Design of forest biofuel supply chains

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Abstract: Designing and building new biofuel supply chains is an emerging theme in the present world energy situation. This paper considers a real-life problem of supplying a bioenergy plant with forest fuel. A mixed-integer linear programming model is proposed to determine the optimal configuration of that supply chain. The model proves helpful in resolving trade-offs between decentralised early treatment of biofuel, resulting in lower transportation costs, and centralised final treatment, allowing to reap economies of scale. It is therefore advisable to apply integrated supply chain planning concepts to design biofuel logistics systems and to support policy making in the energy field.

Keywords*:* logistic systems modelling; bioenergy supply; biofuel logistics; MILP; mixed integer linear programming; network flow models.

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1 Introduction

Ever since the early years of logistics and transportation research, the fuel industry has been the subject of extensive investigations. Early studies on the petroleum industry date back to the 1950s (e.g., Garvin et al., 1957), while there is evidence of research

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on natural gas transportation since the 1960s (e.g., Wong and Larson, 1968). A number of recent papers (e.g., Ríos Mercado et al., 2006; Ulstein et al., 2007; Aas et al., 2007; Trkman et al., 2007) testify that interest in designing and managing fossil fuel supply chains as efficiently as possible is far from diminishing with time. Oil and natural gas supply becomes, in fact, more and more critical because of the increasing demand from developing countries and political instability in some producing countries.

On the other hand, steadily increasing costs of oil and environmental concerns about climate change have recently generated extraordinary interest and investments in renewable energy (UNEP, 2007). Since transportation heavily relies on fossil fuels, logistics specialists were also lately concerned with the opportunity of increasing the energy efficiency of logistics systems (Leonardi and Baumgartner, 2004) and with the quest for alternative fuels. As stated by Rogers et al. (2007) "for logistics and transport managers the access to plentiful and inexpensive fuels has been an important part of building successful supply chains".

Actually, it seems that, as to renewable energy, logisticians mainly take the viewpoint of users, while, with regard to the fossil fuel industry, logistics researchers mostly take the active role of supply chain designers. In fact, just a couple of very recent examples can be retrieved in leading logistics journals as to supply chain design for novel energy vectors, such as hydrogen (Schwoon, 2007) or compressed natural gas including biogas (Frick et al., 2007).

The aim of this paper is to draw the attention of logistics specialists to the design of renewable energy supply chains, by dealing with a case study for a specific source, i.e., residual biomass from forestry activities.

Among renewable energy sources, biomass – including e.g., virgin wood from forestry activities, energy crops and agricultural residues (see Sims and El Bassam (2003) for definitions and discussion) – is especially attractive because its production or collection and use can be planned, which is not true for other 'renewables' (e.g., solar energy and wind energy).

Also, biomass can be sourced locally and provide new business opportunities to rural communities, such as, for instance, mountain communities who can benefit from the exploitation of forest fuels.

Moreover, there is a good scientific basis for studying and modelling forest biomass supply chains moving from similar, well studied supply chains, i.e., those of timber, pulp and paper or plywood. Such supply chains are well established on a large scale, because in many countries traditional forest activities have been progressively replaced by timber collection in industrial frameworks. These have been the object of many investigations reported in the logistics literature of the last few years.

Vielma et al. (2007), for instance, deal with the issue of scheduling forest harvesting, while Troncoso and Garrido (2005) address the problems of forest production, forest facilities location and forest freight distribution.

Carlsson and Rönnqvist (2005) present a variety of supply chain management cases in the forest industry.

On the other hand, residue supply chains have different volumes and features, more similar to those of waste and reverse supply chains (Kovacs et al., 2006). Harvest residuals with lower industrial value (see Kumar et al., 2003) used to be often left behind because collection operations would have been too expensive and their costs would not be compensated by any commercial value of products.

However, recent interest in biofuels generated market opportunities for forestry residues, which can be used, in particular, to feed municipal centralised heat generation plants coupled with district heating systems (see e.g., Harvey, 2006 for details on municipal energy plants), or larger municipal plants where both electricity and heat (cogeneration plants) are generated by means of proper conversion technologies (Obernberger, 1998), mainly based on biomass combustion.

Interest in biofuels resulted also in rising efforts in modelling forest fuel logistics systems. In particular, the organisation culture of large companies, settled in countries where forest industry has a great national importance, leads them to pursue best practices and minimise costs of forest fuel delivery. Gunnarsson et al. (2004) focus on the problem of tactical optimisation of forest fuel delivery. And indeed, as they observe, the problem of delivering forest fuel at minimum cost is a true supply chain problem, as fuel can be obtained from multiple sources, forwarded to several intermediate terminals and with different transportation patterns.

Further decision variables and complexity are added if we do not cope with the operation of an existing system, but rather with the design of a new one from scratch, i.e., with the strategic planning of biofuel supply chains. As underlined by Allen et al. (1998), this is often the case: a difficulty in shaping and comparing biofuel supply chain options is that designers have to model chains that do not currently exist.

This paper treats the issue of designing a forest fuel supply chain from the start and moves from the motivating case study of a small-scale bioenergy venture conceived in North Eastern Italy.

Cost minimisation is important for large and well-established supplying companies, who can benefit from economies of scale and from internal capabilities to optimise their own processes, but it is even critical for small bioenergy ventures, which in many regions are fostered by local governments as a means to promote the economic development of forests and mountain areas.

The profitability of bioenergy plants, especially at small scales, depends considerably on biomass fuel costs (Sundberg and Karlsson, 2000) and there is extensive evidence in practice and literature (Allen et al., 1998; Caputo et al., 2005) that logistics costs represent a significant proportion of total costs of biomass supply to bioenergy conversion plants.

Designing potential biomass fuel supply chains in the best possible way is thus essential to assure a stable development of bioenergy systems based on local residual resources.

Hence, we define the design problem of the motivating case study in Section 2 and review literature on logistics in the biomass sector in Section 3. On this basis, we introduce an optimisation model to support the strategic design of a local forest biofuel supply chain. In Section 4, we focus on system modelling of the operations required to transform forest residuals into biofuel available at bioenergy plants, while in Section 5, we present the network structure of the proposed supply chain design optimisation model. Results are discussed in Section 6 and conclusions are drawn in Section 7, with hints for further research derived from the case study and the literature review.

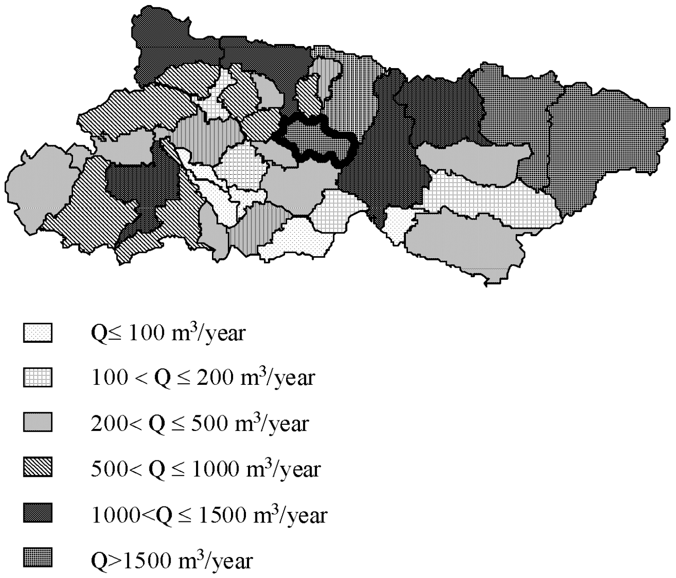
2 Motivating case study and problem definition

The local government of Friuli Venezia Giulia (North Eastern Italy) was recently inclined to support the development of a biomass-fuelled district heating system, possibly associated with cogeneration, in a village located in a mountain district. The village is characterised by a significant concentration of heating demand due to a fairly well-developed tourism industry connected to the existing spa waters. Through this bioenergy initiative, the local government expects to further promote spa and hospitality sectors by making low-cost energy available. Furthermore, a local market for forest residuals can start, thereby promoting a more effective forest maintenance.

To assess the effectiveness and the economic viability of that project and to determine the optimal size and technology for the bioenergy plant, it was necessary to study the feasibility of a local forest fuel supply chain. This involves the surrounding mountain area, which has an overall extension of about 2100 km^2 and comprises 36 municipalities.

Yearly theoretical biomass potentials for energy use were assessed (Chinese et al., 2004) as shown in Figure 1.

Figure 1 Distributions of forestry residues (theoretical potentials) in the municipalities of concern. In bold margins of the municipality where the planned bioenergy plant should be located



It can be observed that there are remarkable differences in biomass quantities available at various municipalities. Besides, we noted that villages also differ in road conditions, as concerns existing connections and viable truck sizes and speeds.

Thus, the first decision to be made in structuring the supply chain is the set of sites (i.e., municipalities, in our case) to be selected as forest residues sources and the related biomass distribution paths. Logistics costs should be expressed per heating value unit, because the heating value, which is the energy content of biomass delivered at bioenergy plants, is the key parameter for energy conversion.

To design biofuel supply chains, we should choose not only where to source rough materials (e.g., residues) but also where and how to process them to deliver suitable fuels at final energy conversion plants.

It is peculiar, in fact, to biomass fuel supply chains to include, besides typical activities of logistics systems (e.g., transport and storage), some specific biomass processing operations such as particle size reduction and drying (see Allen et al., 1998). These may be performed at any stage of the supply chain and modify the state of the biomass fuel, in particular its specific volume and heating value. As a result, transportation costs depend also on the state of transported materials and consequently on processing operations performed before transport.

To state the problem more generally, we can say that biofuel supply costs to energy plants depend on how operative chains are structured, i.e., when and where operations on biomass take place. Earlier biomass processing along the operative chain may lead to lower transportation costs, but it also requires multiple decentralised treatment facilities. This implies increased variable (manpower, energy, etc.) and fixed costs of facilities at each stage.

Therefore, while planning biofuel supply chains, a trade-off arises between economies in treatment postponement and centralisation, on the one hand, and costs of equipment replication in early treatments together with savings in transportation costs, on the other. A systemic approach should be adopted to highlight relations between supply chain stages and to select the best operational chain for total delivery cost minimisation.

Hence, we believe that a biofuel supply chain model should help to manage the following strategic issues:

- definition of the optimal supply area and selection of proper transport paths
- design of the operative chain in terms of both logical operations sequence and physical location of facilities, thereby taking into account the state of transported materials
- sizing of facilities, considering economies of scale, which may lead to prefer centralised solutions rather than distributed small units.

All these issues are apparently interdependent, so we need a model to take them into account simultaneously, to identify the best supply chain configuration.

3 Design of biomass fuel supply chains in literature

Literature review reveals that the problem of providing computational tools to support the design of biomass logistics systems has been repeatedly addressed, though mainly in agricultural engineering and bioenergy literature. Two main methodological strands can be identified: the simulation and the optimisation approach. Both have been adopted in literature to encompass main phases of biomass delivery process, i.e., harvesting, storage, processing and transportation.

Simulation appears to be the most frequently used approach (see e.g., Hall et al., 2001; Van Belle et al., 2003; Sokhansanj et al., 2006). Simulation models, implemented through spreadsheets (Hall et al., 2001) or dedicated languages (Nilsson, 1999a; Sokhansanj et al., 2006) are particularly appropriate to deal with non-linearity or singularities typical of some phases of the process (e.g., effects of weather and of field drying of straw in Nilsson, 1999a) and are therefore especially used to investigate selected stages of the supply chain, for instance with the aim of assessing the application of novel technologies (Nilsson, 1999b). Simulation is particularly used when time dependence of the process becomes of primary importance and regularity of supply needs to be studied in detail, such as by Van Belle et al. (2003). As noticed by De Mol et al. (1997), in fact, including time-dependent effects in optimisation models is possible (see e.g., Cundiff et al., 1997) but difficult because of the required simplifications, while simulation models are particularly suitable to handle inventory problems and supply fluctuations.

Optimisation models, instead, are more powerful at analysing a high number of combinations and design alternatives: they are, therefore, often preferred to or combined with simulation models (De Mol et al., 1997; Tatsioupoulos and Tolis, 2003) to design new supply chains. Optimisation is, therefore, chosen to tackle issues of transportation modes selection (Cundiff et al., 1997; De Mol et al., 1997), of biomass producers' selection depending on their distance from final user (Tatsioupoulos and Tolis, 2003; Gunnarsson et al., 2004). It therefore seems to be the most promising approach to resolve the issues highlighted in the previous section. Methodological approaches to optimisation include linear programming (Cundiff et al., 1997), dynamic programming (Gigler et al., 2002) and heuristic approaches (Gronalt and Rauch, 2007). De Mol et al. (1997) use Mixed Integer Linear Programming (MILP) to select pre-treatments in separate sites or to choose, among different destination plants, the optimal one, while Gunnarsson et al. (2004) use mixed integer programming for tactical optimisation, i.e., to decide which volumes of biomass should be forwarded or transported or stored or chipped within the terminals of an existing forest fuel supply chain, or to support strategic decisions on variations of the existing supply chains.

Though embracing some phases of biofuel supply chain, optimisation models tend to concentrate on separate aspects: even if authors stress the importance of an integral approach to the design of the supply chain, it is clear that including into a unique optimisation model every single aspect, it is quite difficult and in some cases may not be necessary.

Literature review highlights how biomass supply chain design is mainly resolved, in fact, by means of:

- Models that optimise operative chains assuming a given location of treatment facilities, thus considering only biomass processing sequence as variable (e.g., Maia et al., 1997 for agri-chains in general).
- Models that select optimal biomass delivery quantities and storage capacity in each fixed treatment site and account for transport costs, but do not consider different options for biomass processing sequence and distribution paths (e.g., Cundiff et al., 1997).
- Models that identify optimal transport paths and treatments through Boolean variables, but do not size facilities capacities. The model developed by De Mol et al. (1997), for example, describes the system as a graph whose nodes are treatments and arcs transport paths, but does not take into account material losses, moisture variations, timeliness of biomass flows. Even if these aspects are handled in a successive, more detailed simulation model, dependence of transport cost on material state is not considered while configuring the supply chain.

> More emphasis to integrated planning is given by Gunnarsson et al. (2004), who consider treatment and transport costs at the same time and distinguish between chipped and non-chipped products. Still, they assume that the capacity and location of processing are given parameters.

In our case, however, we have to deal with the initial design of a biomass supply chain for a mountain region, whose municipalities differ in forest covered territory and consequently in biomass potentials, forest typology, road conditions, distance from the final energy plant. Therefore, it would be preferable to incorporate all the identified factors in a single model, to select the locations for biomass harvesting and the transport paths to the bioenergy plant. Furthermore, since transport paths and the operative chain structure are interdependent, an optimisation approach should be developed to manage both at the same time. To assess facilities location and capacity and the biomass processing sequence simultaneously, we developed the model presented in the following sections.

4 Modelling operations and costs of biomass fuel production

To model biomass supply chains, whether for simulation or for optimisation, we should first examine feasible technological options for the main activities required to supply biofuel to energy conversion plants.

To obtain bioenergy through combustion technologies (Obernberger, 1998), biomass should be made available at conversion plants in the conditions required for a proper handling and combustion. In other words, this means that biomass must be:

- harvested, i.e., in our case collected at forest sites
- processed, i.e., transformed to assume the physical properties required for energy conversion
- transported to energy conversion facilities.

In the following subsections, we discuss how these operations have been modelled in our case study.

4.1 Biomass harvesting

At the time of this research, exact information on locations of stands and forests within municipalities and on the morphological situation of each area was not available. Hence, for the purpose of supply chain configuration, it was only relevant to decide in which municipalities to harvest. Similarly, owing to limited availability of information on site conditions (some harvesting experiments were in progress), selecting optimal harvesting technologies was beyond the scope of this research.

For economic feasibility assessment, estimates of harvest costs and expert judgements on economic potentials in the area when compared with theoretical biomass potentials were nevertheless needed.

Data retrieved from literature (Fagarazzi, 2005) and from expert judgement were compared with simulations obtained using specific software (Regione Piemonte, 2003);

good agreement on values was observed. Based on available data and simulations, we assume that:

- 17% of the estimated theoretical potential is available in all municipalities at relatively easy harvest conditions (in particular, at less than 20% slope) and at an average harvesting cost of 17.8 € per tonne of residues at harvest conditions.
- An additional 40% of the estimated theoretical potential is available at more difficult but still economically and technically feasible harvest conditions (30% average slope) at an average cost of 27.4 € per tonne of residues at harvest conditions. Globally, we can thus assume that 57% of the estimated theoretical potential is available at an average cost of 24.5 € per tonne of residues at harvest conditions.
- The remaining 43% of the estimated theoretical biomass potential is not practically or economically harvestable.
- Also, to estimate transportation costs within municipalities, forests are considered as located on the border of municipalities; biomass is then transported from forests to central collecting points within each municipality by tractors.

4.2 Biomass processing

Two physical properties of biomass are determinants for energy conversion, namely water content and particle size of bulk biomass.

The first property, i.e., water content of biomass fuel, influences the combustion behaviour. Wet biomass fuels have lower energy density and need a longer residence time before combustion is completed. This leads to bigger combustion chambers (Obernberger, 1998) and larger costs of conversion facilities. Generally, water content should be below 30% to obtain an economical and unproblematic combustion. Therefore, a 25% biomass water content is assumed as specification of the centralised bioenergy plant in our case study.

Water content of forestry residues at harvest is usually between 45% and 55% (FNR, 2001) (55% is hypothesised in our case), so a preliminary drying process is needed to meet the requirements.

Drying processes can be classified in natural drying and artificial or forced drying. Natural drying is a spontaneous phenomenon directly linked with wood storage at environment conditions. Moisture contained in fresh timber is gradually released to the air that flows naturally through woodpiles or heaps of wooden chips. If climate conditions are good, natural drying can be performed outdoors. However, in the case of wooden chips, significant losses of material – about 10% per year (APAT, 2003) – are associated with open storage. Material losses can be reduced with covered storage under sheds, which also entails natural drying. In both cases, we can assume that the water content of biomass harvested at hypothesised conditions can be reduced below 30% in one year (FNR, 2001).

Forced drying is performed by artificial ventilation, usually with warmed air, which allows more efficient and rapid drying. However, it requires higher investments in technology and entails operation costs for energy and workforce, which are negligible in natural drying.

To model costs properly, we retrieved and adapted data from literature (FNR, 2001), from builders of drying facilities and from the local estate market for industrial, marginal and arable land. Cost estimates for single treatment facilities are interpolated to obtain linearised cost functions. We focus on annual costs of processing plants, including annuities equivalent to capital costs and yearly operational costs. A 12-year planning horizon and an 8% discount rate are considered. We model annual capital costs as a linear function of yearly treatment capacity, expressed in terms of the energy content associated with input biomass. Capital costs are null if no capacity is built, while they result in a size-independent component (fixed charge) and a size-dependent cost component, if a positive processing capacity is built (for more details on facilities cost modelling, see Williams, 1990).

Table 1 shows operational costs and annual equivalent capital costs of drying systems; treatment efficiencies take into account the overall energy losses corresponding to the losses of dry matter during storage. Storage and drying are concurrent events both in terms of space and time; moreover, the time period within our planning horizon is one year and seasonal variations are not considered. Given this framework, it is reasonable to assume that setting drying capacity is equivalent to sizing biomass storage within a yearly time horizon. Thus, displayed drying costs should be regarded as drying and storage costs. The table presents all the possible drying phases that can be considered in our case study: other combinations can be modelled depending on different local conditions.

Table 1 Economic parameters for drying processes

Process description	*Initial water content* w_i [%]	*Final water content* w_f [%]	*Annual capital costs, size independent component* [€/year]	*Annual capital costs, size dependent component* [€/(GJ × year)]	*Annual operational costs* [€/(GJ × year)]	*Process efficiency* [%]
Natural outdoor drying of forestry residues as harvested	55	40	0	0.13270	0	98.30
Natural outdoor drying of chipped forestry residues	55	40	0	0.13270	0	96.55
Natural covered drying of chipped forestry residues	55	40	0	0.49764	0	98.30
Forced drying of chipped forestry residues	55	40	1982.4	1.19434	0.02459	99.00
Natural outdoor drying of chipped forestry residues after first drying	40	30	0	0.09165	0	96.55
Natural covered drying of chipped forestry residues after first drying	40	30	0	0.34369	0	98.30
Forced drying of chipped forestry residues after first drying	40	30	1982.4	0.82485	0.01698	99.00
Natural outdoor drying of chipped forestry residues after second drying	30	25	0	0.07595	0	96.55
Natural covered drying of chipped forestry residues after second drying	30	25	0	0.28480	0	98.30
Forced drying of chipped forestry residues after second drying	30	25	1982.4	0.68351	0.01407	99.00

The second important characteristic, i.e., the size of biomass particles, affects handling and combustion technologies. If biomass is reduced to small particles (chips), cheaper handling technologies and simpler combustion technologies (grate firing) can be used, thus reducing the corresponding investments and operation costs (Obernberger, 1998). This is the reason why the preliminary process of chipping is usually required for wooden biomass to be used as fuel for bioenergy conversion plants, especially in the case of forestry residues, whose original size is often big and very inhomogeneous.

Main technologies for chipping include disk chippers and drum chippers. The latter are larger and more expensive fixed installations, but allow to process a wider variety of input materials and to obtain more homogenous output than mobile disk chippers, which are suitable for small scale operations only. For these reasons, we set drum chippers as the chipping technology suitable for our case study. Actually, for many biomass types, chipping can be less expensive if it is integrated with harvesting (Allen, 1998). However, this can be performed only where enough even ground space is available and forest tracks are large and in good conditions, which is seldom the case in the analysed area. This opportunity is, therefore, not taken into account, but chipping is considered as a possible treatment at forest borders, intermediate points or at the bioenergy plant.

Interpolating and averaging cost and productivity data provided by equipment suppliers, we derive annual equivalent capital costs – expressed as the sum of size independent and size-dependent components of linearised cost functions – and yearly operational costs, as shown in Table 2. We assume that chipping entails a limited material loss, which we conservatively estimate at 2.5% of the original energy content.

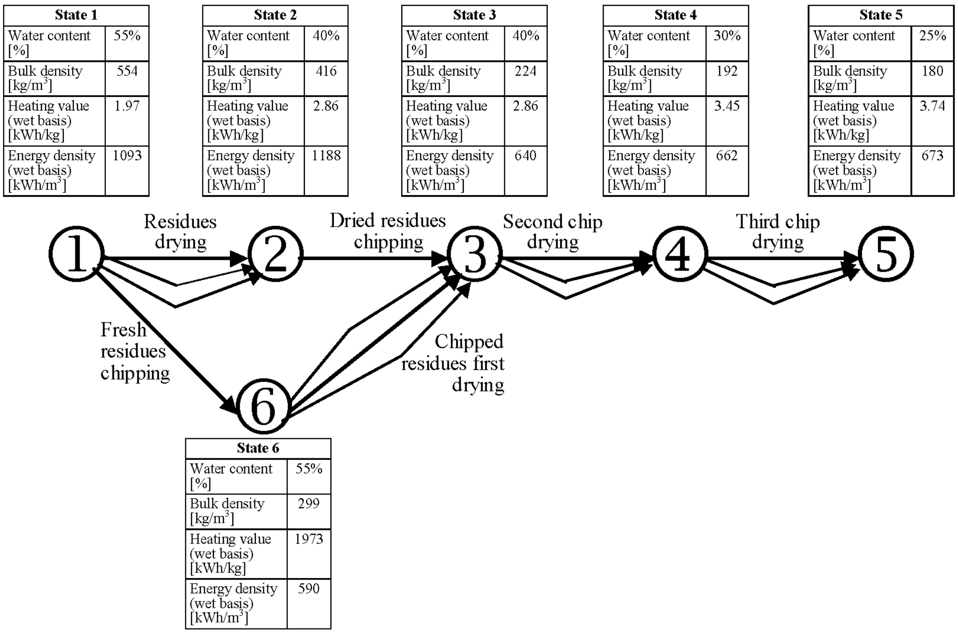
Table 2 Economic parameters for chipping processes

Process description	*Annual capital costs, size independent component* [€/year]	*Annual capital costs, size dependent component* [€ (GJ × year)]	*Annual operational costs* [€/(GJ × year)]	*Process efficiency* [%]
Chipping of fresh forestry residues	2093.7	0.00687	0.96144	97.5
Chipping of dried forestry residues	2093.7	0.00474	0.66420	97.5

Many potential sequences of drying and chipping operations are recognisable. Feasible sequences for our specific case study are represented in Figure 2, which also highlights the states of biomass at various stages of the processing chain and the physical features (bulk density, net calorific value and energy density) of biomass in each state. Circled numbers in Figure 2 represent states, while arrows connecting states represent processes: in our case, six different states of biomass can be identified. Multiple arrows are associated with drying operations, since different technologies can be taken into account, i.e., natural outdoor drying, covered natural drying and forced drying. It can be observed that drying processes influence both heating value and bulk density whereas chipping only affects bulk density. Both drying and chipping result in changes of the energy density of material.

It should be stressed that single operations or subsets of the processing chain or the complete processing chain can take place at every municipality, may it be a harvesting, intermediate or the energy conversion site. Accordingly, biomass can be transported in any state from one site to another.

Figure 2 Possible sequences of drying and chipping processes, including biomass properties at various states



State 1	
Water content [%]	55%
Bulk density [kg/m^3]	554
Heating value (wet basis) [kWh/kg]	1.97
Energy density (wet basis) [kWh/m^3]	1093

State 2	
Water content [%]	40%
Bulk density [kg/m^3]	416
Heating value (wet basis) [kWh/kg]	2.86
Energy density (wet basis) [kWh/m^3]	1188

State 3	
Water content [%]	40%
Bulk density [kg/m^3]	224
Heating value (wet basis) [kWh/kg]	2.86
Energy density (wet basis) [kWh/m^3]	640

State 4	
Water content [%]	30%
Bulk density [kg/m^3]	192
Heating value (wet basis) [kWh/kg]	3.45
Energy density (wet basis) [kWh/m^3]	662

State 5	
Water content [%]	25%
Bulk density [kg/m^3]	180
Heating value (wet basis) [kWh/kg]	3.74
Energy density (wet basis) [kWh/m^3]	673

State 6	
Water content [%]	55%
Bulk density [kg/m^3]	299
Heating value (wet basis) [kWh/kg]	1973
Energy density (wet basis) [kWh/m^3]	590

4.3 Biomass transport

We assume that transport from production or intermediate locations is operated by trucking companies by means of either tractors with trailers or of small tipper trucks or of larger, articulated lorries, depending on road conditions. In this case study, we suppose that harvested material is stored on headland and that direct transport from forest headland to any intermediate storage or to the energy conversion plant can be performed with tractors or small trucks, while larger lorries can be used only on highroads, which connect some of the municipalities.

In accordance with the cost minimisation rationale embodied in the whole optimisation procedure, we assume that, among the vehicles that can be used on a given stretch for a given material, the cheapest one will be selected. Based on this assumption, we determine the average cost $ctrans_{i,j,n}$ of transporting one equivalent energy unit of biomass at state n from site i to site j as the average cost of the cheapest vehicle type v within the set $V(i, j)$ of feasible vehicles for stretch (i, j), according to equation (1):

$$ctrans_{i,j,n} = \min_{v \in V(i,j)} \left[\frac{cmp_v \cdot \left(\dfrac{d_{i,j}}{v_v} + lt_v \right) + cop_v \cdot d_{i,j}}{LHV_{v,n}} \right] [€/kWh] \qquad (1)$$

where

cmp_v: Hourly cost of manpower operating vehicles v the term in round brackets is the operation time for manpower on stretch (i, j)

v_v: Average speed of vehicles v

$d_{i,j}$: Road distance between site i and site j as derived from a geographic information system

lt_v: Average time for loading and unloading the truck

cop_v: Operational cost per kilometre of vehicle v, including fuel, maintenance and vehicle depreciation.

Vehicle types and their economic parameters for our case study are represented in Table 3.

Table 3 Economic parameters for transportation

Vehicle	*Weight load capacity* [t]	*Volume capacity* [m^3]	*Loading time* [h]	*Average speed* [km/h]	*Manpower costs* [€/h]	*Operational costs* [€/km]
Tractor with trailer	6	10	1.5	35	33.33	0.68
Truck	10	35	1.5	50	33.33	0.74
Articulated lorry	25	90	1.5	60	33.33	1.52

$LHV_{v,n}$ is a critical term, representing the energy content (low heating value) of biomass that can be transported with vehicle v at state n. Every vehicle is characterised by a given load capacity in weight and by a given volume capacity, as shown in Table 3. If the bulk density of biomass is low – specifically, below the ratio between weight and volume capacity of the considered vehicle – then the maximum biomass quantity that can be transported is limited by the volume capacity of the vehicle, while if biomass is more dense, the weight load limitation is the most restrictive.

Thus, given the properties of forestry residues displayed in Figure 2, the parameter $LHV_{v,n}$ can be calculated as expressed in equation (2):

$$LHV_{v,n} = \begin{cases} HV_n \cdot \gamma_n \cdot VC_v & \gamma_n \leq \dfrac{LC_v}{VC_v} \cdot 1000 \\ HV_n \cdot LC_v \cdot 1000 & \gamma_n > \dfrac{LC_v}{VC_v} \cdot 1000 \end{cases} \quad \text{[kWh]} \tag{2}$$

where

HV_n: Heating value of biomass on wet basis at various states expressed in kWh/kg (see Figure 2)

γ_n: Bulk density of biomass, in kg/m^3 (see Figure 2)

VC_v: Volume capacity of vehicle v in m^3 (see Table 3)

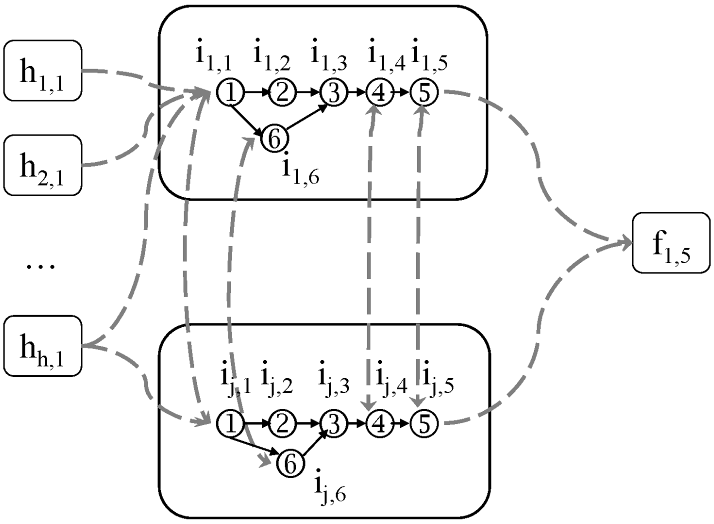
LC_v: Load capacity of vehicle v in tonnes (see Table 3).

5 Optimisation model for structuring a biofuel supply chain

Having recognised harvesting, drying, chipping and transportation as the main operations in the forest biofuel supply chain and having modelled their technical and economic properties, we will formulate our optimisation problem of structuring the forest fuel supply chain by highlighting the network flow nature of the problem.

Using graph symbolism, we can obtain the network model diagrammed in Figure 3. We can allocate a node at each site where biomass is harvested, at state 1 in accordance with Figure 2, thereby obtaining a set $H = \{h_{1,1},...h_{h,1}\}$ of source nodes. (Note that the second foot index stands for the state of material, which in our case is necessarily 1 at harvest and 5 at the furnaces. The model can be nevertheless generalised if multiple harvest conditions are possible or different biomass states are acceptable for combustion).

Figure 3 Network structure of the model



In the examined case study, as forestry residuals are available in each municipality but their exact localisation is not known, we allot a source node to each municipality. Then, we determine the geometrical centre of the municipal area and conservatively assume that all source nodes within the same municipality are located at the maximum distance from the centre.

Set F contains energy conversion facilities, represented in our case by the single node $f_{1,5}$ (i.e., the sink node), located at the centre of the single village (see Figure 1) where the final demand of biofuel is concentrated, at state 5 in accordance with Figure 2.

Biomass processing sites can be represented through a set I of 'macro-nodes', characterised by a location and a processing cycle (see Figure 3). Treatment facilities can be installed in every municipality, i.e., also where biomass is harvested or used. As highlighted above, it is possible that only single operations or portions of different processing chains are completed at various treatment sites. Hence, we need to model the potential operative chain in every location; therefore, an internal 'micro-graph' is associated to every macro-node i. Each micronode m represents a state of biomass, so in our case $m \in M = \{1, 2, \ldots, 6\}$. The ordered pair of micro-nodes (m, n) thus represents the initial and final state of biomass during a step of its processing cycle at treatment site *i*, while the edge (*m*, *n*), which connects them and belongs to micrograph *O*, corresponds to the operation undertaken. As it can be observed from Figure 3 and consistently with processes portrayed in Figure 2, in our case the complete micrograph of feasible edges – i.e., processing steps – is $O = \{(1, 2), (1, 6), (6, 3), (2, 3), (3, 4), (4, 5)\}$. Every subset of *O* could be allocated to every intermediate node $i \in I = \{1, \ldots, j\}$.

Source nodes *h*, intermediate macro-nodes *i* and the sink node *f* are connected by edges that identify all possible transport paths based on actual roads in the mountain area. Edges are represented in Figure 3 as dashed grey double arrows. Every arrow is associated with a single state of transported materials. According to our assumptions, materials can exit forest nodes only at state 1, entering a following treatment node at the same state, and enter the furnace node only at state 5 exiting from a previous treatment node at the same state, because we assume that no treatment can be performed during transport. Multiple arrows connect intermediate nodes because biomass can enter or exit intermediate sites at any state, depending on which processing activities are performed at each site; however, with the constraint that the material enters macro-node *j* at the same state it presented when leaving previous macro-node *i* or forest node *h*.

An optimisation MILP model has been associated with the described network, to select the best paths, flows and facilities size to supply the bioenergy plant. The problem is treated as a single objective, cost minimisation deterministic problem.

5.1 Objective function

The objective function minimised is the total cost of the supply chain in a year, as reported below:

$$\min \left\{ \begin{array}{l} \sum_{h \in H} \sum_{n \in M(h)} charv_{h,n} \sum_{i \in I(h)} x_{h,i,n} + \sum\limits_{i,j,n} ctrans_{i,j,n} \cdot x_{i,j,n} \\ + \sum\limits_{i,m,n} ctreat_{m,n} \cdot yin_{i,m,n} + \sum\limits_{i,m,n} (c\,\mathrm{var}\,inst_{m,n} \cdot Cap_{i,m,n} \\ + cfixinst_{m,n} \cdot bin_{i,m,n}) ann_{m,n} \end{array} \right\}. \tag{3}$$

Four cost groups can be observed in Equation 3, that is biomass harvest costs at the first line, biomass transportation costs at the second line, biomass processing costs at the third line and, at the last line, facilities installation costs, which are formed by a first size dependent term and a second fixed charge to account, where opportune, for economies of scale.

In particular, the following nomenclature is used in equation (3):

$charv_{h,n}$: Harvest cost [€/kWh] per unit of material collected at harvest site *h* and at state *n*

$M(h)$: Set of possible states of biomass at harvest ($M(h) = \{1\}$ at all sites in our case)

$I(h)$: Set of all intermediate sites linked to harvest site *h* through feasible transport paths

$x_{i,j,n}$: Biomass amount [kWh/year] moved from macro-node *i* to macro-node *j* at state *n*

$ctrans_{i,j,n}$: Transport cost [€/kWh] per unit of material moved from macro-node *i* to macro-node *j* at state *n*

$ctreat_{m,n}$: Processing cost [€/kWh] to transform a unit of biomass from state *m* to state *n*

$yin_{i,m,n}$: Biomass quantity [kWh/year] entering macro-node *i* at state *m* to be processed to exiting state *n*

$cfixinst_{m,n}$: Fixed cost [€] of installing equipment for the processing cycle operation, which transforms biomass from state *m* to state *n*

$bin_{i,m,n}$: Binary variables to set actual installation of equipment related to biomass transformation from state *m* to state *n* in facility *i*

$cvarinst_{m,n}$: Cost per capacity unit [€/(kWh/year)] of equipment installed to process biomass from state *m* to state *n*

$Cap_{i,m,n}$: Equipment capacity [kWh/year] made available in macro-node *i* to process biomass from state *m* to state *n*

$ann_{m,n}$: Annuity factor to ascribe installation costs on a year time period, calculated for each processing cycle operation on the basis of expected life of related equipment.

5.2 Constraints

Three main classes of model constraints can be recognised:

1. Capacity constraints, that set the size of processing facilities in intermediate nodes to satisfy production volumes and available commercial sizes
2. Mass balance constraints, which are defined for every cycle operation, for the whole system in each treatment facility and for source and sink nodes
3. Logical constraints to set feasible values of variables.

Concerning the first class, capacity constraints expressed by equations (4)–(7) are considered:

$$yin_{i,m,n} \leq Cap_{i,m,n} \qquad \forall i \in I, \forall\ (m,n) \in O \tag{4}$$

$$bin_{i,m,n} \cdot L_{m,n} \leq Cap_{i,m,n} \qquad \forall i \in I, \forall (m,n) \in O \tag{5}$$

$$bin_{i,m,n} \cdot U_{m,n} \geq Cap_{i,m,n} \qquad \forall i \in I, \forall (m,\ n) \in O \tag{6}$$

$$\sum_{(m,n) \in O} \frac{Cap_{i,m,n}}{SpecCap_{m,n}} \leq Surf_i \qquad \forall i \in I. \tag{7}$$

According to equation (4), material flow entering every macro-node *i* to be transformed from state *m* to state *n* by an operation of micrograph *O* cannot exceed facility capacity for that specific treatment. Constraints (5) and (6) set lower bounds and upper bounds, respectively, to installed capacity of each treatment so that sizes within feasible commercial ranges are selected. With equation (7), we impose that the definition of total treatment capacity takes into account space requirements of each process $SpecCap_{m,n}$ and actual surface availability in every location $Surf_i$.

Mass balance constraints include equations (8)–(11).

$$yout_{i,m,n} = yin_{i,m,n} \cdot \eta_{m,n} \quad \forall i \in I, \forall (m,n) \in O \tag{8}$$

$$\sum_{j \in D(i)} x_{i,j,n} - \sum_{k \in D(i)} x_{k,i,n} = \sum_{m:(m,n) \in O} yout_{m,n,i} - \sum_{g:(n,g) \in O} yin_{n,g,i} \quad \forall i \in I, \forall n \in M \tag{9}$$

$$\sum_{i \in I(h)} x_{h,i,n} \leq Harv_{h,n} \quad \forall h \in H, \forall n \in M(h) \tag{10}$$

$$\sum_{i \in I(f)} x_{i,f,n} \geq Dem_{f,n} \quad \forall f \in F, \forall n \in M(f). \tag{11}$$

With equation (8), we impose the mass balance for each treatment that transforms a quantity $yin_{i,m,n}$ of biomass at state *m* into a quantity $yout_{i,m,n}$ at state *n* with an efficiency $\eta_{m,n}$, as shown in Tables 1 and 2.

Through equation (9), the mass balance is imposed in every macro-node *i* of the supply chain. The net material flow towards other macro-nodes at state *n* equals the material flow entering *i* at the same state minus the quantity at state *n* consumed by treatments in the micro-graph *O* at the analysed facility, which bring material into a following state *g* plus the output of those operations in the micro-graph O_i, which transform biomass from a state *m* to state *n*.

D(*i*) is the set of sites that are linked to the intermediate macro-node *i* through feasible transport paths. *D*(*i*) includes other macro-nodes as well as harvest sites and the energy conversion node *f*: sets *D*(*i*) are thus in general subsets of $H \cup I \cup F$.

The supply constraint (10) requires that the total amount of biomass forwarded from harvest node *h* to all reachable intermediate nodes *I*(*h*) does not exceed $Har_{h,n}$. $Har_{h,n}$ represents the maximum biomass quantity that can be harvested in forest node *h* at state *n*, where *n* belongs to the set *M*(*h*) of feasible biomass states at harvest sites *h*. Given our assumptions, there is only one feasible harvest state, so we have $n = 1$ at every harvest site.

In a similar manner, the demand constraint (11) requires that the total biomass forwarded to the conversion facilities nodes *f* from linked intermediate nodes *I*(*f*), at a state *n* belonging to the set *M*(*f*) of acceptable states for combustion, is greater than or equal to the demand $Dem_{f,n}$ of biomass at conversion facility *f* and state *n*.

Finally, logical constraints presented in equations (12)–(13) follow from the model structure as presented in Figure 3.

$$x_{k,h,n} = 0 \quad \forall h \in H, \forall k \in (H \cup I \cup F), \forall n \in M(h) \tag{12}$$

$$x_{f,j,n} = 0 \quad \forall f \in F, \forall j \in (H \cup I \cup F), \forall n \in M(f). \tag{13}$$

While flows between intermediate sites can be bi-directional, directed flows go from harvest to intermediate sites and from intermediate to energy conversion sites, so:

- no biomass arrives at harvest nodes at any state from other nodes (equation (12))
- no biomass leaves conversion facilities at any state (equation (13)).

6 Model application and results

The mathematical model presented above is general and can be implemented and resolved with a commercial solver. In the following, we present the details of our implementation (Section 6.1). To deal with uncertainty in a deterministic framework, we performed scenario and sensitivity analysis. The way scenarios were defined is explained in Section 6.1, while we discuss the obtained results in Section 6.2.

6.1 Model implementation

The model described in the previous section was implemented in the modelling language AMPL® (see Fourer et al., 1990). Data about sites, existing connections and road distances, potentially available biomass quantities and biomass properties were organised as a relational MS Access database, which was then linked to AMPL. The case study was solved with the commercial solver CPLEX 8.0 (ILOG, 2002). The final model had 9730 constraints and 44,636 variables, of which 3120 were binary. The net time for the model instances solution was usually quite short (between 20 min and 2 h, depending on model instances, on a Pentium 4, 1.7 GHz PC), whereas because of the large size of data sets, about as much as the solution time was usually needed for data reading, upload and for report writing.

The model was deterministic, but several scenarios and sensitivity analyses have been developed to address at least some of the aspects of uncertainty and indeterminacy in this design problem.

First, to account for the classes of harvest potentials highlighted in the previous sections, which differ by ease and costs of harvesting, two scenarios have been introduced:

1 The Easy-To-Harvest (ETH) scenario, considering that available biomass is 17% of theoretical potentials in all municipalities and that harvesting cost is 17.8 €/t of residues at state 1

2 The Hard-To-Harvest (HTH) scenario, considering that in each the biomass available in each municipality is 57% of theoretical potentials, but the harvesting cost is 24.5 €/t of residues at state 1.

Second, while most likely conditions of biomass at various states after processing are those displayed in Figure 2, it should be considered that the properties of biomass at harvest might be quite variable depending on forest composition and the type of harvested residuals.

In particular, if forestry residuals are mainly constituted by limbs and logs, e.g., of young stands, then the density is close to that reported in Figure 2; if, however, small chunks, sticks, branches, leaves and needles form the majority of forestry residuals, then the specific volume of bulk residuals is quite higher and chipping becomes an effective way to reduce it.

To take these differences into account, we conceived two scenarios, that is:

1 The Dense At Harvest (DAH) scenario, assuming that biomass properties at states 1 and 2 are those reported in Figure 2, i.e., that chipping produces an increase in specific volume of biomass

2 The Bulk At Harvest (BAH) scenario, assuming that biomass has the same average water contents and heating values as in Figure 2 and that energy potentials available at various sites remain unchanged, but that at state 1 (residues before drying and chipping) bulk density of residues is 250 kg/m^3 and energy density is 493 kWh/m^3 while at state 2 (dried residues before chipping) bulk density is 188 kg/m^3 and energy density is 537 kWh/m^3, respectively.

Furthermore, a sensitivity analysis with respect to the amount of demanded biomass is performed, because the final size and the yearly operation time of the district heating plant at the user site were not yet fixed when this research started, nor had it yet been decided whether a cogeneration system should be coupled with the heating system, which would largely increase the yearly demand of biofuel. A base demand of 5000 MWh was assumed: this corresponds to an average heating demand of about 1650 kW for 3000 h/year, which could cover the heating requirements of the pool and of some 40 dwellings in the area. We investigate what happens if this demand is increased.

6.2 Results and discussion

Table 4 shows the economic results of model application to the scenarios described above.

In particular, it has been found that, using the whole biomass potential available in the ETH recovery scenario, a maximum demand of 9 GWh per year could be met, i.e., 1.8 times the base demand estimated for the conversion plant at the heating station, while the whole potential of the HTH recovery scenario would yield some 30 GWh/year, i.e., six times the base demand.

For the sake of comparison and to analyse the sensitivity of the optimal supply system to increasing demand, results are shown in Table 4 at the base demand and at 1.8 times as the base demand for both ETH and HTH harvest scenarios, and also at two, three and six times the base demand for the HTH scenario only. The model is solved in each case for both the DAH and the BAH density scenarios.

6.2.1 Economic aspects

Table 4 shows the cost per unit of energy potential of fuel delivered at the plant, divided into harvest, transport and treatment cost and including both operational and annual equivalent capital costs. The obtained results are comparable with analogous literature data, for instance with Van Belle et al. (2003), in particular with their costs of forest fuels supplied by small producers, i.e., the most expensive tier of procurement examined in that paper.

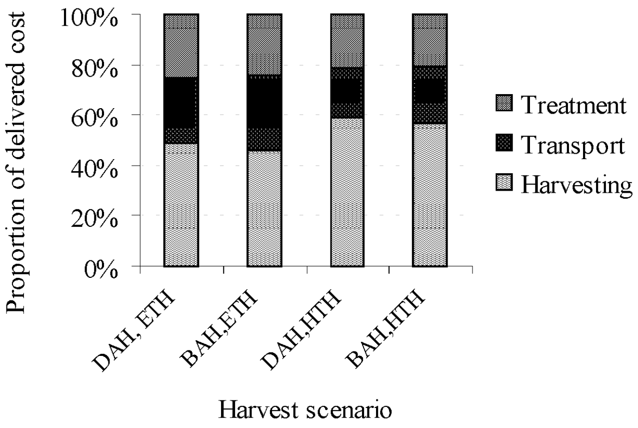
Figure 4 shows that, as could be reasonably expected, the weight of transport costs is lower in HTH than in ETH scenarios (16–18% against 23–28% of total costs, respectively), while the weight of transport costs is higher in BAH than in DAH scenarios (22–29% against 19–26%, respectively). Variations in the proportion of treatment costs are more limited: their share is some 3% points lower in HTH than in ETH scenarios and almost one-percentage point lower in BAH than in DAH scenarios.

It should be observed that because of the impact of harvesting costs, the minimum total cost is achieved in the ETH scenario, in particular at the minimum possible plant size. Even when the maximum ETH potential is exploited, the cost of delivered fuel is lower in the ETH than in the HTH scenario. From a biofuel cost point of view, this means that for plant managers it would be cheaper to harvest small quantities of biomass all over the region, rather than recovering residues from less accessible areas more close to the conversion plant.

Table 4 Optimisation results: unit costs and supply areas for different harvest, residues properties and demand scenarios

		1 x (5GWh/year)		*1.8 x* (9GWh/year)		*2 x* (10GWh/year)	*3 x* (15GWh/year)	*6 x* (30GWh/year)
		ETH	*HTH*	*ETH*	*HTH*	*HTH*	*HTH*	*HTH*
DAH	Harvesting cost [€/kWh]	0.00976	0.01343	0.00976	0.01343	0.01343	0.01343	0.01343
	Transport cost [€/kWh]	0.00456	0.00362	0.00569	0.00403	0.00411	0.00447	0.00572
	Treatment cost [€/kWh]	0.00510	0.00510	0.00491	0.00491	0.00489	0.00482	0.00475
	Total cost [€/kWh]	0.01942	0.02215	0.02037	0.02237	0.02244	0.02273	0.02390
	No. of source municipalities	27	5	36	18	19	26	36
	Max.distance [km]	34	9	111	26	26	34	111
BAH	Harvesting cost [€/kWh]	0.00976	0.01343	0.00976	0.01343	0.01343	0.01343	0.01343
	Transport cost [€/kWh]	0.00555	0.00427	0.00681	0.00484	0.00497	0.00543	0.00684
	Treatment cost [€/kWh]	0.00510	0.00510	0.00515	0.00491	0.00489	0.00482	0.00482
	Total cost [€/kWh]	0.02041	0.02281	0.02172	0.02319	0.02329	0.02368	0.02509
	No. of source municipalities	26	5	36	17	19	25	36
	Max. distance [km]	31	9	111	25	26	31	111

Figure 4 Proportion of operations costs to total costs of forest biofuel delivered at the conversion plant



The total fuel cost is, under all circumstances, competitive with that of traditional fossil fuels. The costs of obtained forest biofuels range, in fact, between 1.94 €c/kWh and 2.51 €c/kWh, while at the moment in Italy the corresponding cost of natural gas is about 6.5 €c/kWh and the cost of fuel oil is about 10.9 €c/kWh. This large margin between traditional and biomass fuel may well compensate larger investments in infrastructure (boilers and district heating systems), which are required to exploit biomass when compared with fossil fuel heating systems. Based on these considerations, we can expect that energy entrepreneurs' decisions will depend on their propensity to risk, on the availability of capital and on economies of scale in plant construction and management. If economies of scale are substantial and companies are inclined to invest large capitals and to accept longer payback rates in exchange for larger returns, than they are likely to install as large as possible heating systems or even cogenerators, thereby meeting all feasible heating demands and possibly recovering the whole biomass potential in the area.

6.2.2 *Supply chain structure*

Table 4 also shows the distance between the conversion plant and the farthest supplying municipality in each scenario and the number of municipalities within the supply area. These numbers increase with growing energy demand at the conversion plant and moving from the ETH to the HTH scenario.

The optimal processing chains resulting from model solutions are as follows:

If residues at harvest are relatively dense (DAH scenario):

- natural outdoor drying of residues at most harvesting municipalities (1–2)
- transportation of dried residuals to the conversion plant in state 2
- chipping and final drying in covered storage at the conversion plant (2–5).

This holds in all demand scenarios. Exceptions concern three municipalities, bordering the user village, from where forestry residues are transported as harvested (state 1) directly from forests to the conversion plant where complete, centralised processing (1–5) is performed.

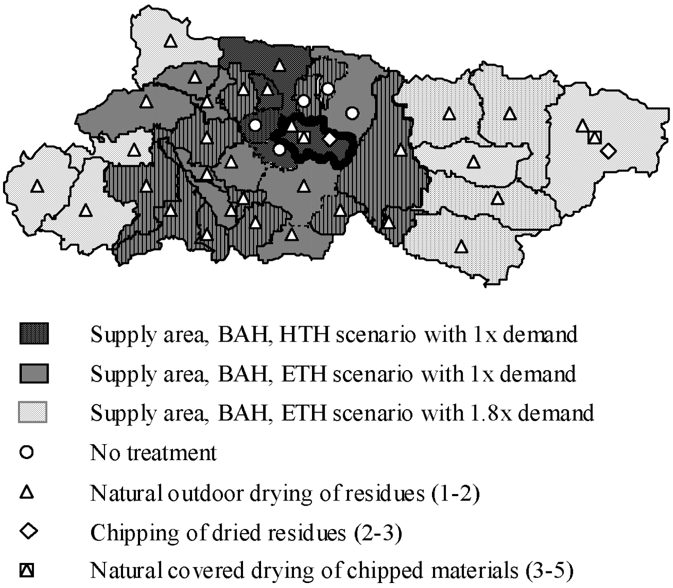
If residues at harvest are relatively bulk (BAH scenario):

- If demand is lower than 30 GWh/year in the HTH scenario or lower than 9 GWh/year in the ETH scenario, the processing chain structure is as in the DAH scenario, but residues are transported as harvested from the forest from two further municipalities, which are close to the plant (see Figure 5 for the 1.8x, ETH scenario).
- For maximum demand, both in the HTH and in the ETH scenario, a second processing station, comprising chipping operations and final drying in covered storage, is located at the farthest municipality (111 km from the conversion plant), as shown in Figure 5 for the 1.8x, ETH scenario. Chipped and dried biomass is thus transported in state 5 from the farthest municipality.

Figure 5 also shows how the supply area expands encompassing new municipalities when demand grows. It can be observed that the supply area in the ETH, 5 GWh demand scenario is rather expanded to the West of the user municipality (left side in the picture), and that the bordering municipalities where no treatment is performed are mostly located at East; this also holds for the 9, 10 and 15 GWh demand, HTH scenarios.

Looking at road conditions, we noticed that while the extreme east of the region is well connected even with highroad to the southern part and, thereby, to the potential conversion plant, local road connections to the user site are worse from the eastern than from the western part because of valley conformations. Thus, only smaller and slower vehicles can be used for local connections from East: as a result, the improvement that can be achieved by previous treatment of residues does not compensate the additional costs it requires, so direct transport from forest with tractors and centralised treatment at the plant is performed.

Figure 5 Supply areas and treatment options in the 'bulk-at-harvest' scenarios for input demands of 5 (1x) and of 9 (1.8x) GWh/year



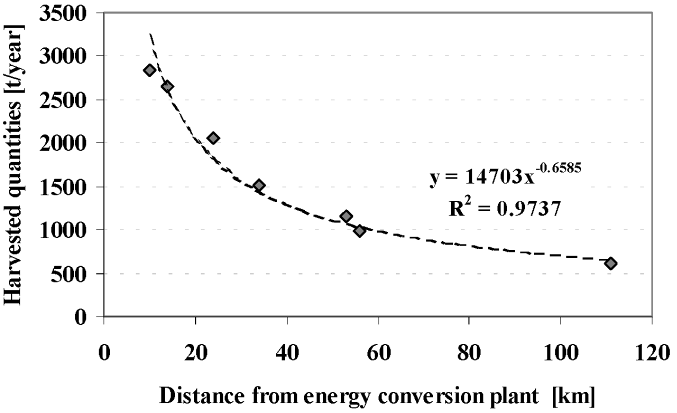
It should be stressed that centralised chipping at the energy conversion plant is performed in most cases and through all scenarios: cost minimisation thus adds up to the strategic advantage of giving the thermal energy station operator greater control over the chipping process and the size distribution of the chips which are fed into the boilers (Allen et al., 1998).

Decentralised chipping is only performed for maximum demand, when the farthest municipality at East is incorporated in the supply area, e.g., as represented in Figure 5 for the ETH scenario.

By comparing Figure 1 with Figure 5, we notice that the second chipping plant is not only located in the farthest but also in one of the most productive municipalities in the area. The question is, then, to what extent does the viability of decentralised chipping depend on distance and to what extent on plant capacity.

To examine this issue, we performed a sensitivity analysis for the HTH, BAH scenario and a 30 GWh/year demand by swapping the quantities available at the farthest municipality with closer ones and by gradually decreasing the amounts available at extreme sides, thereby maintaining constant the total available quantities. The results of this analysis are diagrammed in Figure 6.

Figure 6 Relation between minimum plant size and distance from the energy conversion station of a second treatment facility



The minimum yearly harvested quantity at site *i* that leads the optimisation procedure to allocate a second, decentralised treatment facility (comprising chipping and covered drying) at that site is reported on the vertical axis, while the horizontal axis shows the distance of the harvest site *i* from the first treatment facility *j*, which is always located at the energy conversion plant. The system behaviour is approximated by the interpolating power function reported in Figure 6, which yields a rule of thumb for determining whether decentralised chipping is opportune for bulk-at-harvest residues under our cost structure assumptions: if the combination of distance from the first treatment facility and harvested quantity in wet tons per year is above the curve, than adding a specific treatment facility at the harvesting municipality is advantageous. A main interaction between transport distance and plant capacity is thus shown. More interactions are likely to emerge if wider supply areas and larger fuel demand (e.g., for cogeneration plants) are considered: the model application would be especially useful in that case to solve facility location and allocation problems.

7 Conclusions and future research

The analysis of this case study has shown that specific costs of biofuel delivery from local supply chains to small bioenergy plants can be high: this implies that applying logistics modelling to support strategic supply chain planning decisions may be even more important and beneficial in this case than for systems on a larger, industrial scale.

Hence, our work confirms the central role that logistic specialists can play in solving biofuel supply chain issues: therefore, we reiterate our initial plea for logistics professional to get actively involved in the renewable energy business, also in view of increasing interest for alternative fuels of different kinds (solid, liquid, gaseous), for various purposes (heating, power generation, transportation) and especially from local, small-scale supply chains, which are more and more preferred for ethical and environmental reasons.

The proposed design optimisation model could be a step in this direction. Its application to our case study has highlighted interactions between quantities of collected raw materials, distances from the final user and the expediency of decentralising processing operations that favourably affect transportation costs. An integrated planning of facilities locations and size and of transportation is, therefore, significant. The introduced model, which takes into account the effect of processing on transportation costs, can be useful to support supply chain designs for different fuels, for agri-chains, for residues and, more generally, whenever transformations of fuels and materials, such as e.g., gasification, liquefaction or compaction, result in changes of transportation costs.

In our opinion, both the proposed approach and the numerous biofuel logistics modelling approaches, which, as shown in the review section, are mainly reported in sector-specific literature, can be further improved by taking advantage from modelling approaches and experiences of integrated supply chain planning in other sectors, in terms of functional, spatial and intertemporal integration (Shapiro, 2001). In our case, for instance, further steps towards the integrated strategic planning of the forest fuel supply chain would include the choice between harvesting technologies, as soon as enough data are available, which also entails consideration of harvest timing and a more refined modelling of time dependent aspects, including storage management.

Finally, a practical implication of our study concerns regional governments or communities willing to support the installation of bioenergy plants with the goals of building local markets for biomass residues, fostering forest maintenance and reducing pollution. As shown in the previous sections, high harvest costs may lead to scattered procurement, rather than to a more local and intensive harvest, which results in limited investments in forest maintenance infrastructure, more road transport and corresponding pollution. A further conclusion of our work is, then, a call for local policy-makers to consider the logistics implications of their interventions and to involve logistics specialists to support decision-making. From a research perspective, this entails developing methods to incorporate multiple voices and criteria into models and to resolve possible conflicting objectives in strategic supply chain design for biofuels.

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