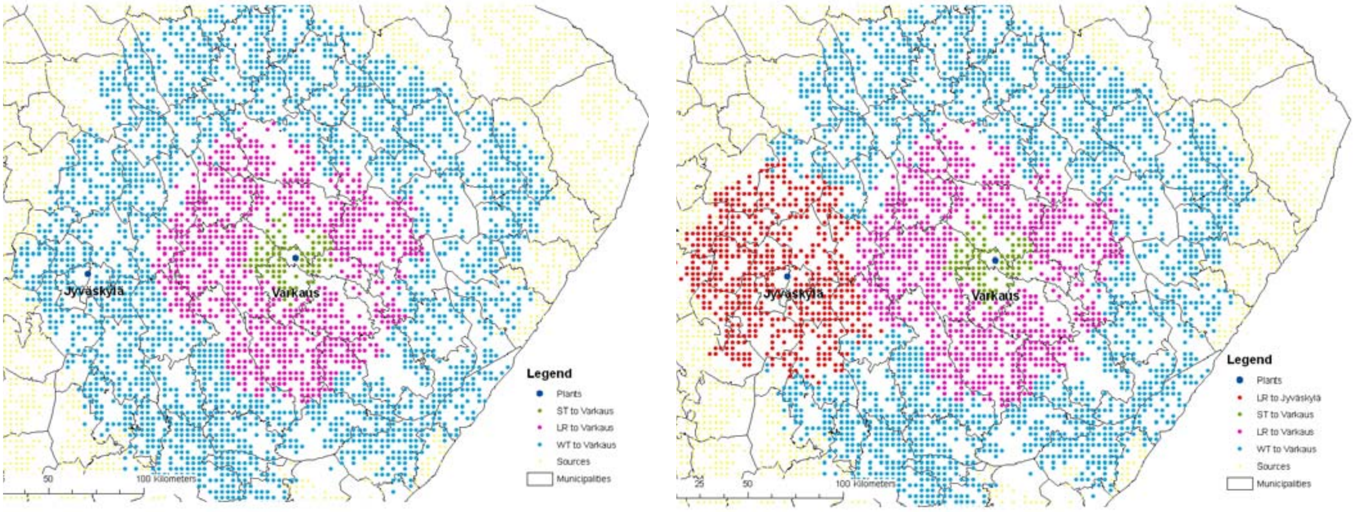


Figure 4.32. Representation of the transported fuel to Varkaus (left) and to both plants (right) in test F

Another sensitive analysis is carried out doubling the Jyväskylä fuel demand considering the original data (Figure 4.33). Diminishing the PA for Varkaus, i.e. Test D (Figure 4.34), Jyväskylä is more competitive and its exploited fuel sources are more concentrated. The maximum supply distance for Jyväskylä considering original data is 109 km, while considering test D conditions is 100 km.

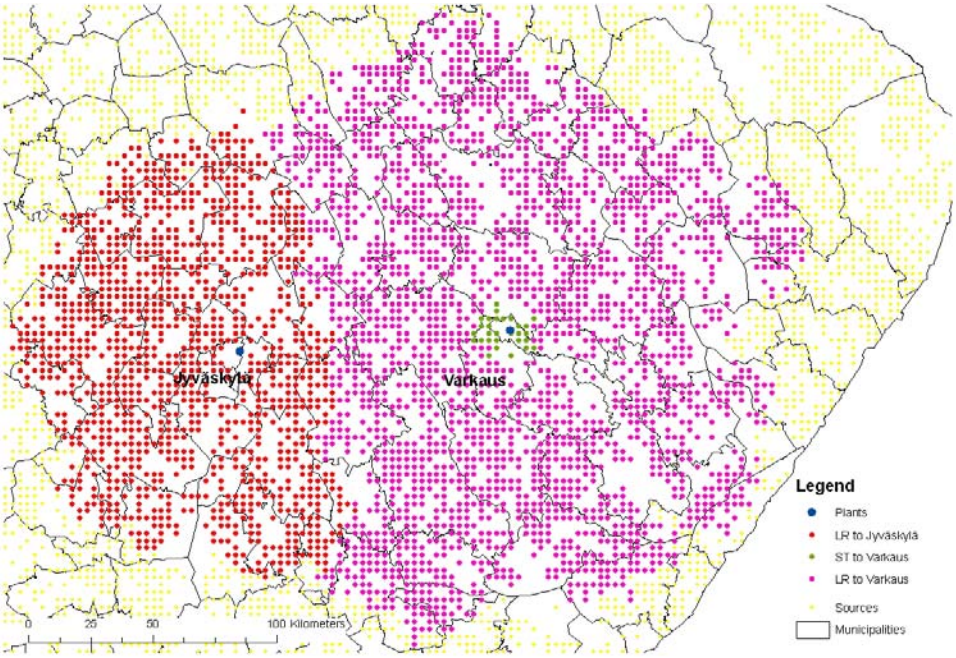


Figure 4.33. Optimal supply considering original data and double demand for Jyväskylä

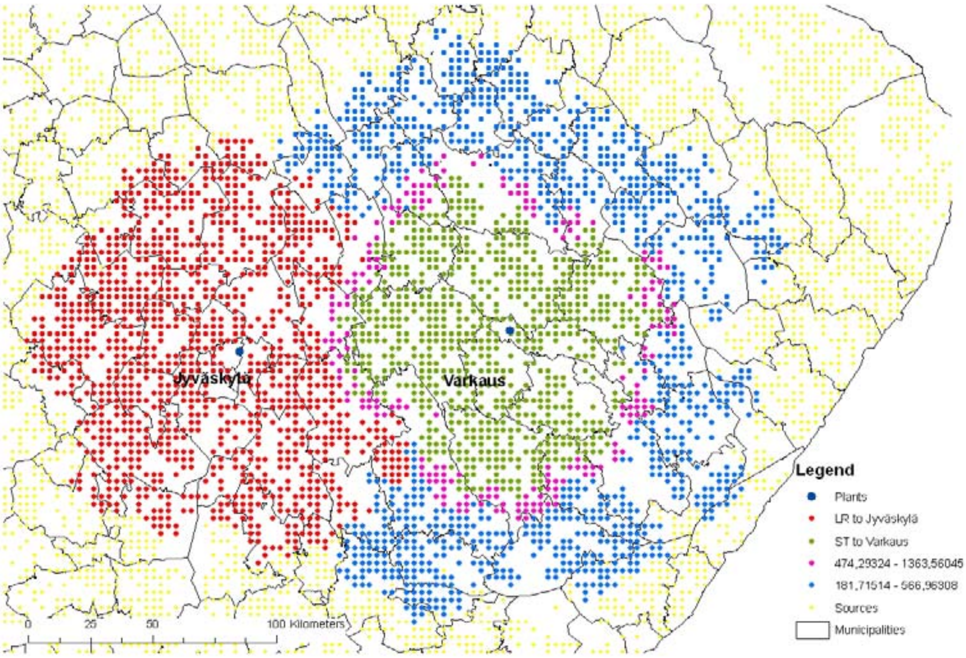


Figure 4.34. Optimal supply considering Test D conditions and double demand for Jyväskylä

5. DISCUSSION AND CONCLUSIONS

Wood fuel and other renewable energy fuels play a key role in the current European Union strategies to mitigate the impact of global warming. Their use is important for the accomplishment of different goals: reduction of greenhouse gas emissions, use of available local fuel resources, reduction of external energies supply and respect of the duties assumed in the International Conference of Kyoto (United Nations Framework Convention on Climate Change, 1997).

Wood biomass is a resource widely and homogenously distributed in the world. Estimation of biomass resources potentially available for energy production is an important step, that can bring to the decision to exploit biomass.

Every European country needs to have a National Renewable Action Plan with a biomass strategy. Availability and use of biomass is the starting point to formulate the strategy.

DRYING TEST

One of the biggest challenges to increase the use of forest biomass is the availability and proper use of sustainable harvesting technology and methods to meet the growing demand. Methods to produce high quality wood chips for a rapidly growing energy sector are essential for the development of the bioenergy sector, particularly in Central Europe where a large share of the installed heating capacity is based on small scale heating systems (Röser *et al.*, 2009). Small wood chips boilers require high quality wood chips to ensure unproblematic operation as well as low maintenance costs (Röser *et al.*, 2009; Cavalli *et al.*, 2007; Nurmi and Hillebrand, 2007). Fuel moisture content plays a key role in the quality of wood chips. In order to facilitate the drying process and thus ensure the availability of high quality fuel in short and long term, supply chains for wood chips should be designed also to account and promote natural drying of timber during the procurement process.

In Nordic countries in cut-to-length timber harvesting with single grip harvesters, debarking is a well known phenomenon. In the production of wood energy, partial debarking of stems has been used for decades in order to promote the drying process of chipped wood.

Natural drying shows to be an effective method to enhance the energy efficiency of wood fuel. For fuel from spruce, covering with paper fabric showed to improve the drying. It is important to use paper based cover, since the plastic based covers promote the growth of fungi in the pile’s top (Röser *et al.*, 2009).

In past years the wood energy demand for plants required the study and development of new design of wood procurement, which impacts on purchase, logging and transport of traditional timber assortments. Several supply chains have been introduced for forest fuels and their competitiveness differs depending on the conditions where they are being used. Systems where chipping is done at plant require large storage areas at the mill and to be effective a stationary chipper should be used. At smaller plants located near settlements, there is not enough space for chipping and the volumes used annually are too small to support large investment in chipping machinery. Forest fuel harvesting needs to be integrated with the roundwood supply chains (Asikainen, 2001). In most situations the ideal is to integrate the extraction of biomasses together with roundwood. In Italy and Finland biomass production is usually integrated (associated activity) to forest management, and many machinery and human resources are used by both activities (timber and biomass production).

Biomass fuel resources affect the commercial feasibility due to variation in type, cost, availability and reliability of supplies. Competition for biomass resources has an impact too. The economical feasibility is influenced also from available infrastructures to transport those resources.

When planning the suitable location for energy facilities is essential considering the actual land use, current regulations, environmental and economic aspects. A site-specific analysis on the commercial feasibility of utilizing biomass fuels is essential before starting a new plant project and activity. The need for site-specific biomass resources assessment will become increasingly important in the coming year, when all states and regions will have to fulfill their agreements on green energies.

OPTIMIZATION

Forest fuel supply chain has been modeled by Gunnarsson *et al.* (2004). They concluded that the transportation costs constitute the most essential part of the total costs. Moreover the optimal solution often included the use of flows with mobile chippers and direct transportation to heating plants.

Panichelli and Gnansounou (2008) used the least cost approach to allocate biomass quantities between predefined candidate site combinations to find the best set of location for the energy units. Perpiñá *et al.* (2009) developed a methodology based on GIS for biomass and transport optimization. They used the “closest facility” analysis that considers the shortest time taken to travel a distance without using a LP software.

Kanzian *et al.* (2009) constructed a procedural method that calculated optimal material flows and expected costs at plant level for different demand scenarios and supply options and demonstrated the differences between direct flow and flow via terminal. They divide the model into two sub models: one optimizes the transport from terminal to plant, the second optimize the flow from forest to terminal or plant. They modeled a local optimum due to the stepwise procedure.

In the present study is instead developed a LP that takes into account all cost factors along the supply chain, providing a global optimal solution. This study is carried out combining geographical information systems (GIS) and optimization through linear programming method. In the optimization software, a transportation problem is modeled and solved.

Model and solution approach can be used as a decision support tool for strategic analysis as well as tactical planning of the supply of wood fuel. The mathematical models here developed give a description of the supply chain problem considered. Modeling produces more flexible solutions compared to manual planning, and allows easy testing of different strategies and scenarios. Using a GIS for modeling biomass supply allows to study the effect of variation of geographical factors on the supply and costs of biomass production. With GIS is possible to have the geographical visualization of the studied situation, easier to understand and analyze than a list of numbers. Data collection and interpretation of results are very time consuming if the model is not user-friendly. The problem can be solved using a mask to input data and GIS to show results. User friendliness is a key threshold in applying research into practice.

Studies (Kanzian *et al*, 2008; Freppaz *et al*, 2004) refer the usefulness of the combination of GIS and linear programming in solving problems concerning the optimal location of plants or fuel terminals. GIS can be used to locate origins and destinations and easily calculate their distances including constraints in speed, type of roads, one way restriction.

In tactical planning, GIS is a powerful tool for logistic decisions, i.e. optimizing the truck minimum system costs of a forest fuel supply chain guarantee its competitiveness against other energy supply lines (Gronalt and Rauch, 2007).

Managing the transportation activities on a tactical/operational level encompasses several sub problems in need of an integrated solution, i.e.:

- which supply chain is the most economically convenient for supplying different plants and therefore what mean of transportation should be used
- how much material should be stored at terminal in order to guarantee plant supply throughout the year and minimize the storage costs
- which assortment should be used to fulfill a specific plant demand.

Plants and/or terminals need to be located close to forest, otherwise significant transport efforts, lower cost-efficiency and higher environmental impact occur. Preferable sustainable and socio-economical friendly solutions minimize transport by prioritizing local fuels. Transport can be minimized by optimal utilization of vehicle payload and choosing the shortest travel paths.

ITALIAN CASE STUDY

In Northeast Italy, wood chip quality and price classification still must be determined, considering moisture content, green particles and bark share. Chips derived from sawmills show a constant level of moisture content and they are clean of soils and stone. Therefore they are preferred by DH managers and boilers owners who wish to purchase wood chips out of local areas when there is a lack of residues from the local wood industry.

In most parts of Italy, forest chip supply is not yet well developed and not yet well known. Usually, forest wood chips come from the processing of raw materials and have to be chipped and transported out of the forest area within a short time because of a lack of intermediate storage or because coniferous of bark beetles (*Ips typographus L.*). Forest wood chips transported fresh to the plant usually have high contents of moisture, green particles and bark and sometimes contain soils and stones. Forest enterprises can add more quality to wood chip production by adapting strategies such as natural drying of selected un-merchantable logs.

In Northeast Italy, if logging residues are stored at roadside or in storages, the better quality of wood chips (in terms of moisture and green particle content) can be sold to small and medium size boilers that commonly present a higher buying power than larger size boilers. This strategy can support the forest wood chip supply and increase the possibility of better using the energy available in the local areas.

In order to design local strategies for sustainable biomass energy use it is necessary to know the biomass demand and supply. Surveys, personal interviews and calculation have been conducted in order to prepare the input for the optimization.

The results of the optimization of fuel supply during ten years show that chipping forest residues before being transported is cheaper than transporting logging residues. Chips from residues stored one year are preferred because of the higher energy content.

Results of scenario II show that terminal is used for only few volume of forest residues. To make the terminal infrastructure worth of being built, the optimization should consider a minimum amount passing through the terminal during the year. As the formulation has been done, there are not significant differences in total costs comparing the three terminal positions. This can be due also to the small scale area considered in the study.

The second scenario takes into account all aspects already considered from Diekema *et al.* (2005), such as: the seasonal fluctuation in supply and demand, the moisture losses and therefore the energy increasing of biomasses when stored, and the dry matter losses during storage. The multi period model provides the potential to adequately model inventory management and seasonal variation.

After observing results of scenario II, more constraints, such as a minimum quantity of fuel that has to be stored at terminal during the year should be added to the LP.

Observing results of sensitive analyses carried out during the study, the most useful is the one concerning the truck payload.

The case study here presented is hypothetical but with some good relationship with the real world. In order to represent the situation in LINGO, simplification of the reality is considered. Productivity of machines involved in the supply chains has been modeled considering previous studies and operational costs are calculated according to Miyata model (1980). When machines involved in the supply chains are different, also costs and productivities change.

In Fiemme Valley the tested optimization is just pure theory because the chips market and dynamics and contacts between forest owners and plant managers (personal choices) have big influence on plant supply. Besides, the study shows how the local resources should be exploited in the least cost manner.

If all wood or most of it would be processed at roadside the optimization would give a different result and the plants would be supplied with lower transportation costs and distances.

Piling sites (wood gathering points where it is supposed to gather material from 3-6 stands) are in this study positioned observing the digital map. To have a more exact calculation those points should be verified and located with surveys. Relocation of machines from one site to the next one is not considered to have an extra cost in this study.

In the real world logistic and all operations must be organized in such way to produce wood chips in the most cost-efficient way according to the forest and infrastructure conditions. Forest enterprise must choose the machines to be used. Moreover the landing suitability for wood residues piling must be evaluated and if necessary moving the wood to an intermediate storage must be chosen.

Similar optimization can be planned for timber supply chain for forest industries.

In the Italian case study, the availability of forest residues has been considered only if the available volume is greater than two truckloads (30 m^3). A further development of the model can consider using a mixed integer linear programming and using a minimum quantity of residues to be transported to plant, exploiting the truck load. This minimum quantity would be the relative unit. In this way transportation of too small quantities, i.e. lower than a truckload, would be avoided.

Gunnarsson *et al.* (2004) solved a similar problem with a mixed integer programming (MIP). The binary variables were related to the observance of some constraints such as the yarding and chipping of forest residues in a time period, the contracting or not of a sawmill and the usage or not of a terminal. The problem here studied can be modified into a MIP and using a fixed minimum quantity to be transported to plant, exploiting the truck load.

FINNISH CASE STUDY

Available fuel from logging residues, whole trees from pre-commercial thinning and stumps at municipality level are first compared to the demand of local district heating. The excess of fuel is considered available to be sold to bigger plants or biorefineries. The two big scale plants considered in this study are Varkaus and Jyväskylä, that need respectively 2 million MWh and 370 800 MWh energy from wood fuel.

Comparing the supply chains, transporting loose material is preferred to chips transportation up to 73 km for logging residues and up to 32 km for whole trees. Bundling option has the breakeven point with the transporting loose material option at 61 km. Asikainen (2001) states that the intersection point between forest fuel supply chains transported as loose residues and transported as chips or as bundle is around 40-60 km.

Here is analyzed how changes in fuel demand and PA for fuel affect the two supply regions of the two large scale plants. Simulating the situation with an optimization model and visualizing results with GIS is possible to display areas with high competition for resources.

Increasing the Jyväskylä demand, this plant can take advantage towards Varkaus in supplying closer resources. The same effect is reached when there is a limited PA for resources, and in particular for logging residues, from the Varkaus unit. Competition between Jyväskylä and Varkaus plants is competition for logging residues, the cheapest fuel for both plants.

The scale of forest fuel procurement affects the productivity and costs of harvesting. When it increases, forest fuel must be recovered over a larger geographic area. Transport distance becomes longer and residues must be gathered from less favorable areas from a harvesting point of view (Ranta, 2002).

The simulation considers that all the available fuel, as calculated in material and methods chapter, may be used as energy wood. In reality the option of collecting energy wood from the stands depends on the individual forest owner’s decision, so that over the 80% of the annual domestic roundwood cuttings derive from private forests.

The optimization takes into account the procurement costs taken from METLA’s calculations and literature and defined fuel moisture content. When those values change, the optimization would give different results.

Chipping of logging residues at roadside storage and transportation of chips (supply chain 1) and chipping of whole trees at roadside storage and transportation of chips (supply chain 5) are the most common supply chains in Finland, where the energy wood is chipped at roadside storage into truck load and transported to the plant (Kärhä 2007).

For the Finnish case study the competitiveness analysis of forest fuel is based on estimated supply and demand without commercial, environmental or socioeconomic externalities caused by fossil fuels. The simulations try to represent how local resources should be optimally organized and managed in order to minimize the total supply costs for both plants.

For the best management of local resources and the minimization of supply costs, the decision maker should consider the results derived from the optimization. The results scenarios should be considered together with the market rules, which play a big role in the supply.

Where there is a plant with high demand, the smaller plant (in this case Jyväskylä) suffers competitiveness. Increasing fuel demand for the minor plant, there is an advantage in its competitiveness for fuel.

A different study concerning the PA could be done with an allocation model. This means that the supply resources are allocated between demand site from overlapped supply areas and finding the optimal location according to supply resources. The formulation of the problem would consider an optimization with linear programming and using heuristic rules. The objective function could be maximizing the profit for the chips seller-producer (in this way if the smallest plant has a PA higher than the bigger, the fuel will go to the first one).

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